CLIMATIC SENSITIVITIES OF NAVAJO FORESTLANDS: USE-INSPIRED RESEARCH TO GUIDE TRIBAL FOREST MANAGEMENT

Christopher H. Guiterman

School of Natural Resources and the Environment
Laboratory of Tree-Ring Research
University of Arizona
chguiterman@email.arizona.edu

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EXECUTIVE SUMMARY

- Climate change is already affecting forest ecosystems throughout the Southwestern US, with drought-related tree mortality on the rise and large, high-severity portions of wildfires increasing in numbers and area.
- Climate projections show that extreme drought conditions over the last 1,000 years in the Southwest region will be more like average conditions by the year 2050. This is driven almost entirely by warming temperatures from anthropogenic greenhouse gasses.
- Future droughts mean greater losses of old trees and forestland in general, which could have detrimental downstream effects on ecosystem services provided by forests, including clean water and stable soils. In the case of Native American communities in rural areas, such as for the vast Navajo Nation, losses of ecosystem services would have a disproportionate effect on human well-being compared to more built urban areas in the region.
- Uncertainties remain regarding how these changing climate conditions at the regional scale (10^5 km^2) will manifest at landscape (10^3 km^2) to stand (10^{-1} km^2) scales, where forest management is concerned. Specifically, we lack a complete picture of what stands growing under what types of physiographic conditions may be more or less at risk to increased temperatures and drought.
- This study was initiated and designed under a collaborative partnership between the Navajo Forestry Department and researchers at the Laboratory of Tree-Ring Research in order to address concerns voiced by the NFD regarding the vulnerabilities of their forests to climate change.
- The study represents the first attempt to assess climate sensitivities of differing forest stands on the Navajo Nation to past climate conditions in order to parse the landscape based on likely future vulnerabilities. In so doing, the study partners have utilized an existing network of Continuous Forest Inventory (CFI) plots to ensure representation of the landscape and provide additional information useful to the forest managers.
- The methods were to extract increment cores from CFI plot trees in order to (1) estimate long-term (>100 years) stand-level productivity and variability in tree growth, (2) perform correlation analyses between plot-level tree growth and instrumental climate data (monthly/seasonal precipitation, temperature, and vapor pressure deficit), and (3) generate detailed age-structures for the sample plots.
- Results show good correspondence between tree-ring derived growth metrics and repeated plot inventories by the NFD across the plot network, varying climate sensitivities between plots based on physiographic factors (aspect and slope angle in particular), and generally multi-aged stand structures that could help managers in designing prescriptions aimed at increasing resilience. A complete picture of landscape-scale forest vulnerabilities to climate change will require more work with these same methods, but as a pilot study this effort was a certain success.
- The co-production of dendrochronological and climate-relevant datasets by the NFD and LTRR personnel has enabled this study to act as a boundary object that brings scientific information to the forefront of management needs. With the goal of answering research questions put forth by the NFD, the study described here represents the first step in a multi-year effort to provide relevant and useful data for addressing concerns regarding the potential effects of climate change on the forestlands of the Navajo Nation.

INTRODUCTION

Climate change is profoundly affecting forest ecosystems, with drought-related tree mortality documented globally (Allen et al. 2010) and rates of tree mortality on the rise in the western US (van Mantgem et al. 2009). Climate projections put the Southwestern US (SW) in particular risk due to increased temperature (Seager et al. 2007, 2012; Garfin et al. 2013), which amplifies drought via an exponential influence on atmospheric moisture demand (i.e., vapor pressure deficit [VPD]; Breshears et al. 2013; Williams et al. 2013). In recent decades, roughly 20% of forests and woodlands in the SW have been impacted by drought-related mortality, bark beetle outbreaks, and high-severity wildfires (updated from Williams et al. 2010). By ca. 2050, increased temperatures in the SW are projected to drive the average level of forest drought stress to levels unsurpassed since the "megadroughts" of the mid-1100s, late 1200s and late 1500s (Williams et al. 2013). Evidence in the tree-ring record indicates that these past extreme and long-lasting droughts were associated with tree die-offs across the SW region (Swetnam and Betancourt 1998), suggesting that more widespread die-offs and severe disturbances should be expected.

These are grim projections for the people and forests of the Southwest. Many SW communities, and larger cities alike, rely on the ecosystem services provided by healthy forests. These include clean water supply, stable and fertile soils, and forest products (Garfin et al. 2013). Native peoples of the region are particularly vulnerable because they often live in widespread and rural communities or in isolated settlements, with a disproportionate reliance on ecosystem services for basic and economic needs (Lynn et al. 2013; Voggesser et al. 2013; Gautam et al. 2013).

The Navajo Nation is the largest tribal landholder in the US, and climate change is already impacting its supply of drinking water, abundance of important medicinal plants, and economic vitality of livestock grazing across the vast reservation (Ferguson et al. 2011; Cozzetto et al. 2013). The Navajo Forestry Department (NFD) is tasked with preserving and enhancing resilient forests (> 2 million hectares) to mitigate the effects of increasing temperatures and drought, but due to a paucity of forest research on Navajo lands, they have few data or analytical tools to address current and potential changes. Recognizing this hurdle to forest management, the NFD has identified research needs to assess vulnerabilities of their forests to severe drought and climate change. These needs include (1) quantifying forest growth across a range of forest types, (2) identifying the climatic drivers of forest growth, and (3) producing landscape-scale estimates of age structure.

This study was designed to meet the needs voiced by the NFD foresters, and was done as a collaborative partnership between the NFD and researchers at the Laboratory of Tree-Ring Research. The study design meets the definition of "use-inspired" research (Stokes 1997), because it has direct applicability for the NFD, who are in the process of developing their next 10-year management plan, and addresses a fundamental question in science. Our broader scientific question concerns how regional-scale (10^5 km^2) climatic sensitivities and projections of tree growth manifest at landscape (10^3 km^2) to stand (10^{-1} km^2) scales where forest management is concerned.

METHODS

Study Area

This study took place in the Chuska Mountains, situated on the eastern portion of the Navajo Nation and on the Arizona-New Mexico border. The Chuskas comprise the majority of commercial forestland on the Navajo Nation (approx. 150,000 ha; BIA Division of Forestry 1995) and some of its most vital watersheds (NNDWR 2011). The top of the mountain range consists of a long and narrow (800 – 1000 m) crest of sandstone oriented northwest (Wright 1956), with higher peaks located throughout the range, as well as late Oligocene volcanic features (Appledorn and Wright 1957; Cather et al. 2008). The east flank of the range slopes steeply for over 600 m, including a 10-30 m cliff band that extends for nearly its full length. The west flank is more gently sloped, but cut through by canyons. The majority of the crest is flat, with broad, shallow lakes and depressions (Wright 1964) that fill with water seasonally and remain year-round except during prolonged drought.

The climate of the Chuska Mountains is continental and semi-arid. Precipitation is dominated by summer convective storms (rain) associated with the North American Monsoon, with highly variable winter precipitation (snow) (Sheppard et al. 2002). Mean annual precipitation is 332 mm, with July-September accounting for 45% of the total (1900-2010; PRISM 2012). The wettest month on average is August with 62.1 mm, and March is the wettest winter month averaging 22.1 mm of precipitation. Average minimum temperatures range from -8.6^0 C in January to 10.2^0 C in August, and average maximum temperatures range from 4.9^0 C in January to 27.0^0 C in July (1900-2010; PRISM 2012).

The spatial distribution of forest types across the Chuskas is defined mainly by elevation and secondarily by aspect (Lowry et al. 2007). The lowest elevations (> 2000 m) are dominated by piñon-juniper woodlands that grade into ponderosa pine forests above 2400 m. The crest top (2700 - 2800 m elevation) consists of patchy stands of ponderosa pine surrounding grassy meadows and lakes. North-facing aspects are often dominated by wet mixed conifer or spruce-fir forests, despite being at the same or lower elevation than the ponderosa pine forests of the crest. Gambel oak is a common species throughout all forests, except at the wettest sites where quaking aspen can be major stand component.

Field sampling

For tree-ring sampling in the Chuskas, we utilized an existing network of forest monitoring plots to help ensure representation of the landscape. The systematically located Continuous Forest Inventory (CFI) plots lie within the commercial forest areas of the Navajo Nation, and are managed by the Navajo Forestry Department and the Bureau of Indian Affairs Division of Forestry. Within the Chuskas, the CFI network consists of 146 plots, each with three fixed-area 0.10 ha circular subplots. The grid is laid out in squares with 1.6 km sides, and one plot every 4.83 km along the horizontal direction (east-west) and every 2.26 km diagonally (northeast) (BIA Division of Forestry 1995). Initial installation of the network began in 1974, and most plots have been measured every decade since, with the last measurement in 2004 (Alexious Becenti

Sr., Navajo Forestry Department, pers comm.). During regular inventories, trees over 12.7 cm dbh (1.37 m) on each subplot are tallied and measured for height and diameter.

For this pilot study, we sampled plots from the Chuska CFI network in the southern portion of the Chuska Mountains, where access would be easiest (Figure 1). We selected individual plots that were classified as either ponderosa pine or mixed conifer overstory composition. At each plot, we sampled from one subplot that had at least 10 trees, and if all subplots had more than 10 trees, we chose the one with the middle tree density. We recorded plot attributes such as forest type, slope angle and aspect, soil type and characteristics, evidence of previous fire and logging, and general observations of the plot, stand, and site conditions. We tallied all previously inventoried trees on the subplot for live/dead condition and measured dbh on living trees. The largest 10 ten trees were then cored twice at 90^0 below 0.9 m, with one core on the uphill side and the other perpendicular to the slope in order to more accurately estimate past diameter growth (Bakker 2005; Nehrbass-Ahles et al. 2014). For each cored tree we recorded location with a GPS, measured coring height, diameter at coring height, azimuth and slope position of the core, crown ratio, and noted crown class and any injuries.

In the lab we mounted, sanded, and visually crossdated the cores following dendrochronogical standards (Speer 2010), and then measured ring widths to 0.001 mm on a Velmex® machine. Quality control and crossdating accuracy were verified with COFECHA (Holmes 1983; Grissino-Mayer 2001). From these measurements of tree-growth we constructed two types of chronologies: standardized ring-width index and basal area increment chronologies. For the standardized ring-width index chronologies, the ring widths of all trees were detrended by division against a cubic smoothing spline with a frequency response of 0.5 at a wavelength of 50 years (Cook and Peters 1981). Chronologies were then built for each plot by robust bi-weight averaging of the detrended series (Cook et al. 1990). Basal area increment chronologies were built by using the ring widths to estimate past inside-bark diameters and converting to basal area growth, then summing all of the trees on a plot, and converting to m^2 ha^{-1}. Tree-ring standardization and chronology building were carried out in the *dplR* library in R (Bunn 2008; R Core Team 2014).

We assessed the climatic drivers of tree growth with comparisons of the plot-level ring-width index chronologies and instrumental climate data. Instrumental climate data included gridded monthly total precipitation (PPT), average maximum daily temperature (Tmax), and average minimum daily temperature (Tmin) from seven nearby PRISM points (PRISM 2012). We also calculated mean monthly VPD for the Chuska Mountains from daily minimum, maximum, and dew-point temperatures as in Williams et al. (2013). Timeseries data from PRISM gridpoints were averaged together. We performed correlation analyses between the climate variables and tree-ring chronologies in R using the *treeclim* library (Zang 2014). The month, season, or combinations of months with the strongest correlation to tree growth variability were selected as the primary predictors for tree growth.

RESULTS AND DISCUSSION

Working together with foresters from the Navajo Forestry Department, we sampled seven plots from the Navajo Nation CFI plot network, including 111 trees and 222 increment cores. Basal area increment chronologies derived from the cores paired well with measures attained from repeated plot inventories, which began in 1974 (Figure 2). One advantage of the tree-ring data is that it provides annual measures of productivity that show the range of variability in stand and tree growth (Biondi 1999). The ring-width index chronologies for each plot display this variability in another way, with a greater emphasis on year-to-year changes in relative growth as opposed to total productivity of the stands (Figure 3). The ring-width chronologies show the influence of multi-year droughts on reducing tree growth, including during the 1840s-1850s, beginning of the 1900s, 1950s, 1970s, and the 2000s.

Differences in the variability of average annual growth between the plots likely reflect differences in the physiographic conditions present at the plot. For example, plot 33302 is situated on a southwest-facing slope with thin and rocky soils, the type of site that dendrochronologists target for enhanced climate signal (or sensitivity) in tree growth (Fritts 1976; Speer 2010), and its ring-width pattern is highly variable on annual to decadal scales. This is in contrast to the chronologies from plots 29411 and 32352, which were located on easterly slopes with deeper and well-drained soils. These types of sites have generally high moisture availability for trees and thus tree growth is rapid and non-varying (or what is referred to as "complacent"). Interestingly, at plot 32352, there is very little decadal variability until the 1970s when the number of trees contributing to the chronology tripled. The effect could be related to greater sample depth and therefore better signal, or the younger trees are growing with greater environmental stress – due to competition or lower water tables from the recent drought – that is reflected in higher overall variability in growth.

During particularly stressful years, trees may not activate the cambium at the location where they were sampled (near the base of the tree), resulting in locally absent or "missing" rings (Speer 2010). In the Southwestern US, moisture is the critical limiting factor, and as such drought years will have a higher incidence of missing rings (St. George et al. 2013). The distribution of locally absent rings on the sampled CFI plots highlights the years in which climate was most stressful (Figure 4). For example, in 2002, 42% of all sampled trees had a locally absent ring. Differences between plots are also apparent: plot 33302 has the highest incidence of missing rings, while very few are present at plot 32352; suggesting in the former case that growth stress is higher at the exposed and thinly soiled 33302 than at the more gently-sloped and east-facing (sheltered) 32352.

Tree growth across the plots responded most strongly to early winter (October through December) precipitation and summer (June through July) maximum temperatures and vapor pressure deficit (VPD) (Figure 5). Correlations with monsoonal (July through September) precipitation were weak overall and nonexistent at four plots. That winter precipitation shows up as a significant driver of tree growth across the CFI plots is no surprise given the high degree of tree-growth sensitivity to winter precipitation across the Southwest region (St. George and Ault 2014). Likewise, these correlations were made with total ring-width chronologies, as opposed to partial ring-width chronologies, where the latewood portion of the tree-ring may be a better indicator of monsoon activity (Meko and Baisan 2001; Griffin et al. 2011). The influence of summer temperatures is to suppress ring growth through moisture loss, and therefore the summer temperature and VPD correlations highlight seasonal drought sensitivity. Interestingly, the correlations with VPD are nearly equal in absolute terms to those of maximum temperature, despite a nonlinear relationship between temperature and VPD (Williams et al. 2013). What changes, however, is that more plots reflect the influence of VPD than do maximum temperature, suggesting that VPD may be a better metric for assessing sensitivity to temperatures, which generally supports the findings of Williams et al. (2013). In general, those plots that most strongly correlate to precipitation also correlate strongly to temperature and VPD, once again reflecting the physiographic differences among the plots that drive climate sensitivity. In other words, our data point to more exposed stands being more sensitive to climate variability and extremes. It may be that these types of site are most at risk to the effects of future droughts, but our data are too incomplete for this to be anything but speculative for the forests of the Navajo Nation.

Age structures between the sampled plots are highly variable, but all show a multi-aged stand structure (Figure 6). Probably the most consistent pattern of tree recruitment is a pulse ca. 1850, present in four plots. This period is relatively dry with low tree growth across the plot network (Figure 3), and so the reason for a pulse of tree recruitment is uncertain. It is plausible (but speculative) that trees could have begun recruiting in the 1840s following the 1830s disruption of the surface fire regime in the Chuska Mountains (Savage and Swetnam 1990). However, Savage (1991) showed that recruitment in the Chuskas was lagged until the early 1900s when climate was presumably more favorable (Savage et al. 1996). In our sample, there is little regeneration during the 1910s “pluvial” event, and a pulse of trees is present at plot 32352 in the 1950s, which may have been the worst drought recorded by our tree-ring chronologies. That recruitment tends to occur during drought events in this sample suggests that local conditions and disturbances may override the influences of regional climate, as was recently shown for one area of northern Mexico (Meunier et al. 2014), but more direct tests are required to be sure if this pattern indeed holds through space and time.

This project was forged out of a science-management partnership between the NFD and LTRR, and has benefitted both sides from active and iterative discussions and collaborations. This so-called boundary work (Fisher 1989) has been shown to successfully bridge between scientists and decision makers toward the goal of achieving usable results (Lemos and Morehouse 2005). In our case, the project inception, design, and data collection were done in collaboration, representing substantial co-production of information. The pilot study described here has laid the groundwork for further work by us as a collaborative enterprise toward the ultimate goal of answering the research questions put forth by the Navajo Forestry Department.

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FIGURES

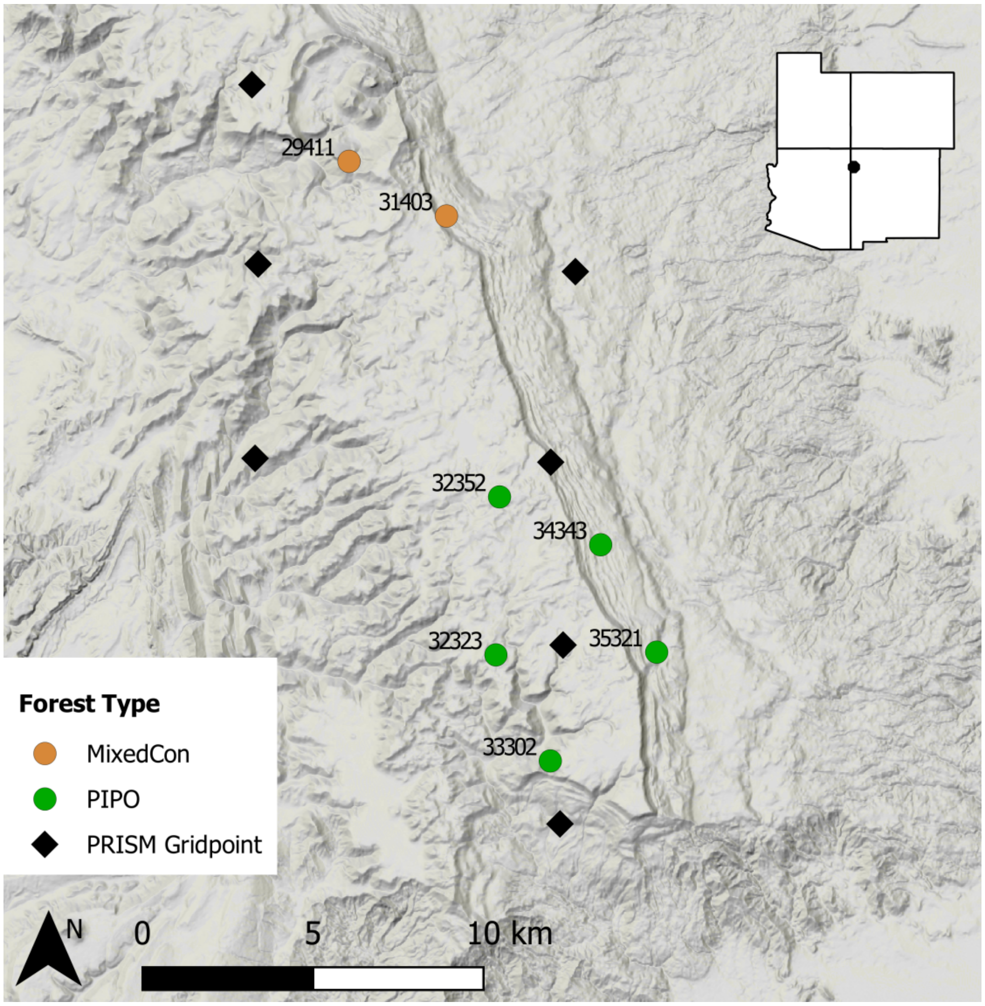

Figure 1. Sampled plots in the southern portion of the Chuska Mountains, Navajo Nation. Plot IDs and forest type designations are indicated. PRISM gridpoints where instrumental climate data were attained are shown.

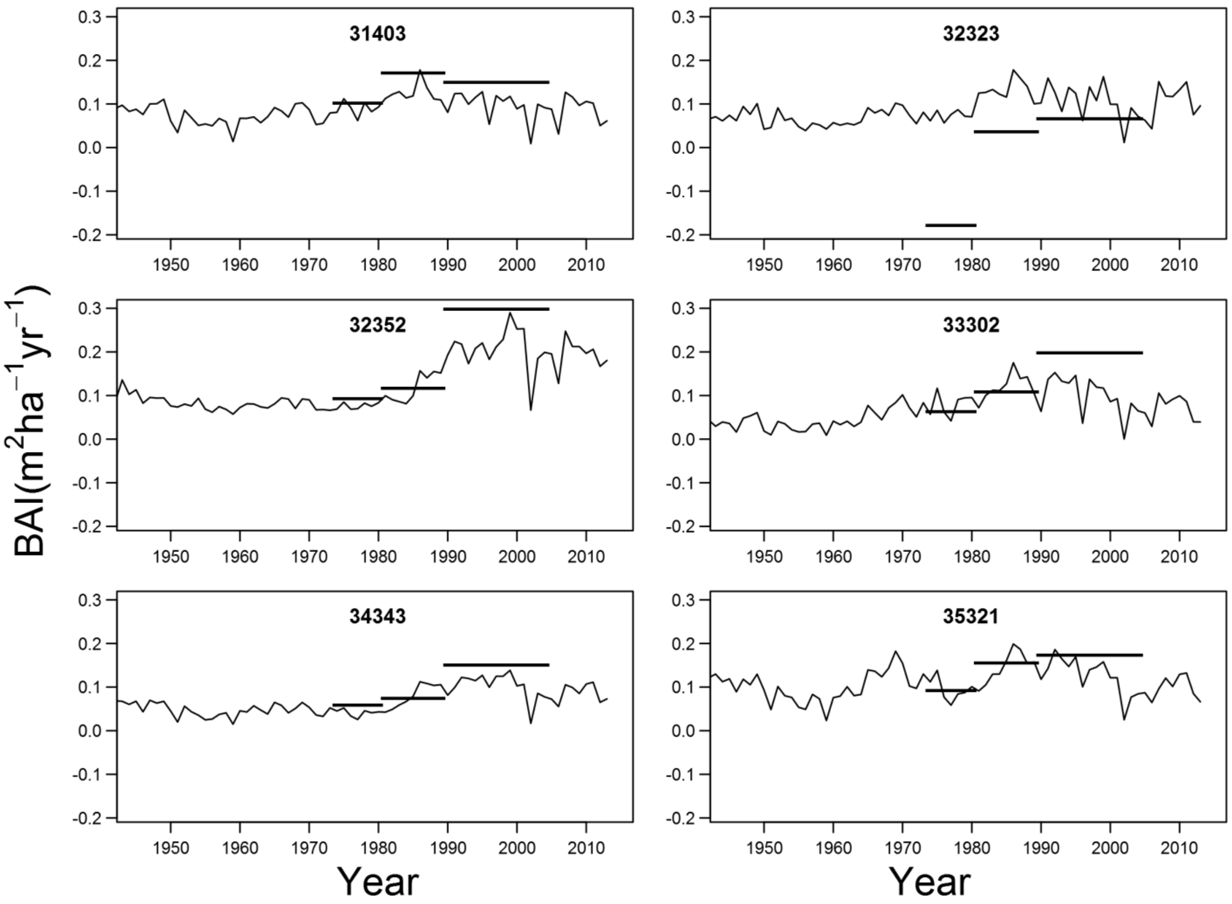

Figure 2. Basal area increment for the six plots with repeated inventory data. Solid, horizontal lines represent BAI derived from inventory data and curves show annual values from tree-ring data. The two sets are for sampled trees only.

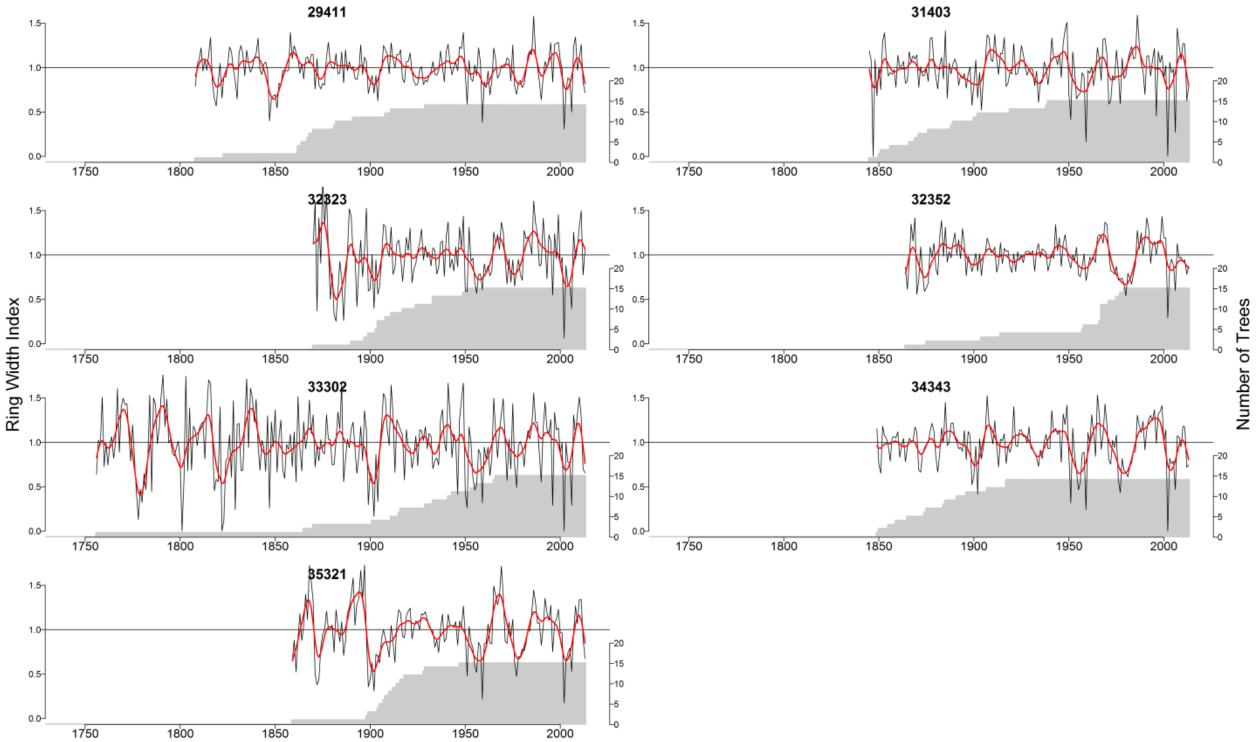

Figure 3. Standardized ring-width chronologies for each sample plot. Grey shading represents the number of trees in the chronology, black lines show annual values, and red lines represent 10-year cubic smoothing splines.

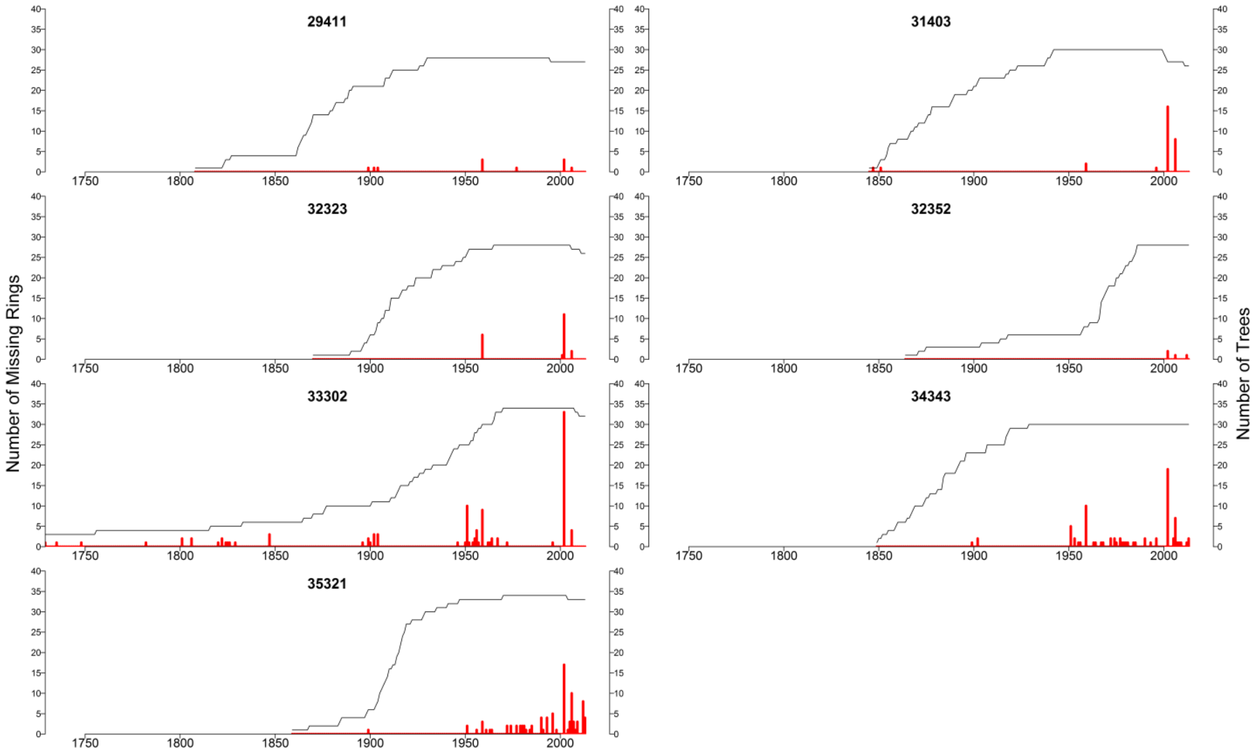

Figure 4. Histograms for the number of locally absent or “missing” rings by year for each plot. Stressed trees may not grow a ring in that year at the location where increment cores were extracted (near the base of the tree). This record documents particular years when trees were stressed; for example in 2002, 42% of sampled trees did not show a ring.

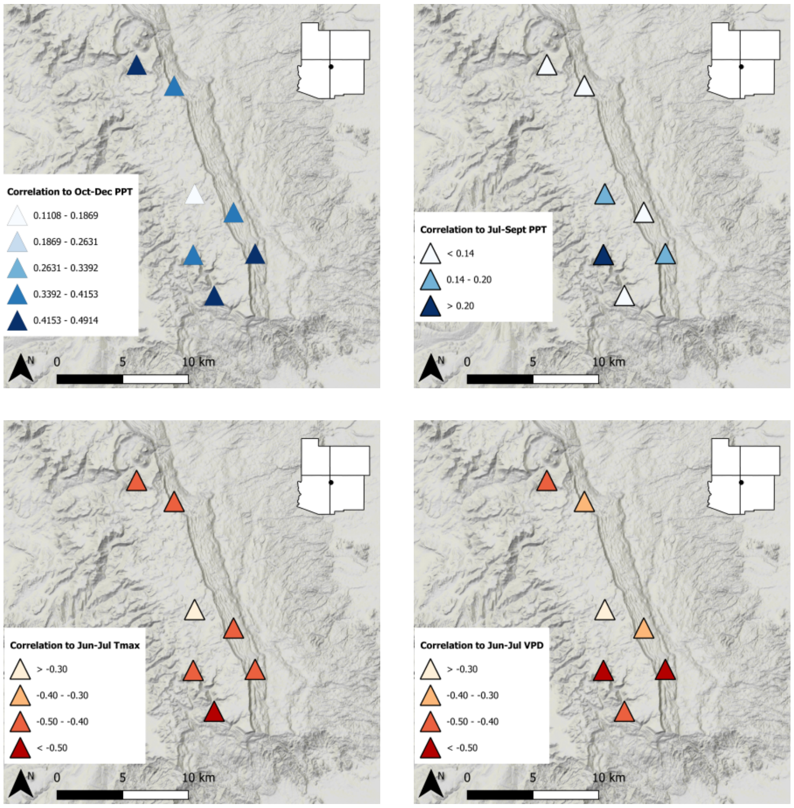

Figure 5. Spatial variation in sensitivity to climate. Each map shows the correlation of plot-level ring-width chronologies to specific climate variables, with colors designating the strength of the relationship: top left, spring (Mar-Jun) precipitation; top right, summer (Jul-Sept) precipitation; bottom left, summer (Jun-Jul) maximum temperature; bottom right, summer (Jun-Jul) VPD.

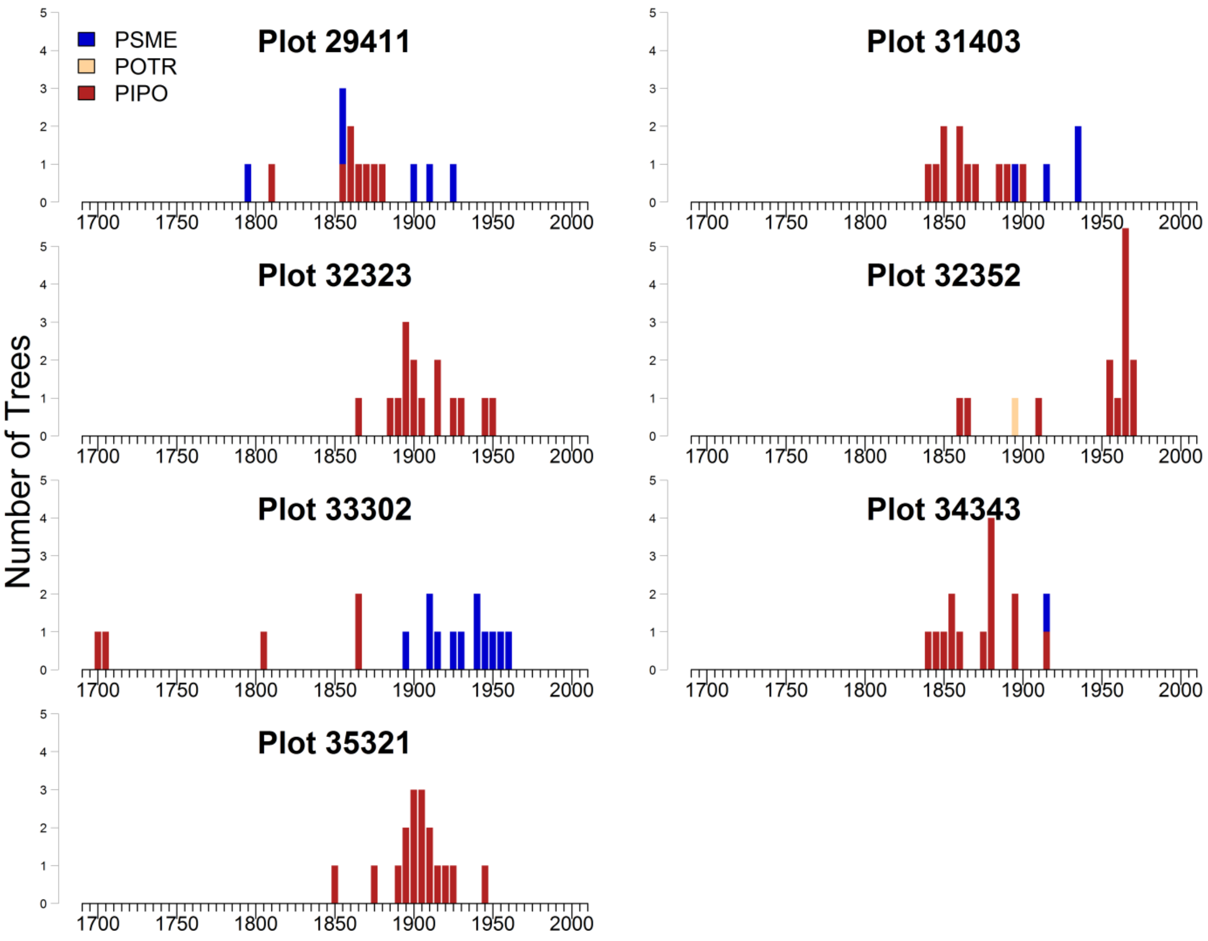

Figure 6. Age structure timeseries for the seven sampled plots. Recruitment pulses appear in the 1840-1850s, 1890-1900s, and 1970s. Species are Douglas-fir (PSME), quaking aspen (POTR), and ponderosa pine (PIPO).