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Episodic Recruitment and Climate Analysis of Ponderosa Pine on the Palmer Divide, Eastern Colorado

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EPISODIC RECRUITMENT AND CLIMATE ANALYSIS OF PONDEROSA PINE ON THE PALMER DIVIDE, EASTERN COLORADO

A Thesis
Presented to
the Faculty of Natural Sciences and Mathematics
University of Denver
In Partial Fulfillment
Requirements for the Degree
Master of Arts

By
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Advisor: Donald G. Sullivan
Abstract

Previous recruitment studies on populations of ponderosa pine (*Pinus ponderosa* P. & C. Lawson) in Colorado have been limited to the western mountains and the Front Range. In this research I used tree-ring data to reconstruct recruitment for ponderosa pine near the eastern limits of its distribution at two sites on the Palmer Divide, Eastern Colorado, to determine the relative climate sensitivity of the two sites, and the extent to which climate or other factors may have influenced recruitment at the sites. The results of the tree-ring analysis suggest that ponderosa pines in more the easterly site lower elevation population are more sensitive to climatic factors than are in the more westerly site. Both higher elevation populations showed a history of episodic recruitment that only partially reflects local climatic conditions. Climate is probably the most important factor in recruitment pulses, but only if there is opportunity within the stand for recruitment. Although favorable climate patterns were present at both sites at the same time, the opportunity for recruitment within each stand was different at separate times. While climate conditions must be favorable for seedling establishment and growth, conditions of stability and competition within the stand dictate the ultimate recruitment success.

Key Words: Dendroecology, Episodic Recruitment, Climate, and Palmer Divide
Acknowledgements

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CHAPTER ONE: INTRODUCTION


In spite of these studies, little is known about the episodic recruitment and climate response of ponderosa pine near the eastern limits of its distribution on the Palmer Divide in Colorado (Fig.1). Previous research involving tree recruitment in Colorado has been limited to areas that are either in the mountains or along the Front Range. None of these studies have examined tree recruitment on the eastern end of the Palmer Divide, where
the stands of trees exist on montane islands surrounded by grasslands with insufficient precipitation to support tree growth (Thompson et al. 2000).

Understanding past climate variation and its effect on vegetation is vitally important to researchers, land managers, and policy makers. Unfortunately, many parts of the western U.S. have less than a century of reliable instrumental climate records. Proxy data such as tree rings have filled the gap in knowledge of past climate in many parts of the region.

Ponderosa pine (Pinus ponderosa P. & C. Lawson) is the dominant species in the montane forest at the lower elevation in the Colorado Front Range (Schubert 1974). The elevational range of the montane forest is approximately 1850-2770 m (Huckaby et al. 2003). The Palmer Divide is a dissected upland south of Denver and north of Colorado Springs that separates the drainages of the South Platte and Arkansas Rivers. Elevations on the divide range from about 1700-2350 m. Stands of ponderosa pine are found in several locations along this broadly sloping ridge. In this project I analyze the climatic sensitivity of the tree-ring record, and the conditions that influence the recruitment of ponderosa pines at two sites, one located near the base of the Front Range, and the other at the easternmost ponderosa pine stand on the Palmer Divide.

**Literature Review**

Examining old and newly acquired tree-ring chronologies, Woodhouse and Brown (2001), and Woodhouse et al. (2002) found a strong correlation between spring and summer Palmer Drought Severity Index (PDSI)(Palmer 1965) and tree-ring widths
from the eastern plains of Colorado. Previous research involving tree recruitment in Colorado has been largely limited to study areas in the Front Range. Mast et al. (1998), in a study in Rocky Mountain National Park and Boulder County, identified a correlation between recruitment and climate. Mast et al. (1998) cored trees at uniform (1.4m) height and assumed that trees all reached that height at the same age. However, coring at uniform heights does not necessarily translate to consistent establishment years; since trees may grow at different rates, so their results suffer from necessarily coarse chronological resolution. Despite problems associated with determining the recruitment year, the authors determined that successful ponderosa pine recruitment was positively linked to above average precipitation in the spring and early summer.

Similar results were reported by Brown and Wu (2005) in a study of ponderosa pines on Archuleta Mesa near Pagosa Springs, Colorado; they studied germination success as it relates to El Niño Southern Oscillation (ENSO). This study used uniform coring heights to estimate germination dates. Results showed an increase in germination during wet springs and early summers of El Niño years above that of La Niña years, which were dryer and had a higher occurrence of fires. Brown and Wu (2005) compared climate factors, including ENSO, with fire chronologies in the Four Corners region and recruitment dates for ponderosa pine and other tree species. They found that pulses of recruitment coincided with periods of low fire and moister conditions. Major recruitment pulses occurred around 1700-1715, 1825-1840, 1860-1900, and 1905-1920, summarized in Fig 2.
League and Veblen (2006) studied recruitment of ponderosa pines on the Front Range by “destructively sampling” seedlings in an effort to effectively date the establishment year to annual resolution. Seedlings, including the root ball, were removed to more precisely date the year of germination.

Research Questions

1. Do the tree-ring data sets from the eastern and western extremes of the Palmer Divide differ in their sensitivity to climate, particularly precipitation?

2. To what extent can tree-ring data be used to determine if there are differences between annual recruitment in stands of Pinus ponderosa (ponderosa pine) growing near its extreme eastern distribution limit, and at higher elevations near the west side of the Palmer Divide?

3. Can any differences in recruitment be attributed to differences in precipitation? If so, do the data indicate a relationship with broader, hemispheric scale anomalies such as sea-surface temperatures (SST) such as El Niño-Southern Oscillation (ENSO) or Pacific Decadal Oscillation (PDO)?

Hypotheses

1. Eastern and western stands of ponderosa pine on the Palmer Divide provide sufficiently sensitive dendroecological information to reflect local changes in precipitation.
2. Successful recruitment in the eastern stands of ponderosa pine is limited to years with favorable climatic factors such as wet springs or early summers.

3. Successful recruitment in the western stands is more or less randomly distributed in wet and dry years.

4. Successful recruitment in the eastern stand is related to warm phases of PDO during El Niño years, which are generally related to wetter years.

**Palmer Divide**

**Topography**

The Palmer Divide is a remnant of the mid-Tertiary high plains surface that extends east from the Colorado Front Range to the eastern plains near Limon, Colorado (von Ahlefeldt 1992, Skinner 1996, Gilmore 2004, Hays 2008). Since the mid-Tertiary, tributary streams of the South Platte and Arkansas Rivers have down cut into an older high plains surface, producing a landscape of isolated buttes and ridges on the Palmer Divide whose summit elevations decline from the west side of the divide to the east. At the extreme east end the divide grades into the rolling surface of the high plains. The “wedge shaped” Palmer Divide ridge is an area of great transition in elevation (Trimble 1980, Hays 2008, von Ahlefeldt 1992), from the Rocky Mountains to the high plains, and separates the South Platte River basin to the north from the Arkansas River basin to the south. The highest elevation on the Palmer Divide is at the western end near the Front Range at Palmer Lake on Ben Lomand Mountain (2,336 meters), and the lowest elevation is on the eastern end of the divide is near Cedar Point at an elevation of 1,700 meters, (Skinner 1996). The bedrock of much of the Palmer Divide is Dawson Arkose.
The buttes, mesas, and ridges on the divide are usually capped by Castle Rock Conglomerate, especially on the west side of the divide (Skinner 1996).

**Climate**

Due to the relatively higher elevation on the Palmer Divide, mean annual temperatures are lower and mean annual precipitation is higher than in the lowlands to the north, south, and east of the divide. At various times throughout the year three major air masses may converge on the Palmer divide: the polar, Pacific, and Gulf air masses (von Ahlefeldt 1992).

Precipitation decreases easterly towards the plains. For example, Palmer Lake, near the west side of the divide, receives an average of 510 mm of annual precipitation; Kiowa, farther to the east receives an average of 435 mm of precipitation; and Limon, near the eastern end of the divide averages 395 mm of annual precipitation (Skinner 1996). All of these sites receive more moisture than Denver (355 mm annually) (Skinner 1996). The elevation of the highest portions of the divide are ca. 700 meters higher than Denver, creating an environment unique from the surrounding plains with sufficient moisture to support stands of montane forest.

**Vegetation**

The vegetation of the Palmer Divide is a mosaic of montane conifer forest, gamble oak, and short grass prairie. The cooler, wetter conditions on the divide permit stands of ponderosa pine and Douglas fir to establish on favorable sites. These stands are larger and more common on the higher elevations along the western and central parts of
the Palmer Divide, and restricted to the ridge tops on the eastern side of the Divide. On the extreme eastern side of the Palmer Divide the ponderosa pines are limited to east facing slopes near the tops of isolated ridges.
CHAPTER TWO: METHODS

Site Selection

Because this study focuses on analyzing the recruitment at elevation extremes on the Palmer Divide, we identified study sites at the easternmost stand of ponderosa pine on the Divide and on the westernmost end of the Divide. Two field sites were used in this study (Fig.3). The eastern site (39.3°N, -104.14°W, elevation 1,860 meters) is located on a north-south trending ridge 40 km west of Limon, Colorado. I cored the trees at this site, East Ridge (ER) in April 2006 and August 2007. It is likely that moisture levels are insufficient to support tree growth at lower elevations east of the eastern study site. The property on which the stand is located is owned by Charles Guetz, and the site is used for low intensity grazing of cattle in the summer months.

The western site, Spruce Mountain (SM) (39.156°N, -104.882°W, elevation 2,286 meters), is located 3.5 km southwest of Greenland, Colorado, and 3 km east of the base of the Colorado Front Range. I cored the trees at this site in September 2009. This site was selected as a control for the eastern site, being at the westernmost edge of the Palmer Divide, but not part of the Colorado Front Range. Spruce Mountain is part of the Douglas County Open Space.
Field Methods

Because episodic recruitment was a main focus of the study, random sampling rather than targeted sampling methods were used (Speer 2010). The methods for both study sites were similar: The objective of the study was 50 trees for both East Ridge and Spruce Mountain. 100 m transects were randomly placed and all standing ponderosa pines > 4 cm d.b.h. (Mast et al. 1998) within 5 meters of the transect line were cored. The eastern site was sampled in two transects, one in April 2006 and one in August 2007. Sampling at the western site was along one transect in September 2009.

Data recorded for each tree sampled included its location along the transect tape, diameter at breast height (d.b.h.), GPS coordinates, and overall tree condition. All trees were cored with an increment borer and an effort was made to capture the pith. Two cores were removed, from opposite sides of each tree, parallel to the slope contours. Cores in this study were collected as close to the base of the tree as possible (approximately 23 cm height, half the length of the increment borers) and parallel to the ground in order to maximize estimation of the recruitment years and allow for analysis of climate. Extracted cores were placed into individual paper straws for transport back to the lab.

Laboratory Methods

After drying, cores were removed from straws and glued, with the cross-sectional view facing up, into prefabricated wooden coremounts. The cores were held in place by masking tape while the glue dried. The site identification, tree number, sample number, species, and date sampled, were written on the side of the wooden blocks. A belt sander was used to sand each core with progressively finer belts starting with ANSI-60 and
ending with ANSI 400-grit. Each core was then hand sanded with ANSI-600 grit finishing film. The cores were visually counted using a low-powered stereo-microscope to mark the ring years (Stokes and Smiley 1996, Speer 2010).

A combination of memorization and list methods (Douglass 1941, Phipps 1985, Yamaguchi 1991, Speer 2010) were used to crossdate the cores. Annual ring widths of the crossdated cores from the Palmer Divide were measured to the nearest 0.001 mm using a Velmex linear-measurement encoder stage with Measure J2X software. The output files were then run through the measuring and crossdating verification program COFECHA (Holmes 1983, Grissino-Mayer 2001).

Three verified ponderosa pine chronologies from the International Tree-Ring Data Bank (ITRDB), part of the National Climatic Data Center, were used to identify and produce a regional list of narrow ring years. “Black Forest East” (ITRDB 2012), “Jefferson County Colorado Recollection” (ITRDB 2012), and “Ridge Road” (ITRDB 2012) were combined in COFECHA to form a regional chronology I refer to as “region1”. The tree ring measurements from the Palmer Divide study sites were compared in COFECHA with “region1”. A listing of narrow rings was produced and used to assist in crossdating the cores from the Palmer Divide.

Once the crossdating of the Palmer Divide study sites was verified by COFECHA, the measurements were processed with ARSTAN (Cook 1985, Cook and Krusic 2005). ARSTAN removes the growth trend, converts the tree-ring measurements into indices, and offers a selection of detrending options to aid in removing the noise in the chronology, to assist in climate reconstruction analysis (Cook 1985, Cook and Holmes 1984). Output includes three versions of chronologies with different levels of
It is customary to evaluate the different chronologies against climate variables to identify the best signal for further analysis.

**Climate Analysis**

Three ARSTAN-produced indices (‘STNDRD’, ‘RESID’, and ‘ARSTAN’) from both Palmer Divide study sites were correlated in Excel against summer (JJA) Palmer Drought Severity Index, (PDSI) (Palmer 1965) from Colorado Climate Division 1 (ftp://ftp.ncdc.noaa.gov/pub/data/cirs/).

Analysis of climate data was made using data from 1932-2007 for both sample sites. Prior to 1930, the Spruce Mountain chronology lacks a robust sample depth desired for the analysis. Post 1930, the methods and standardization of procedures were more uniform collecting instrumental climate data (H. Grissino-Mayer, per. comm.).

All monthly climate data were examined for significant correlations with the tree-ring widths. Correlation analysis was performed using the climate analysis program DENDROCLIM 2002 (Biondi and Waikul 2004) using bootstrapping (Guiot 1990, 1991), with replacement at the 95% confidence level to analyze climate and teleconnection variables. The program correlates (running each equation 1,000 times) yearly tree indices to 24-months of climate from the previous year of the subject year through the current year. Variables examined were Colorado Climate Division 1 (ftp://ftp.ncdc.noaa.gov/pub/data/cirs/) monthly mean temperature (1895-2007), monthly precipitation (1895-2007), monthly PDSI (1895-2007), monthly El Nino-Southern Oscillation (ENSO) (1931-2007) (http://jisao.washington.edu/data/globalsstenso/) (data is from the International
Comprehensive Ocean-Atmosphere Data Set version 2.5 (ICOADS), and monthly Pacific Decadal Oscillation (PDO) (1930-2007)
(ftp://ftp.ncdc.noaa.gov/pub/data/paleo/treering/reconstructions/pdo.txt)(data is from
UKMO Historical SST data set for 1932-81, Reynold’s Optimally Interpolated SST (V1)
for 1982-2001, and OI SST Version 2 (V2) beginning 2002). Correlation analysis was
run on Excel between tree-ring widths and summer seasonal (JJA) PDSI (1895-2007),
and reconstructed summer seasonal (JJA) PDSI (Cook et al. 1994) (1800-1978).

**Episodic Recruitment Analysis**

All cores were accurately dated identifying the pith year or the oldest year on each
core. Since two cores were collected from each tree, the core containing the pith was
used for the analysis. Where neither core contained the pith, the core containing the
oldest year was retained for the analysis.

For well-dated cores that did not contain the pith, we used a pith estimating
procedure (Applequist 1958, Speer 2010), in which a collection of five various sized
rings with uniform concentric circles was copied into a transparency and placed over the
ends of the cores to reach an estimated pith date. There were two circumstances for
which the pith estimator was not used: if the oldest core of a given tree did not accurately
crossdate to the earliest part of the core, another core from the same tree was used in its
place; and if a given tree contained no cores that produced an accurately-dated early year,
the tree was not included in the episodic recruitment analysis.

Basic statistics were produced for each study site including average pith year,
average pith year including estimated pith years, oldest pith year, oldest estimated pith
year (if older), youngest trees, and histograms of pith/estimated pith dates. Figures were produced identifying annual pith year for each study site.
CHAPTER THREE: RESULTS

A total of 117 trees from the East Ridge and Spruce Mountain sites were cored. From these, master chronologies were constructed for each site, and statistical analyses were conducted to determine the climate sensitivity of each site. Pith years were determined on 103 trees and these were used to construct histograms for each site. Pith years were plotted against d.b.h. for each site (Fig. 4 and 5).

COFECHA Results

At the East Ridge (ER) study site I sampled 63 trees, collecting two cores per tree. 53 trees were used for the episodic recruitment study. The ER master chronology (Table 1) consisted of 24 cores with no problem segments, yielding a series intercorrelation of 0.771, and average mean sensitivity of 0.468. Mean length of series was 118 years. The longest series for the climate analysis was 157 years (1851-2007).

At the Spruce Mountain (SM) study site I sampled 54 trees, collecting two cores per tree. 50 trees were used for the episodic recruitment study. The SM master chronology (Table 1) consisted of 22 cores with no problem segments, a series intercorrelation of 0.756, and average mean sensitivity of 0.433. Mean length of series was 86.1 years. The longest series for the climate analysis was 122 years (1888-2009).
**ARSTAN Results**

ARSTAN graphically displays each of the four chronologies: raw, STNDRD, RESID, and ARSTAN with a mean line, and sample depth chart (Figs. 6-12). As is customary, all three chronologies are run against climate variables to identify which has the best correlation.

After running correlation equations between the three ARSTAN outputs and two versions (instrumental (IPDSI) and reconstructed (RPDSI)) from tree-ring chronologies with seasonal (June, July, and August or JJA) Palmer Severe Drought Index (PDSI) the ‘ARSTAN’ chronology was selected over both ‘STNDRD’ and ‘RESID’, due to a better correlation value with the PDSI data (Figs. 13-16). The ER correlation between ARSTAN and IPDSI was $r = 0.561$, ARSTAN and RPDSI was $r = 0.553$. The SM correlation between ARSTAN and RPDSI was $r = 0.479$, ARSTAN and RPDSI was $r = 0.718$. A comparison of the two sites is shown in Table 2.

As identified in the methods section, a combination of memorization and list methods were used to crossdate the cores (Douglass 1941, Phipps 1985, Yamaguchi 1991, Speer 2010). As an aid to crossdating, three verified chronologies from the International Tree Ring Data Bank (ITRDB 2012) were used to help establish narrow ring years. The data from the three chronologies, ‘Black Forest East’, ‘Ridge Road’, and ‘Jefferson County Update’ were downloaded from the ITRBD website as .rwl files and processed individually and in combination with COFECHA. ‘Black Forest East’ (Tables 1 and 3), CO564.rwl located at 39.30°N, -104.13°W, elevation 1,800m, has ring dates
between 1709-1997, with 33 cores, no problem segments, series intercorrelation of 0.775, and has an average mean sensitivity of 0.242. ‘Jefferson County Update’ (Tables 1 and 3), CO608.rwl located at 39.14°N, -105.12°W, elevation 1965m, has ring dates between 1487-2003, with 28 cores, no problem segments, series intercorrelation of 0.757, and has an average mean sensitivity of 0.399. ‘Ridge Road’ (Tables 1 and 3), CO565 located at 39.23°N, -104.12°W, elevation 1850m, has ring dates between 1779 and 1998, with 16 cores, no problem segments, series intercorrelation of 0.629, and has an average mean sensitivity of 0.394.

The three ITRDB chronologies were combined to form a single chronology referred to here as region1. This single chronology (series intercorrelation of 0.67 and average mean sensitivity 0.407) was used to identify the following narrow ring years: 2006, 2004, 2002, 1989, 1966, 1963, 1956, 1954, 1934, 1925, 1916, 1911, 1908, 1899, 1880, 1870, and 1863. (The years in bold indicate a missing ring in either one of the Palmer Divide chronologies and at least one of the reference chronologies).

**Episodic Recruitment Results**

In order to estimate recruitment years, pith dates at 23cm height were determined for 53 trees at ER and 50 trees at SM (Figs. 17 and 18, respectively). Pith dates for ER span the period 1836-1960. The greatest concentration of years falls between 1850 and 1864 (21 trees, 39.6% of the total). Pith dates at SM span the period 1860-1945, with the greatest concentration of pith years between 1905 and 1916 (25 trees, half of the total).
Climate Results

All monthly climate data were examined for significant correlations with the tree-ring widths. The most significant correlations were charted (Appendix B) with both chronologies. East Ridge has higher correlations with all tested variables than Spruce Mountain. The highest correlations are for Monthly and Summer Season PDSI.

Using the ARSTAN data presented in Figures 6 and &, and assuming that dry conditions are particularly highlighted in the data, several notable dry periods can be identified from the ER and SM data sets.


CHAPTER FOUR: DISCUSSION

In this section the new data presented in the previous sections are interpreted and these results are compared with those of previous researchers. While both ER and SM sites showed sensitivity to climate variables and episodic recruitment pulses, the two sites differed from one another in a number of ways.

Pith Years and D.B.H.

The pith years vs. d.b.h. (Figs. 4 and 5) illustrated differences between the two sites. Trees at East Ridge showed a moderately strong correlation between pith year and d.b.h. ($r = -0.562$). In general, trees at the ER site had a greater diameter than those at the SM site. The largest d.b.h. at ER exceeded 50 cm.

Trees at Spruce Mountain showed a more random relationship between age and diameter ($r = -0.316$), and were generally smaller than those at ER. The greatest d.b.h.s at SM were less than 30 cm. The stand of trees on Spruce Mountain is on the top of the mountain, where thinner soils may hold less moisture than the soils at the ER site (Skinner 1996), accounting for the slower growth at SM.

Climate sensitivity

The East Ridge site showed greater sensitivity in COFECHA statistics interseries correlation, average mean sensitivity and all tested climate variables including
precipitation, mean temperature, PDSI, ENSO and PDO (Figs. 13-16)(Table 2). These results are not surprising since the eastern site is located at a lower elevation with drier conditions. But the western site is also sensitive, probably because it is still near the low elevation limit for ponderosa pine despite being located at higher elevation than the eastern site. The series intercorrelation and average mean sensitivity at the ER and SM sites compares favorably with those reported for the Black Forest East, Jefferson County Colorado Recollection and Ridge Road reference chronologies.

**Recruitment**

I hypothesized that recruitment at the eastern site would be more influenced by climate, where wet phases of ENSO and PDO would be a factor, while the western site would have more or less consistent recruitment not as heavily influenced by climate. The data (Figs. 17 and 18) show two pulses of episodic recruitment for East Ridge and Spruce Mountain. These pulses occurred at different times. High pith year recruitment occurred at East Ridge 1850-1864 and 1870-74. High pith year recruitment occurred at Spruce Mountain 1895-1900 and 1903-1915. Using the pith dates from the trees with the smallest d.b.h. (Figs. 4 and 5) and calculating approximate growth rates at both study sites, I estimated an approximate 5-year lag between the pith date at 23 cm height, and the actual establishment year. Adjusting for the lag, the years with the high numbers of tree establishment are *ca.* 1845-1859 and 1865-69 for East Ridge, and *ca.* 1890-95 and 1898-1910 for Spruce Mountain.

I compared these periods with the data reported by Woodhouse and Brown (2001) and Woodhouse *et al.* (2002) and Brown and Wu (2005). The pulses for both sites are
synchronous with periods of higher moisture, lower fire frequency, increased recruitment, and wet phases of ENSO identified by Brown and Wu (2005), and shown in Fig. 2.

Brown and Wu (2005) showed that tree recruitment in southwest Colorado tended to reach highest values when climate conditions were favorable combined with periods of fire quiescence. In other words, while drought conditions corresponded with low recruitment, wetter years did not necessarily produce high recruitment, unless those (Fig. 2) wetter years also coincided with low fire frequency—favorable climate conditions served as a prerequisite for strong recruitment, but only when other local conditions were also favorable.

The Black Forest East (BFE) data indicate pulses of recruitment in the early 1700s and 1859-1870 (Fig 20) and with the one of the pulses of establishment at ER. These dates compare well with two of the pulses reported by Brown and Wu 2005. However, the BFE site does not show a recruitment peak corresponding with Brown and Wu’s 1825-1840 pulse, despite evidence that climatic factors were favorable. In addition the BFE site shows a pulse of recruitment around 1775-1790 that is not reflected in the Brown and Wu 2005 data, although this period also corresponds with a moist interval in the Four Corners region.

The recruitment chronology for SM extends from the mid 1800s to 1940. There are two periods of peak establishment in this record, around 1890-95 and 1898-1910. These dates correspond with the last two pulses of recruitment shown by Brown and Wu. Brown and Wu note that these pulses occurred during periods of fire exclusion after Euro-American settlement (Euro-American settlement in Colorado began in the 1860s,
but much of the eastern plains of Colorado was not settled until near the end of the century).

The ER recruitment chronology includes pulses of recruitment for the period 1845-1859, and a major pulse beginning around 1865 and extending through 1870. These were both wet periods in the Four Corners region. The ER site does not show a large pulse of recruitment in the late 1800s or early 1900s.

The SM and ER sites have periods of establishment that correspond with some of the high recruitment years identified by Brown and Wu 2005, but neither site agrees entirely with the data presented by these authors. I suggest that this indicates that while moister conditions may set the stage for successful recruitment, other local factors, including stand density, fire history, etc., may inhibit germination and growth. ER had no recruitment from 1880-1890, and 1907-1925 despite wet conditions indicated with the ER climate data and Brown and Wu (2005). SM had no recruitment from 1873-1890, and 1915-1930, also despite wet conditions. Brown and Wu 2005 showed recruitment during these times, leading me to the conclusion that although wet conditions are necessary for recruitment the condition at the site ultimately controlling recruitment.

The oldest ring dates with BFE data were not reported as pith dates, but the trees were cored by experienced researchers, and we assume that most cores intersected the pith of the tree. Assuming a 10-15 year lag between the BFE pith dates and the actual establishment years, the 1845-1859 recruitment pulse on East Ridge appears to be approximately synchronous with the high recruitment shown in the graph of oldest ring dates on the cores from Black Forest East (BFE) (Figs. 19 and 20). The BFE record also
indicates two small pulses in the 1700’s with little establishment between pulses.

Examining the three study sites (BFE, ER, and SM), the data suggest that although climatic conditions must be favorable for recruitment to occur, conditions of stand stability and competition within the stand after a pulse of recruitment may prevent further recruitment until some disturbance occurs.

**Potential Alternative Hypotheses**

In this section we review potential alternative hypotheses for the recruitment record seen in the ER and SM data, including the possible roles of logging, grazing, and fire.

**Logging**

The south branch of the Smoky Hill Trail passed near East Ridge from 1859-1871. It is conceivable that pioneers using the trail could have impacted the tree stands in the area (fire, cutting trees, etc.). There is no evidence of fire scars on the standing trees or in the cores. There is a pulse of recruitment between 1860 and 1870 that could reflect an opening of the stand as a result of logging, but this may also be attributable to a period of wetter conditions.

On the west side of the Palmer Divide, the Denver and Rio Grande Western Railroad began in Denver in 1870 and crossed the Palmer Divide not far from Spruce Mountain in 1871-72. There is anecdotal evidence and unpublished data suggesting that larger trees were cut along the rail route for ties and construction (D. Sullivan, pers. comm.). Smaller trees (those less than about 20 years old) were evidently too small, and
were not cut. If the forest on Spruce Mountain had been logged by the railroad during that time, trees germinated during the 2-3 decades prior to 1870 would probably have been left standing. Had the railroad logged older trees in the 1870s, it might be expected that there could also have been a pulse of new recruitment in the 1870s- early 1890’s in the Spruce Mountain area. However, the SM data (Fig. 18) indicate no significant recruitment during this time. This suggests that if any logging had occurred at Spruce Mountain in the late 1800s, it was not extensive, and played no important role in the recruitment story.

Cattle Grazing

The impact of cattle grazing on ponderosa pine mortality has been studied by several authors (Rummell 1951, Madany and West 1983, and Kingery and Graham 1991). These authors concluded that cattle grazing had no significant impact on ponderosa pine mortality (Knight and Graham 1991), or actually benefitted ponderosa pine establishment and higher stand density (Rummell 1951, Madany and West 1983). This would suggest that grazing had little negative impact on the establishment of pines at the two sites, nor is there evidence of a positive grazing impact.

Fire

Ponderosa pine forests evolved with a regime of frequent, low intensity fires. Fire suppression policies over the last century have allowed Douglas fir trees (Pseudotsuga menziesii) to encroach on ponderosa pine stands in many areas. The presence of Douglas fir trees increases the chances of stand-replacing, high intensity fires
in ponderosa pine stands (Colorado State Forest Service, n.d.), as the Douglas fir trees allow a fire to “ladder” into the canopy.

There are currently no Douglas fir trees in the East Ridge stand. A few Douglas fir trees are scattered through the Spruce Mountain stand, occupying moister locations. There was no evidence of fire scars in any of the 117 trees (234 cores) sampled for this study, nor was any evidence of charred stumps observed. It seems unlikely that even low intensity burns would have passed through these stands without leaving some evidence. While the impact of fire on the recruitment pulses at the two stands cannot entirely be ruled out at this point, it does not appear to have played a significant role.
CHAPTER FIVE: CONCLUSION

In this research I attempted to establish recruitment data for ponderosa pine trees at two sites on the Palmer Divide, to determine the relative sensitivity of the two sites, and the extent to which climate factors or other factors may have influenced recruitment at the sites.

The results of the tree-ring analysis suggest that the East Ridge site is more sensitive to climatic factors than the Spruce Mountain site, as hypothesized.

Both the East Ridge site and Spruce Mountain site showed a history of episodic recruitment. The data suggesting episodic recruitment in the west (Spruce Mountain) is a departure from the original hypothesis which suggested that recruitment at the western site would be more or less consistent, and that climate would play a minor role, if any, in recruitment. In fact, climate apparently plays a significant role, although, perhaps not the largest, in the recruitment pulses at both sites. Although the two sites correlate well together ($r = 0.551$) in response to climate, the pulses of recruitment occur at different periods at each site.

Three potential sources of disturbance, logging, cattle grazing, and fire were examined as possible alternative explanations for the dissimilar periods of recruitment
between the sites. My conclusion is that none of these stand disturbances were likely the cause of the differences in recruitment in the two stands.

Climate is probably the most important factor in recruitment pulses, but only if there is opportunity within the stand for recruitment. Both sites are near the low elevation limit for ponderosa pine in eastern Colorado, and intra-stand competition for resources is strong. Although favorable patterns in climate have been present for both sites at the same time, the opportunity for recruitment within each stand has been different at different times.

I would argue that at the local stand level, this is because seedling germination and growth are more likely to be hindered by shading, competition, human activity, etc. even when climate conditions are favorable. While climate conditions must be favorable for seedling establishment and growth, conditions of stability and competition within the stand dictate the ultimate recruitment success.
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Figure 1. North American distribution map of ponderosa pine
(Source: http://esp.cr.usgs.gov/data/atlas/little/pinupond.pdf)
Figure 2. Comparison of ENSO, hydroclimate, fire-year, and tree recruitment chronologies. (a) ENSO time series (blue, Niño3 SST index [Cook 2000]; red, SOI [Stahle et al. 1998]). SOI is reversed to be consistent with other moisture indices. Heavy lines are annual series smoothed with 20-yr cubic smoothing splines. Years of significant triennial wet/dry oscillations ($y_t - y_{t-2}$) identified by superposed epoch analyses (SEA) in Fig. 3c, d are shown by arrows centered on the drought years. Biennial oscillations ($y_t - y_{t-1}$) also were tested and found to be largely absent during the fire-quiescent periods of 1684–1724 and 1818–1851. (b) Reconstructed hydroclimate time series, smoothed with 20-yr cubic splines. The solid line shows the annual precipitation in northeastern New Mexico (Grissino-Mayer 1996), and the dashed line shows the Palmer drought severity index for the four-corners area (Cook et al. 2004). (c) Fire-year chronology for Archuleta Mesa. Horizontal lines mark time spans of individual trees, with fire scars designated by inverted triangles. Fire years at bottom are those recorded on $\geq$2 trees and used for SEA in Fig. 3. (d, e) Tree recruitment dates by 5-yr periods for (d) ponderosa pine and (e) other tree species. Recruitment dates are truncated toward the present, since we only collected data on trees $>20$ cm. The red vertical bar marks the 1580s megadrought, green bars mark fire-quiescent periods, the blue bar marks recent decades of fire exclusion after Euro-American settlement, and the purple bar marks the early 20th-century wet period and pulse of recruitment in ponderosa pine centered on 1919 (Savage et al. 1996) (Brown and Wu 2005).
Figure 3. Map of the Palmer Divide region. The East Ridge (yellow) and Spruce Mountain (blue) sampling sites are indicated.
Figure 4. East Ridge comparison of pith year to d.b.h. $r = -0.562$

Figure 5. Spruce Mountain comparison of pith year to d.b.h. $r = -0.316$. 

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Figure 6. ARSTAN output charts showing raw measurement chronology and standard chronology along with sample depth chart for East Ridge.

Figure 7. ARSTAN output charts showing residual chronology and ARSTAN chronology along with sample depth chart for East Ridge.
Figure 8. ARSTAN output charts showing raw measurement chronology and standard chronology along with sample depth chart for Spruce Mountain.

Figure 9. ARSTAN output charts showing residual chronology and ARSTAN chronology along with sample depth chart for Spruce Mountain.
Figure 10. East Ridge ARSTAN chronology shown in red.

Figure 11. Spruce Mountain ARSTAN chronology shown in blue.
Figure 12. Overlapping East Ridge and Spruce Mountain ARSTAN chronology $r = 0.551$
Figure 13. Significant correlations between East Ridge and monthly climate variables ($r$ values).

Figure 14. Significant correlations between Spruce Mountain and monthly climate variables ($r$ values).
Figure 15. Significant correlations between East Ridge and monthly ENSO/PDO ($r$ values).

Figure 16. Significant correlations between Spruce Mountain and monthly ENSO/PDO ($r$ values).
Figure 17. Annual East Ridge tree recruitment, showing concentrations of pith years in 1840s, and 1852-64.

Figure 18. Annual Spruce Mountain tree recruitment, showing concentrations of pith years between 1895-1900 and 1903-1917.
Figure 19. East Ridge tree recruitment by year

Figure 20. Black Forest East oldest ring year. (Woodhouse et al. 2002) Common surges in recruitment for both sites between 1856-1871.
<table>
<thead>
<tr>
<th>Location</th>
<th>S/I</th>
<th>MS</th>
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<td>0.468 (1)</td>
</tr>
<tr>
<td>Spruce Mountain</td>
<td>0.756 (4)</td>
<td>0.433 (2)</td>
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<tr>
<td>Jefferson County</td>
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</tr>
<tr>
<td>Ridge Road</td>
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<td>0.394 (5)</td>
</tr>
<tr>
<td>Black Forest East</td>
<td>0.775 (1)</td>
<td>0.424 (3)</td>
</tr>
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</table>

Table 1. COFECHA summary ranking and comparing series intercorrelation and average mean sensitivity between East Ridge and Spruce Mountain and the three reference chronologies. (Source: Woodhouse and Brown 2001, Woodhouse et al. 2002) Note that series intercorrelation and average mean sensitivity of both East Ridge and Spruce Mountain are comparable to the three reference chronologies used in this study.
Site Sensitivity comparison using COFECHA Statistics and Climate Variables

<table>
<thead>
<tr>
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</tr>
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<td>Ave Mean Sensitivity</td>
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<tr>
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<tr>
<td>Monthly PDSI</td>
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<tr>
<td>Monthly ENSO</td>
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<tr>
<td>Seasonal (Summer JJA) PDSI</td>
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*Table 2.* East Ridge and Spruce Mountain comparison of COFECHA statistics and climate variables—results are correlation coefficients ($r$ values).
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Table 3. Comparison of East Ridge, Spruce Mountain, three other regional chronologies, and ITRDB averages demonstrating similar statistics to experienced researchers (results are correlation coefficients ($r$ values)).
Appendix A

Selected Terms
**Master Chronology** is a record of ring widths representing the stand level signal.

The **List Method** is a technique used to develop the chronology of marker rings without the added steps of plotting on graph paper.

**Memorization Method** is a method of chronology building that uses an established set of verified chronologies, and can be used with the list method.

The **International Tree-Ring Data Bank (ITRDB)** is a repository of worldwide tree-ring chronologies and maintained by the NOAA Paleoclimatology Program and World Data Center for Paleoclimatology.

**Ring-Width Chronology**: The averaged standardized ring-width indices from a number of trees sampled in a particular site that can be used for crossdating.

**COFECHA** is a quality-control program used to check the crossdating and overall quality of tree-ring chronologies.

**Series Intercorrelation** is a measure of the strength of the signal (typically the climate signal) common to all the sampled trees at the site. It is the average correlation of each series with the master chronology derived from all other series.

**Average Mean Sensitivity** is a measure of the relative change in ring-width from one year to the next in a give series. Mean sensitivity is positively correlated with series intercorrelation; trees with stronger common signals tend to be more sensitive.

The default **Segment Length** in COFECHA is 50 years.

**Number Problem Segments**: The number of 50-year segments that were flagged by COFECHA (includes A and B flags). A flag issued indicates lower signal strength in those segments and can be used to identify potential dating errors.

**Percent Problem Segments**: The number of problem segments divided by the total number of segments x 100. About 25% of all ITRDB chronologies have no problem segments; most chronologies have less than 10% problem segments.

An **“A” Flag** indicates that a segment has a correlation with the master chronology of less than 0.328, the 99% significance level (one-tailed), but the segment does not correlate better with the master chronology in any of the other shifted positions.

A **“B” Flag** means that COFECHA has found a better correlation for that segments in a 20-year window of -10 to +10 years from the place where it is currently dated.

The program **ARSTAN** produces chronologies from tree-ring measurement series by detrending and indexing (standardizing) the series, then applying a robust estimation of the mean value function to remove effects of endogenous stand disturbances.

**Autocorrelation** is the correlation of a variable with itself over successive time intervals.
Standardization: The raw ring width data verified by COFECHA are standardized and the results are averaged into a site chronology. The standardization process involves fitting a curve to the ring-width series, and then dividing each ring-width value by the corresponding value to generate a series of growth indices. Standardization removes age-related growth trends and other long-term variability that can be considered noise, and produces a series mean equal to 1.0.

ARSTAN creates four chronologies: raw, STNDRD (standardized), RESID (Residual), and ARSTAN.

Index Values (Indices) are unitless with a nearly stable mean and variance, allowing indices from numerous trees to be averaged into a site chronology.

The Raw chronology is a simple average of the raw ring widths (i.e. no standardization has been performed on the series).

STANDRD chronology: Detrended (standardized) tree-ring series are combined into a mean value function of all series. This chronology does not have the autocorrelation removed.

The RESID (residual) is similar to the standard chronology except it has had all of the autocorrelation removed from the series.

The ARSTAN chronology is calculated by removing the autocorrelation from the series, modeling it, and reintroducing a stand-level autocorrelation back into the chronology.

DENDROCLIM 2002 is a program specifically written for dendrochronological applications to identify correlations with bootstrapping (with replacement) technique between tree-ring and meteorological data.

Bootstrapping is a statistical technique that is used to determine the significance of any statistic even when the data are over correlated, not normally distributed, or when the data set is small.

National Climatic Data Center (NCDC) is the world’s largest active archive of weather data.

Monthly Average Temperature- Colorado Division 1 (1895-present) from the NCDC

Monthly Precipitation- Colorado Division 1 (1895-present) from the NCDC.

Monthly Palmer Drought Severity Index (PDSI) (1900-2003) is a measurement of recent dryness based on precipitation and temperature.

Reconstructed PDSI- (Cook et al. 2000) (1700-1978) reconstructed from tree-ring chronologies

EL NINO-Southern Oscillation (ENSO) International Comprehensive Ocean-Atmosphere Data Set version 2.5 (ICOADS)
Pacific Decadal Oscillation (PDO) UKMO Historical SST data set for 1932-81, Reynold’s Optimally Interpolated SST (V1) for 1982-2001, and OI SST Version 2 (V2) beginning 200
Appendix B

East Ridge and Spruce Mountain Chronologies

Compared with Selected Climate Indexes
East Ridge and current monthly March precipitation. $r = 0.44$

Spruce Mountain and current monthly June precipitation. $r = 0.366$
East Ridge and previous monthly October temperatures. \( r = -0.435 \)

Spruce Mountain and previous monthly October temperatures. \( r = -0.407 \)
East Ridge and current monthly June PDSI. \( r = 0.633 \)

Spruce Mountain and current monthly June PDSI. \( r = 0.55 \)
East Ridge and previous monthly July ENSO. $r = 0.37$

Spruce Mountain and previous monthly March ENSO. $r = 0.322$
East Ridge and current monthly March PDO. $r = 0.322$

Spruce Mountain and current monthly March PDO. $r = 0.296$
East Ridge and summer (JJA) PDSI. $r = 0.561$

Spruce Mountain and summer (JJA) PDSI. $r = 0.479$
East Ridge and summer (JJA) RPDSI. $r = 0.553$

Spruce Mountain and summer (JJA) RPDSI. $r = 0.718$