Dendroclimatology and Woodland Dynamics on the Volcanic Badlands of Western New Mexico, U.S.A.

A Dissertation
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M.D. Spond
Knoxville, Tennessee
2011

DEDICATION

This dissertation is dedicated to Dr. Saskia L. van de Gevel. Thank you very much!

ABSTRACT

My dissertation research addressed woodland dynamics and dendroclimatology on the volcanic badlands of western New Mexico. The research was intended to complement previous studies by: (1) assessing vegetation structure and composition dynamics at El Malpais National Monument between 1948–2010 using repeat photography; (2) improving knowledge of the influence of climate and land use on vegetation dynamics at El Malpais National Monument; (3) providing a unique tree-ring data set from Rocky Mountain juniper growing on the malpais; (4) elucidating relationships between Pacific teleconnections and radial growth in Rocky Mountain juniper; and (5) improving understanding of the dynamic nature of climate in the Southwest. I used tree-ring data from the interior of the Bandera Lava Flow and repeat-photography sequences from a nearby location at the edge of the flow to assess vegetation changes at two ecologically different locations on the malpais. I concluded that noticeable vegetation changes occurred during the 20th and early 21st centuries at the periphery of the Bandera Lava Flow. Vegetation changes at the lava-substrate interface could be linked to human activity, resource management, and drought.

I also sampled Rocky Mountain junipers on a lava flow in Cibola National Forest to produce a multi-century tree-ring chronology. The data set is the first Rocky Mountain juniper chronology produced in New Mexico and is one of few conifer chronologies from the Southwest with a significant temperature-growth relationship. Dendroclimatic analyses identified growth relationships with monthly mean temperature, monthly total precipitation, monthly PDSI, and local water year precipitation. Trees appeared most

sensitive to climate factors that influence and indicate moisture availability during dry periods of the growing season. Tree-ring data indicated positive relationships between SSTs in the El Niño 3.4 region of the central Pacific Ocean and Rocky Mountain junipers on the malpais. Positive PDO-growth relationships during the cool months prior to current growing season further suggest a link between SSTs in the Pacific Ocean and trees on the badlands. Positive relationships between monthly PNA index values and annual radial growth may result from the large distances between the malpais and PNA centers of activity.

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Chapter One

INTRODUCTION

"A sense of time is feared and rejected by some, but others cherish it as adding a revealing dimension to observation and thought." – Alton A. Lindsey, *Naturalist on Watch*, 1983

1.1 Purpose

Dendrochronology and repeat photography allow for the investigation of relationships between tree growth and environmental factors such as climate, biotic agents, fire, and anthropogenic activity, and have been used extensively to study both the modern landscape and paleoenvironment of the American Southwest (Hastings and Turner; Dean *et al.* 1985; D'Arrigo and Jacoby 1991; Grissino-Mayer 1995; 1996; Hastings and Turner 1965; Turner *et al.* 2003). High-resolution tree-ring reconstructions of these factors through time, produced at multiple spatial scales, assist resource managers in their efforts to interpret contemporary ecosystems and forecast future environmental conditions in the region (Grissino-Mayer 1995; Swetnam and Betancourt 1998; Cook *et al.* 2007; Stahle *et al.* 2007; Stahle *et al.* 2009). Existing tree-ring studies show dramatic fluctuations in climate in the Southwest over the past two millennia (Grissino-Mayer 1995; Stahle *et al.* 2009). This variability likely influenced the cultures and migrations of local Native American populations during past centuries (Douglass 1929; Grissino-Mayer 1995; Nash 1999; Benson *et al.* 2007), and could present challenges to the current and future residents of the region (Hughes and Diaz 2008; MacDonald *et al.* 2008; Baron *et al.* 2009).

Dendroclimatological and dendroecological studies also suggest that climate variability influences the growth, vitality, and spatial distribution of some tree species (Swetnam and Betancourt 1998). Repeat photography studies from the Southwest provide a visual tool for investigating links between climate, land use, and vegetation growth/ distribution at fine spatial scales (Hutchinson 2000; Turner *et al.* 2003). Predictions of 21st-century global climate change (IPCC 2007), coupled with the possibility of associated impacts on plant populations, are the impetus for continued study of climate and vegetation dynamics in the Southwest.

The American Southwest is experiencing persistent drought (NOAA 2011). Instrumental records and dendroclimatological drought reconstructions indicate that the current drought is among the most severe in decades (NOAA 2011; Cook *et al.* 2007; Stahle *et al.* 2007). Increased attention has been directed toward monitoring and managing forests, woodlands, and other southwestern U.S. plant communities in response to the current drought and continued regional "drying" throughout the 21st century (Seager *et al.* 2007; Baron *et al.* 2009). Despite these efforts, uncertainty remains regarding the full impact of drought on vegetation in the region. Specifically, more information is needed concerning drought effects in plant communities that are highly adapted to moisture stress. Detrimental impacts to growth and vitality in these drought-tolerant communities could warn of imminent mass mortalities in less adapted systems (Swetnam and Betancourt 1998; Breshears *et al.* 2005; McDowell *et al.* 2008). I addressed this knowledge gap by investigating relationships between climate and radial-tree growth on the volcanic badlands (malpais) of west-central New Mexico. The rugged malpais provides a protective environment that conserves moisture (Lindsey 1951) and

minimizes intrusions by humans (Grissino-Mayer 1995). The interface between the mixed-conifer woodlands that cover the basalt malpais and neighboring plant communities often contrasts the insular qualities of the lava flows (Figure 1.1) against the impacts of human disturbance on surrounding substrates (Lindsey 1951; Grissino-Mayer *et al.* 1997; Lindsey 1997; Lewis 2003). Therefore, the malpais is an ideal environment to study the effects of anthropogenic impacts and climate using dendroclimatology and repeat photography.

My research had three goals: (1) rephotograph sites in and around El Malpais National Monument (EMNM) that were visited during the 20th century by the ecologist and photographer, Alton A. Lindsey; (2) create a multi-century tree-ring chronology from Rocky Mountain junipers (*Juniperus scopulorum* Sarg.) on the volcanic malpais for use in dendroclimatological analyses; and (3) investigate relationships between the El Niño-Southern Oscillation (ENSO), the Pacific Decadal Oscillation (PDO), the Pacific North American Oscillation (PNA), and Rocky Mountain juniper growth on the malpais. My research was designed to augment prior studies by: (1) assessing vegetation structure and composition dynamics at EMNM between 1948–2010 using repeat photography; (2) improving our knowledge about the influence of climate and human-land use on vegetation dynamics at EMNM; (3) providing a unique tree-ring data set from Rocky Mountain junipers growing on the malpais; (4) elucidating relationships among ENSO, PDO, PNA, and radial growth in Rocky Mountain juniper; and (5) improving our understanding of the dynamic nature of climate in the Southwest. I asked the following questions concerning the climate, land use, and vegetation dynamics of the American Southwest:



Figure 1.1 The mixed-conifer woodlands on the volcanic malpais stand in sharp contrast to the shrub-grasslands that cover the surrounding substrate (Photo by Mark D. Spond, July 2009).

1. *Is Rocky Mountain juniper a species suitable for use in dendrochronology?* Tree-ring evidence suggests that Rocky Mountain juniper is the longest-lived conifer at EMNM. Some of these trees may be among the oldest living organisms in the Southwest (Grissino-Mayer *et al.* 1997). However, prior to my study, the ancient Rocky Mountain junipers on the Colorado Plateau had not been thoroughly investigated using dendrochronology.

2. *Do relationships exist between radial growth in Rocky Mountain junipers growing on the malpais and local climate?* Grissino-Mayer (1995; 1996) revealed a strong, persistent relationship between annual growth rings in ponderosa pine (*Pinus ponderosa* Douglas ex P. Lawson and C. Lawson) and Douglas-fir (*Pseudotsuga menziesii* (Mirb.) Franco) and local water year (previous 1 July–current 30 June) precipitation for west-central New Mexico. However, the ancient Rocky Mountain junipers on the malpais have received minimal attention from dendrochronologists (Grissino-Mayer *et al.* 1997).

3. *If relationships exist between climate and radial Rocky Mountain juniper growth, how stable are they through time?* Paleoenvironmental data generated by tree-ring studies can affect domestic and international policy (IPCC 2007). Dendroclimatic research often addresses potential problems caused by temporal instability (Jacoby and D'Arrigo 1995) to ensure confidence in climate-growth relationships and paleoenvironmental reconstructions (D'Arrigo *et al.* 2008).

4. *Do relationships exist between annual radial growth in Rocky Mountain juniper on the malpais and sea surface temperatures in the Pacific Ocean?* Teleconnections are

associations between oceanic-atmospheric oscillations and distinct meteorological and climatological effects in areas that are often thousands of kilometers away from the causative source (Caviedes 2001). ENSO, PDO, and PNA are known to influence atmospheric conditions across much of North America (Ropelewski and Halpert 1986; Wu *et al.* 2005; Mo 2010; Franzke *et al.* 2011). Dendroclimatic analysis may identify relationships between ENSO, PDO, PNA, and annual radial growth in Rocky Mountain juniper on the malpais.

5. *Does rephotography confirm the insulating effects of the volcanic badlands in and around EMNM?* Historical photographs from EMNM and surrounding locations provide visual accounts of local land use and vegetation dynamics that are useful for assessing land-cover changes and other apparent trends (Lindsey 1981; 1997). Repeat-photo sequences can be used to complement tree-ring data and vegetation assessments from the malpais to further advance our knowledge of the environmental history at EMNM.

1.2 Organization of Dissertation

This dissertation consists of six chapters. I introduce my research in Chapter One by presenting the research questions to be addressed to advance our knowledge of climate-growth relationships and vegetation dynamics at EMNM and adjacent locations. I include background information on both research foci and justify the need for continued inquiry regarding each. In Chapter Two, I discuss the biotic and abiotic characteristics of the malpais and describe its setting within the greater Southwest. Chapter Three discusses repeat photography and vegetation dynamics in and around EMNM.

My dendroclimatological research is presented in two chapters. Chapter Four describes the establishment a multi-century Rocky Mountain juniper tree-ring chronology for the malpais and relationships between annual radial growth and local climate. Chapter Five addresses the influence of ENSO and PDO on Rocky Mountain juniper growth on the malpais. In Chapter Six, I summarize the major conclusions of my research. A list of references used in this dissertation follows. Tree-ring measurements generated by this dissertation research are included as an appendix.

1.3 Vegetation Dynamics at El Malpais National Monument

1.3.1 Background

Repeat image analyses are often used to investigate environmental conditions and how they change through time (Hastings and Turner 1965; Michel *et al.* 2010). The analyses compare two or more photographs, depicting the same subject, captured at known times (Rogers *et al.* 1984). Rephotography can be used to monitor the spatial and temporal aspects of ecological and anthropogenic trends. Although remotely sensed images are used to produce robust datasets for similar research, ground-based, oblique photography often provides higher resolution analyses and longer temporal perspectives (Turner *et al.* 2003). Numerous studies have used the method to provide visual evidence of natural and anthropogenic impacts to western landscapes (Hastings and Turner 1965; Veblen and Lorenz 1991; Allen *et al.* 1998; Noel and Fielder 2001; Griffin *et al.* 2005). Repeat photography analyses can be used to complement information produced by remotely sensed data. Although not as spatially comprehensive as aerial photographs and

satellite imagery, ground-based photographs allow for high-resolution assessment of vegetation types and stand structure (Turner *et al.* 2003).

The famed ecologist Alton A. Lindsey pioneered vegetation dynamics studies on the malpais during the 1940s (Lindsey 1951). In addition to writing an ecological monograph about the area that is today EMNM, he produced a collection of photographs that depicted the flora and geology of the lava flows. Lindsey repeated many of his photographs in 1981. He found significant ecological changes in some scenes, while others remained virtually unchanged (Lindsey 1981; 1997). Lindsey never quantified the changes he observed, nor did he group photo sets by apparent similarities or differences. However, Lindsey's personal notes and private correspondences with Bureau of Land Management (BLM) officials convey his desire for the photography project to continue after his retirement from active research (Lindsey 1981).

1.3.2 Objectives

The specific objectives of my vegetation research were to:

1. Rephotograph areas at EMNM to extend existing photographic records collected by Alton A. Lindsey during the 20th century.

2. Analyze land cover and vegetation at EMNM using repeat photography to qualify 20th and early 21st-century dynamics.

3. Compare land cover and vegetation dynamics at heterogeneous locations within EMNM to identify site characteristics associated with persistence or change.

1.3.3 Justification

The southwestern United States is projected to become drier over the next century (Seager *et al*. 2007; Hughes and Diaz 2008; Stahle *et al.* 2009). Ecological models suggest that the resulting changes to Southwestern vegetation assemblages could be dramatic (Loarie *et al.* 2009; Wiens *et al.* 2009). Unpublished tree-ring data (Jones *et al.* in preparation) from Cibola National Forest show a reduction in aggregate radial growth during the current drought. While dendroclimatological analyses allow us to compare radial-growth effects during periods of drought, rephotography provides a visual complement to those data. Repeated photographs may also permit unique analyses and inference, especially regarding vegetation fragmentation, changes to plant morphology, species composition, and stand structure. Variability among featured species and different photo sites is sometimes apparent, allowing land managers to allocate rehabilitation resources where needed most (Turner *et al.* 2003; Baron *et al.* 2009).

Increased aridity in the Southwest could create no-analog assemblages of vegetation, which would affect ecological processes at all spatial scales (Allen 2007; Keith *et al.* 2009; Loarie *et al.* 2009; Romme *et al.* 2009). Post-industrial development increased access to western New Mexico for non-indigenous settlers (Mangum 1997). Escalating resource demands by humans in the Southwest compound challenges associated with climate change. Although the malpais is a refuge for ancient mixed-conifer woodlands, surrounding grasslands and shrublands bear the scars of human disturbance (Lindsey 1981; 1997; Bleakly 1997; Mangum 1997). Decades of livestock grazing, fire suppression, and landscape fragmentation have allowed invasive species, alien pathogens, and excessive fuel loading to become problems (Mangum 1997;

Grissino-Mayer and Swetnam 1997). The changes necessitate continued research on historical and contemporary vegetation dynamics on the insular malpais and across the Southwest to ensure proper resource management (Swetnam *et al.* 1999).

1.4 Dendroclimatic Research at El Malpais National Monument

1.4.1 Background

Dendrochronology is the science of dating tree rings to their exact year of formation to analyze spatial and temporal patterns of processes in the physical and cultural sciences (Kaennel and Schweingruber 1995; Speer 2010). The science is rooted in a biological principle recognized for centuries; in temperate climates, trees from many species annually increase their stem diameters by adding a ring of new cells around those cells that formed prior to the last period of winter dormancy (Fritts 1976). Annual rings can be further divided into light-colored earlywood and dense bands of latewood (Stokes and Smiley 1996). Wide rings typically represent years of optimal environmental conditions, while narrow years indicate stressed growing conditions (Fritts 1976). Dendrochronologists analyze the patterns within this growth sequence to make inferences about possible environmental phenomena influencing annual tree growth. Dendrochronology emerged as a discipline during the early 20th century (Douglass 1934; 1935; 1941; 1942). The most celebrated early application of dendrochronology was assigning precise cutting dates for construction timbers recovered at numerous pueblos in the American Southwest during the 1920s (Douglass 1929; Nash 1999). Today, dendrochronological methods are a refined, standardized research tool used in many

scientific fields, including anthropology, climatology, geomorphology, hydrology, and forestry (Kaennel and Schweingruber 1995; Speer 2010).

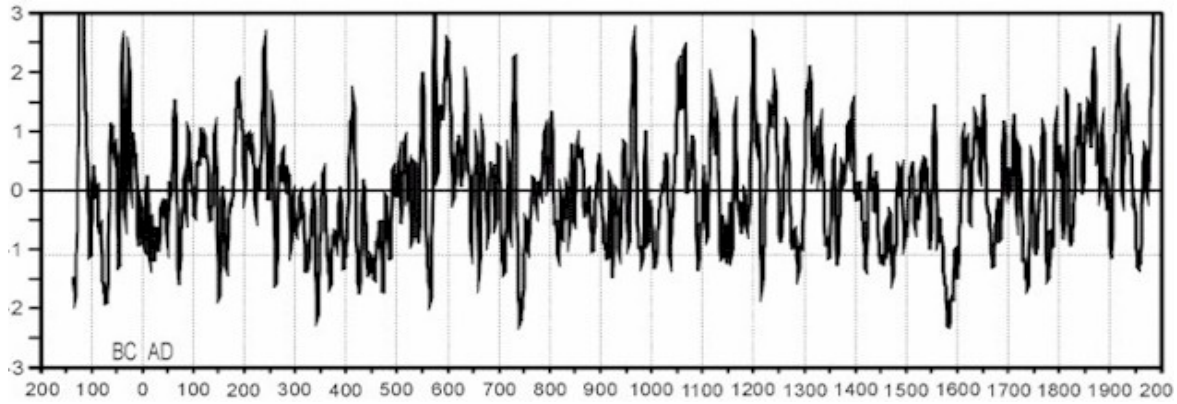
Crossdating, the most important technique in dendrochronology, involves matching the absolutely dated annual rings sampled from one tree with those sampled from neighboring trees (Stokes and Smiley 1996; Fritts 1976). Conventional dendrochronological samples are 5 mm diameter increment cores or cross-sectional discs removed from living trees, standing snags, downed logs, or archaeological structures. Dendrochronologists seek to isolate the growth response or "signal" from one limiting factor that has a shared effect on all the sampled trees. Climate often constitutes the environmental condition that serves as the primary limiting factor of tree growth (Fritts 1976). Although tree rings dated to a precise period may be wider on one sample than contemporaneous rings dated on another sample, the overall pattern of wide and narrow rings will remain consistent among all samples. This consistency results from the shared influence produced by the dominant environmental factor acting as the principal determinant of annual radial growth within the stand (Fritts 1976). The construction of crossdated tree-ring chronologies provides high-resolution, time-series analyses of the principal influences on tree growth.

Climate is not the only factor that affects tree growth. While climate is often the shared growth determinant within a stand, individual trees can be strongly affected by other growth factors. Cook (1987) provided an aggregate model for annual radial growth where: G (growth) = f (A (age-related growth trend) + C (climate) + δD_1 (endogenous disturbance) + δD_2 (exogenous disturbance) + E (error)). Age-related growth trend is important because rapid juvenile tree growth may not correlate well with data collected

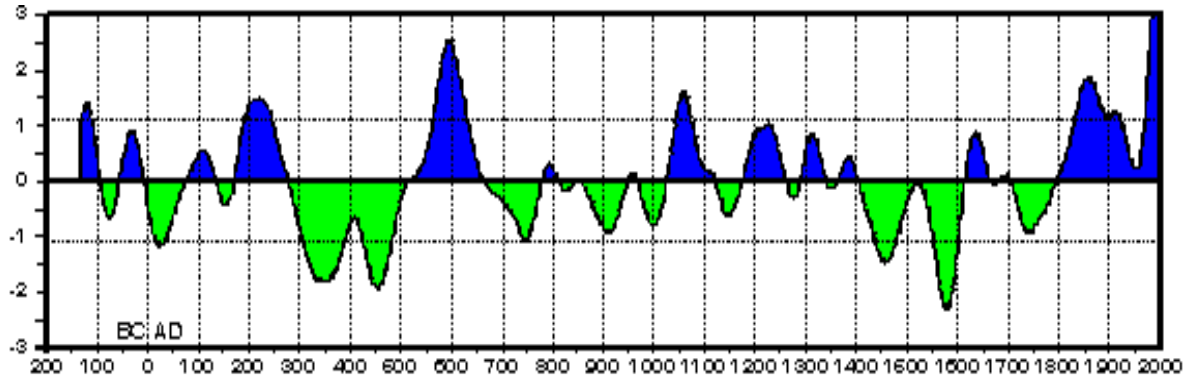
from older trees more influenced by climate than competition (Fritts 1976). Climate consists of the average atmospheric conditions at a particular location during a specified time period. Endogenous disturbances are growth perturbations that originate within a tree, while exogenous disturbances are those that originate in the environment surrounding the tree. Error includes incorrect measurements or procedural mistakes that produce inaccurate ring-width values.

Long-lived trees can provide multi-millennial records of the principal environmental factors associated with tree growth. Dendrochronologists have identified that some broadly distributed Southwestern conifers, including Douglas-fir, ponderosa pine, and Rocky Mountain juniper, can live to old ages (> 500 years) in certain forest settings. These sites are often semi-arid woodlands with poorly developed soils (Douglass 1941; 1942; Schulman 1954; Fritts 1976). Major contributions to this research were made on the EMNM badlands (Grissino-Mayer 1995). Previous tree-ring studies at EMNM sampled moisture-stressed Douglas-firs and ponderosa pines to produce a 2,129-year proxy record (136 B.C.–A.D. 1992) for annual precipitation in west-central New Mexico (Grissino-Mayer 1995; Grissino-Mayer *et al*. 1997). Grissino-Mayer (1995) showed that the malpais experienced both periods of drought and periods of above average precipitation during the past two millennia (Figure 1.2). Grissino-Mayer's findings agreed with other regional tree-ring chronologies, suggesting that climate signals embedded in the growth rings of certain trees at EMNM may be representative of climate conditions at larger spatial scales (Grissino-Mayer 1995; 1996).

Recent work by Stahle and others (2009) looked at intra-annual ring anatomy to reconstruct cool-season (November–May) and early warm-season (July) precipitation at



1.2a.



1.2b.

Figure 1.2a and 1.2b Pre-instrumental precipitation reconstructions from tree rings provide insight on paleoenvironmental conditions related to tree growth. Figures 1.2a and 1.2b show total annual precipitation reconstructed from tree rings at EMNM ("The Malpais Long Chronology," Grissino-Mayer 1995). Figure 1.2a shows standardized ring-width data using a 25-year cubic moving spline, while Figure 1.2b shows the same data using a 100-year cubic moving spline. Values above 0 are wetter than average, values below 0 are drier than average (Images courtesy of Henri D. Grissino-Mayer, *Ultimate Tree-Ring Web Pages, 2010, http://web.utk.edu/~grissino/*).

EMNM over the length of Grissino-Mayer's initial reconstruction of total annual precipitation. The resulting earlywood and latewood chronologies suggest that above average winter/spring precipitation is influenced by ENSO and the positive phase of the PDO. Heavy July precipitation was linked to the onset of the North American Monsoon. Their reconstructions did not indicate interannual correlation between cool-season and warm-season precipitation totals. However, they observed that the wettest cool seasons tended to be followed by early summer dryness, while the driest winters were often associated with wet conditions the subsequent July. This antiphasing of precipitation extremes could be caused by large-scale ocean-atmospheric forcing, land-surface feedbacks, or the interactions of climate forces at multiple spatial scales (Stahle *et al.* 2009).

1.4.2 Objectives

The specific objectives of my dendroclimatological research were to:

1. Crossdate Rocky Mountain juniper samples from the malpais, and use statistical modeling to assess potential relationships between local climate and Rocky Mountain juniper growth.

2. Investigate possible relationships between radial growth in Rocky Mountain juniper and ENSO, PDO, and PNA

3. Analyze the temporal stability of relationships identified between climate and annual radial growth in Rocky Mountain juniper on the malpais.

1.4.3 Justification

Previous dendroclimatological research provided the scientific community and land management agencies important information about environmental conditions in western New Mexico prior to the 20th century (Grissino-Mayer 1995). However, dendrochronologists have subsequently become more able to recognize relationships between tree growth and broad-scale climate oscillations such as ENSO and PDO (Stahle *et al.* 1998; McCabe *et al.* 1999; Biondi *et al.* 2001). The detection of temporal variations in precipitation, and associated effects in tree growth, remains a topic of scientific inquiry in the Southwest as well (Mock 1996; Cook *et al.* 2007; Stahle *et al.* 2009). The longest-lived conifer at EMNM, Rocky Mountain juniper (Grissino Mayer *et al.* 1997), will be a valuable species for identifying additional relationships between multi-scale climatic variables and tree growth in west-central New Mexico.

The distribution of Rocky Mountain juniper includes many mid-elevation sites (1,500–2,700 m) across the western United States and Canada (Little 1980). Rocky Mountain juniper could be used a control species in climate analyses as it resists insect infestations that have caused high mortality in other western conifers. However, the species has been used in few dendrochronological studies. Only three Rocky Mountain juniper chronologies are archived in the ITRDB, none of the chronologies were created using wood from New Mexico or neighboring states (ITRDB 2011). Despite tree-ring evidence (Grissino-Mayer *et al.* 1997) that living Rocky Mountain junipers at EMNM are > 2,000 years old (older than the maximum observed ages for ponderosa pine and Douglas-fir at EMNM), the species had not been used in existing dendroclimatological studies conducted at the monument (Grissino-Mayer 1995; Grissino-Mayer 1996;

Grissino-Mayer *et al.* 1997; Lewis 2003; Stahle *et al*. 2009). The lack of Rocky Mountain juniper data represents a significant gap in the proxy record available to scientists investigating multi-scale climatic phenomena and climate-growth relationships in the region.

Chapter Two

GENERAL SETTING OF THE VOLCANIC MALPAIS

"Below the ponderosa pine forest around the sink, I had to traverse eight other distinct zones of vegetation . . . Beyond the last belt of plants, the cave mouth was occluded completely by a pond of ice water a foot deep over a mass of solid ice." – Alton A. Lindsey, *Naturalist on Watch*, 1983

2.1 Introduction

The Spanish word *malpais*, "bad country," has been associated with the Quaternary lava flows of western New Mexico for centuries (Mangum 1990; Eury 1997; Laughlin and Wolde-Gabriel 1997). El Malpais National Monument (EMNM) was established 31 December 1987 to protect the unique volcanic landscape near Grants, New Mexico (Grissino-Mayer 1995; Eury 1997). The monument is managed by the United States Department of the Interior National Park Service (NPS). EMNM preserves over 46,000 ha of the arid tableland of northwestern New Mexico. The monument protects unique geologic features, cultural sites, and rich biological diversity (Lindsey 1951; Mangum 1990; Bleakly 1997). Much of the surrounding landscape is administered by the United States Department of the Interior Bureau of Land Management (BLM), the United States Department of Agriculture Forest Service (USFS), and Native American communities.

Plant species on the malpais evolved to suit the dynamic natural history and harsh environmental conditions characteristic of western New Mexico. A mosaic of mixed conifers, shrubs, and grasses blankets much of the malpais, including one of the most celebrated old-growth woodlands on the Colorado Plateau (Grissino-Mayer 1995;

Grissino-Mayer *et al*. 1997). The natural history of the malpais is linked to the human history of the region. For thousands of years people have inhabited the malpais country (Mangum 1990). The arrival of European settlers brought a new era of resource exploitation that lasted until the establishment of EMNM and other conservation initiatives (Mangum 1990; 1997). Therefore, to assess the general setting of the volcanic malpais it is necessary to discuss both the environmental characteristics and human history of the region.

2.2 Physiographic Setting of the Malpais

The Colorado Plateau is a collection of smaller plateaus and mountain ranges positioned over southeast Utah, northeast Arizona, northwest New Mexico, and southwest Colorado (Orme 2002) (Figure 2.1). High mesas (1,500–3,000 m), intrusive granite mountain ranges (3,500–4,300 m), and volcanic features produce a complex and dramatic landscape. The sedimentary sequences that comprise parts of the Colorado Plateau were deposited over hundreds of millions years (Dutton 1884). Some of these sandstones, shales, and other sedimentary rocks are composed of eroded materials from the ancestral Rocky Mountains, while others are the product of shallow inland seas and ancient sand dunes (Orme 2002).

EMNM, located in west-central New Mexico, is situated on the Zuni-Bandera volcanic field, which is part of the Datil Section of the Colorado Plateau (Laughlin and Wolde-Gabriel 1997; Orme 2002). The Zuni-Bandera field is part of the larger Jemez Lineament, which stretches from central Arizona to northeastern New Mexico (Laughlin and Wolde-Gabriel 1997). The Zuni-Bandera volcanic field contains cinder-cone

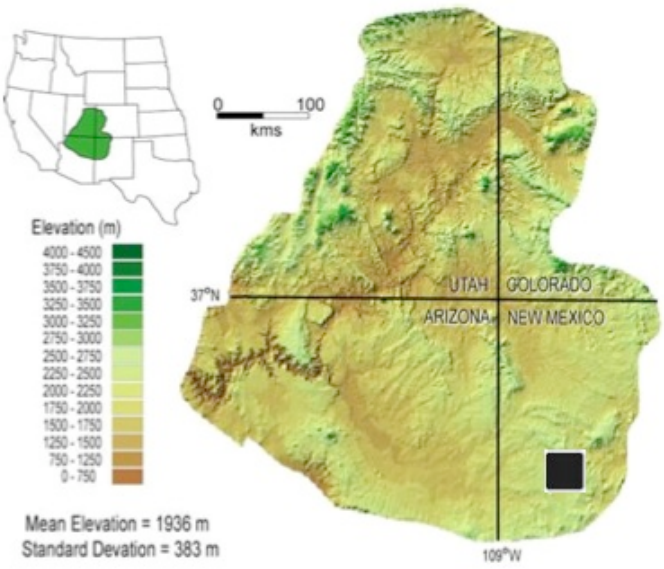


Figure 2.1 Geographic location and topography of the Colorado Plateau. El Malpais National Monument, and surrounding areas discussed in this dissertation, is located within the black rectangle.
(Base image courtesy of http://www.usu.edu/hydrology/mackley/plateau 2002)

volcanoes, shield volcanoes, stratovolcanoes, and relict lava flows. Elevations within EMNM range between 2,100–2,562 m. In general, the greatest topographic relief is in the northern sections of the monument, while the southern sections are flatter. The Continental Divide follows the Chain of Craters, a series of cinder cones and shield volcanoes on the western boundary of the monument (Laughlin and Wolde-Gabriel 1997).

Perhaps the most notable topographic features at EMNM are the rugged basalt formations created by multiple extrusive events that occurred between *ca.* 700,000–3,000 years ago (Laughlin and Wolde-Gabriel 1997). The oldest exposed basalts at EMNM are weathered surfaces that form the base material beneath rocks created by more recent volcanism. Quaternary basalt substrates were produced by two eruptive episodes that occurred *ca.* 150,000 years ago (episode 1) and *ca.* 600,000–700,000 years ago (episode 2). Today, these flows have well-developed soils that sustain grasslands, mixed-conifer woodlands, and ponderosa pine forests. Initial volcanic episodes at EMNM were followed by five distinct eruptions. The first eruption formed the El Calderon Lava Flow *ca.* 115,000 years ago, while the second event, *ca.* 50,000–100,000 years ago produced the Twin Craters Flow. Both flows feature vegetation assemblages similar to those of the grasslands, woodlands, and forests growing on the surrounding substrate. Approximately 30,000 years ago, volcanic activity covered parts of EMNM with lava that soon cooled to form the Hoya de Cibola Lava Flow. This formation is less eroded than the older lava flows and has poorer soil development. Therefore, the Hoya de Cibola Flow has lower vegetation cover than the Twin Craters and El Calderon Flows.

The next major eruption at EMNM occurred *ca.* 10,000–11,000 years ago. This eruption oozed lava from Bandera Crater, creating the craggy Bandera Lava Flow (Figure 2.2). Soil development on the Bandera Lava Flow is minimal; however, the basalt supports an old-growth woodland that harbors some of the oldest trees in the Southwest (Grissino-Mayer 1995; Grissino-Mayer *et al.* 1997). The most recent lava flow at EMNM, The McCarty's Lava Flow, formed *ca*. 3,160–3,200 years ago (Figure 2.3). McCarty's Lava Flow has little soil development or groundcover, but the formation is partially covered by an impressive forest of "pygmy" ponderosa pines (*Pinus ponderosa* Dougl. ex Laws.) (Lindsey 1951). The twisted pines are generally less than 3 m tall, yet many of the trees are hundreds of years old (Lindsey 1997) (Figure 2.4).

The lava flows at EMNM contain an elaborate complex of caves, natural bridges, and collapsed lava tubes (Rogers and Mosch 1997). The basalt insulates the subsurface from intense heating, which allows some of the caves to sustain perennial ice deposits (Dickfoss *et al.* 1997). The most famous and accessible malpais ice cave is on private land near Bandera Crater (Figure 2.5). Islands of limestone, sandstone, or weathered volcanic substrate called kipukas are also scattered across some sections of the flows. Kipukas within the malpais range in size from *ca.* 10–600 ha (Grissino-Mayer 1995). The largest kipuka, Hole In The Wall, is located almost entirely outside the EMNM boundary and is administered by the BLM.

EMNM is bordered to the north by the Zuni Mountains. Much of the range is within Cibola National Forest, which is managed by the USFS. Elevations in the Zunis range from *ca.* 2,000–2,820 m. The Zunis differ from other mountains in the area in that they formed by geologic uplift (Chronic 1987). The Zuni Mountains initially

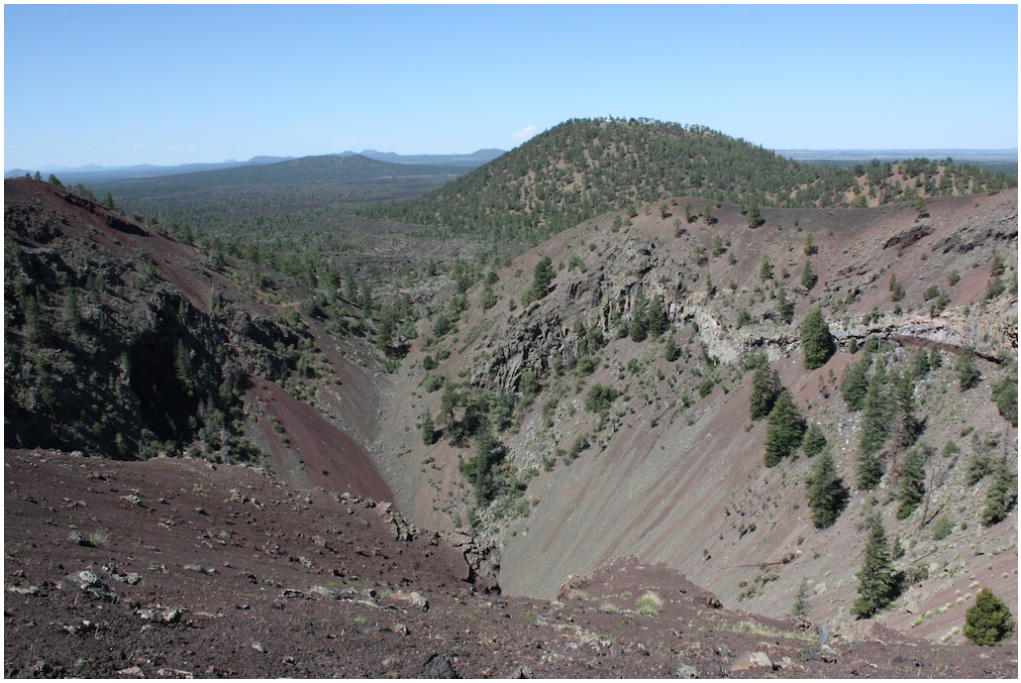


Figure 2.2 View south from the summit of Bandera Crater toward the Bandera Lava Flow and the Chain of Craters (Photo by Mark D. Spond, July 2009).



Figure 2.3 View northwest across the McCarty's Lava Flow from the Sandstone Bluffs Overlook (Photo by Mark D. Spond, July 2009).



Figure 2.4 A “pygmy” ponderosa pine growing near the Narrows section of El Malpais National Monument (Photo by Mark D. Spond, July 2009).



Figure 2.5 The world-famous Candelaria Ice Cave located on the Bandera Lava Flow (Photo by Mark D. Spond, July 2009).

consisted of a Precambrian core of igneous and metamorphic rocks, overlain by sedimentary strata that were deposited during subsequent periods. As the Zunis were uplifted, the sedimentary rock was eroded away, exposing the underlying core rock (Chronic 1987). However, the abundant volcanism in the region also left its mark on the Zuni Mountains. Some of the data used in this dissertation were collected on the Paxton Springs (Zuni Canyon) Lava Flow, located in the southern foothills of the mountain range. The lava flow originates at the Paxton Springs Crater, the most distinguishable cinder-cone volcano in the Zuni Mountains, and flows northeast before terminating in Zuni Canyon (Laughlin *et al.* 1993).

2.3 Climate

The Köppen Climate Classification System categorizes much of western New Mexico as a hot steppe. The malpais region is located near the boundary of New Mexico Climate Division 1 (Northwestern Plateau) and Climate Division 4 (Southwestern Mountains) (NOAA 2011). Most of the Zuni Mountains are included in New Mexico Climate Division 1 (NOAA 2011). Summers are typically hot (average maximum July temperature > 30 °C) and winters are cold (average minimum January temperature < –10 °C) (NPS 2011). Precipitation is bi-modally distributed, with a pronounced maximum during July, August, and September and a secondary peak during December–March. Average annual precipitation at El Morro National Monument, *ca*. 40 km west from my study area, is 406 mm (NPS 2011). A large percentage of regional precipitation is associated with the North American Monsoon during the summer months (Sheppard *et al.* 2002; Stahle *et al.* 2009).

2.4 Paleoenvironments

Fossil evidence, geologic data, and paleoenvironmental proxies indicate that the climate and vegetation of the American Southwest have not remained static through deep time (Axelrod and Raven 1985; Axelrod 1988). Tertiary orogenesis within the Western Cordillera altered atmospheric conditions and biological communities in the region by redirecting the subtropical and polar jet streams, blocking easterly sources of moisture, and producing orographic precipitation and rain shadow effects (Christiansen and Lipman 1972; Axelrod and Raven 1985). Prior to these uplifts, some deciduous angiosperms that are now characteristic of forests in eastern North America inhabited lower and middle elevations on the Colorado Plateau. Meanwhile, conifers comprised forest communities at higher elevations (Axelrod and Raven 1985; Axelrod 1988).

Variations in continental arrangement also affected the distribution of plant species in what is today the American Southwest. A 10° latitudinal shift southward of North America during the Eocene compounded climate changes in the region caused by Tertiary mountain building. The shift positioned what is today the American Southwest under the subtropical high-pressure belt, a position that inhibited the precipitation necessary to sustain most temperate broadleaf tree species (Axelrod and Raven 1985). In addition to changing precipitation regimes, the Tertiary tectonics responsible for uplifting the Colorado Plateau raised the mean elevation of the region, subjecting local plants to colder temperatures (Axelrod and Raven 1985).

Increased aridity and colder temperatures in the Southwest restricted many deciduous angiosperms from the region and allowed more drought-tolerant species to migrate north from Mexico during the Late Eocene and Early Oligocene (Axelrod and

Raven 1985). Rapid speciation occurred as plants evolved to access resources abandoned by more mesic species. Montane conifers remained present at higher elevations, but new grasses, shrubs, and drought-tolerant trees replaced lower elevation deciduous forests (Axelrod and Raven 1985; Axelrod 1988). Evidence from packrat middens (*Neotoma spp*.) suggests that the Southwest was wetter during intervals of the Pleistocene (Van Devender and Spaulding 1979; Betancourt and Van Devender 1981; Thompson and Anderson 2000). Pleistocene conditions allowed conifers such as white fir (*Abies concolor* Hildebr.) and Douglas-fir (*Pseudotsuga menziesii* (Mirb.) Franco) to migrate from high elevation refugia to lower areas. The Holocene environment on the Colorado Plateau has been comparatively drier, forcing these species to retreat to mountain locations (Thompson and Anderson 2000) (Figure 2.6).

Dendrochronologists have shown that some southwestern conifers, including Douglas-fir, ponderosa pine, and Rocky Mountain juniper (*Juniperus scopulorum* Sarg.), can live to very old ages in certain forest settings (Douglass 1941; Schulman 1954; Grissino-Mayer *et al.* 1997). Long-lived trees allow for robust tree-ring chronologies that can be used to reconstruct past environmental conditions (Fritts 1976). Significant contributions to our current research were produced with data collected at EMNM. Prior studies at EMNM used non-destructive techniques (*i.e.*, Swedish increment borers and partial chainsaw sampling) to sample moisture stressed Douglas-fir and ponderosa pine trees, providing a 2,000-year proxy record of annual precipitation, as well as data pertaining to local disturbance regimes and broad-scale climate phenomena (Grissino-Mayer 1995; 1996; Grissino-Mayer *et. al.* 1997; Grissino-Mayer and Swetnam 2000;



Figure 2.6 Conifer species that inhabited the malpais lowlands during past millennia are now restricted to the cooler, wetter climate of nearby Mt. Taylor (> 3,500 m) and other high peaks (Photo by Mark D. Spond, July 2009).

Stahle *et al.* 2009). Grissino-Mayer (1995) used tree-ring data from Douglas-fir and ponderosa pine samples collected at EMNM to reconstruct total annual precipitation for the period 136 B.C.–A.D. 1992. The reconstruction showed significant fluctuations in precipitation for western New Mexico during the past two millennia. In addition to providing information about prehistoric droughts that likely affected the human inhabitants of the region, Grissino-Mayer identified the last 200 years (especially the late 20th century) as one of the wettest periods during the past 2,000 years.

2.5 Contemporary Flora

Although EMNM is geologically part of the Colorado Plateau, it is within the Southern Rocky Mountain-Mogollon Floristic Area (McLaughlin 1989). Bleakly (1997) identified more than 440 plant species at the monument. EMNM contains four general vegetation communities: (1) mixed-conifer woodland, (2) shrub-conifer woodland, (3) grassland or grass-shrubland, and (4) barren to sparse grass-shrubland (Bleakly 1997). An earlier classification by Lindsey (1951) included five vegetation categories: the "Douglas-fir Belt," the "Ponderosa Pine Belt," the "Apache Plume Belt," ponds located within lava sinks, and ice cave entrances.

Mixed-conifer woodland dominates the older the lava flows, making it the most widespread vegetation community at EMNM (Figure 2.7). The second most expansive community is the barren to sparse grass-shrubland, which covers much of the McCarty's Lava Flow and portions of the Bandera Lava Flow. Locations classified as grasslands or grass-shrublands occupy the weathered basalts surrounding the more recent lava flows. However, these areas are primarily outside the boundary of the monument.



Figure 2.7 Old-growth trees comprise the mixed-conifer woodlands at many locations on the malpais (Photo by Mark D. Spond, July 2009).

Shrub-conifer woodlands are uncommon at EMNM, restricted to sedimentary substrates and cinder deposits (Bleakly 1997). Most of the data used in this dissertation were collected within the mixed-conifer vegetation community. The mixed-conifer woodlands at EMNM are composed of old-growth Douglas-fir, ponderosa pine, Rocky Mountain juniper, one-seed juniper (*Juniperus monosperma* (Engelm.) Sarg.), and piñon (*Pinus edulis* Engelm.). Trees growing on the malpais are primarily non-commercial timber characterized by irregularly shaped stems, sparsely foliated crowns, and other diagnostic old-growth features (Schulman 1954; Stahle and Chaney 1994; Grissino-Mayer 1995).

Research by Shields and Crispin (1956) on a lava flow in south-central New Mexico suggested that highly-fractured basalt effectively stores surface run-off like a sponge, allowing deep-rooted conifers to endure sustained periods of low precipitation. Therefore, the volcanic malpais often exhibits more tree species and greater stem density than the surrounding sedimentary substrate (Bleakly 1997). Poor timber quality and the inhospitable terrain serve as deterrents to anthropogenic disturbances on the lava flows (*e.g.*, livestock grazing and logging), allowing many conifers to live for centuries. Trees living on the malpais are also protected from natural phenomena (*e.g.,* wildfires and pathogens) due to the isolating effects of life on the basalt (Grissino-Mayer and Swetnam 1997; Lewis 2003).

Ancient alligator junipers (*Juniperus deppeana* Steud.) found on local cinder deposits are absent from the mixed-conifer woodland that covers much of the malpais. Shorter-lived quaking aspen trees (*Populus tremuloides* Michx.) and Gamble oak (*Quercus gambelii* Nutt.) are present at some margins of the lava flows and in lava sinks where more moisture is available (Bleakly 1997). Despite poor soil development and

heavy precipitation run-off, a patchwork of grasses, shrubs, and herbs inhabit the jagged lava flows, including: wax current (*Ribes cereum* Douglas), Apache plume (*Fallugia paradoax* (D.don) Endl. ex Torr.), skunkbrush (*Rhus trilobata* Nutt.), rockspirea (*Holodiscus dumosus* (Nutt.) ex. Hook.), wild buckwheat (*Eriogonum jamesii* Benth.), skyrocket (*Ipomopsis tenuifolia* (A. Gray) V.E. Grant), and mountain muhly (*Muhlenbergia montana* (Nutt.) Hitchc.) (Bleakly 1997). The kipukas at EMNM are floristically and ecologically different than the coarse *pahoehoe* (*i.e.*, ropey) and *aa* (*i.e.*, jagged) basalt of the lava flows. Bleakly (1997) found that the kipukas at EMNM support plants that do grow on the volcanic malpais, including: dwarf blue-eyed grass (*Sisyrinchium demissum* Greene), showy fameflower (*Talinum pulchellum* Woot. & Standl.), painted milkvetch (*Astragalus ceramicus* Sheldon), and alderleaf mountain mahogany (*Cerocarpus montanus* Raf.). Lewis (2003) concluded that some of the kipukas at EMNM are experiencing woodland encroachment due to decades of fire suppression during the 20th century.

2.6 Land-Use History on the Malpais

A primary objective of management officials at EMNM is to rehabilitate the appearance and function of the landscape from decades of human impact. To reach this goal, officials must carefully examine the land-use history of EMNM and surrounding areas, especially impacts that occurred after the incursion of Spanish forces into New Mexico during the 16th century. Native populations prior to this time were comparatively small, sedentary, and restricted to several locations across western New Mexico. Therefore, the land-use impacts of these peoples at EMNM were minimal (Grissino-

Mayer 1995). Pronounced human alterations to the landscape at EMNM (*e.g.*, vegetation changes and changes to disturbance regimes) probably began after European contact and are associated with: (1) domestic livestock grazing, (2) logging, and (3) fire suppression (Grissino-Mayer 1995).

2.6.1 Pre-Anglo Land-Use History

Grissino-Mayer (1995) examined the pre-Anglo settlement and land-use history of EMNM (*ca.* 1540–1880) by ethnicity: Hispanic (Spanish and Mexican populations), and Native American. Local indigenous peoples included the Navajo and three Pueblo communities: Acoma, Laguna, and Zuni, all of whom still inhabit western New Mexico. Both Hispanic and Native residents relied heavily on the livestock trade during this period. Domesticated stock animals were first brought to New Mexico in 1540 by the Spanish expedition led by Francisco Vasquez de Coronado (Bailey 1980; Baxter 1987; Mangum 1997). Most of Coronado's sheep died between Mexico City and the arrival of his force at "Cibola," which was likely the Zuni village of Hawikuh located *ca.* 75 km west of EMNM (Bailey 1980; Mangum 1997). Juan de Oñate more successfully drove 3,600 sheep and goats up the Rio Grande from Mexico to Santo Domingo Pueblo in 1598 (Bailey 1980) (Figure 2.8). Shortly afterward, Puebloan populations began raising domesticated livestock to supplement their traditional methods for producing food and raw materials. The Navajo also received sheep from the Spanish missions sometime before 1630 (Bailey 1980), but the Navajo did not migrate south to the malpais country until the late 18th century (Grissino-Mayer 1995).

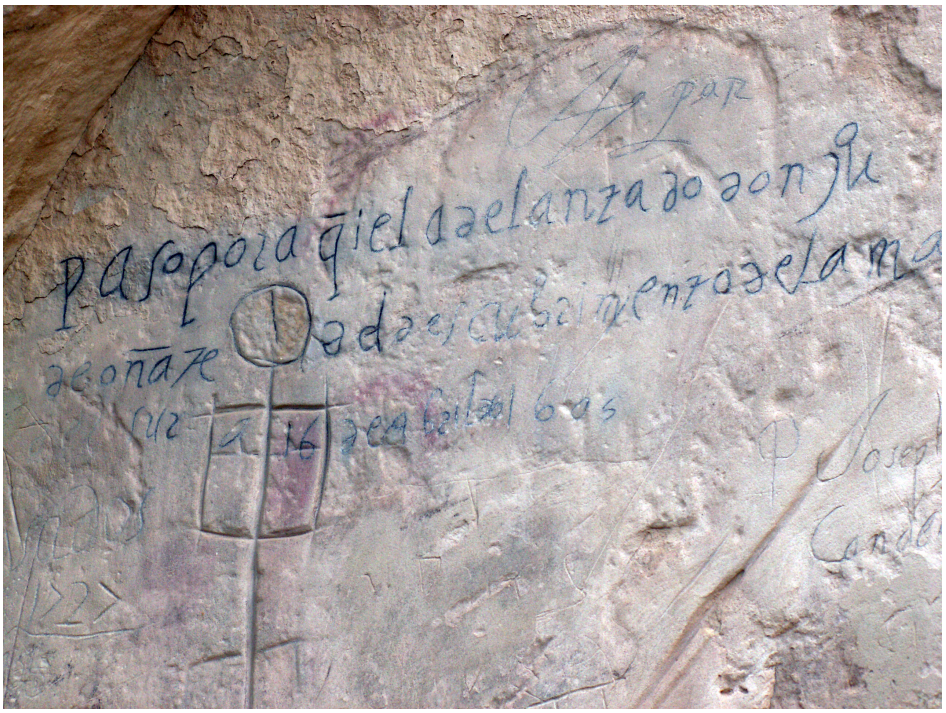


Figure 2.8 Several Spanish conquistadors carved their names at Inscription Rock (El Morro National Monument) just west of the malpais. Later, American settlers would visit the same site and engrave their names into this prominent stone outcrop (Photo by Mark D. Spond, July 2008).

Livestock populations in New Mexico increased significantly following the Pueblo Revolt of 1680 (Bailey 1980; Roberts 2005). Fray Francisco de Vargas granted thousands of sheep to loyalists from New Spain who had helped defeat the Indian rebellion and restore colonial rule to New Mexico. Navajo sheep populations skyrocketed as well during the 18th and 19th centuries. The total Navajo herd numbered nearly 500,000 in 1850 (Bailey 1980). The local Ramah branch of the Navajo grazed small numbers of sheep in the Zuni Mountains, but most of the Navajo herd was restricted to rangeland in the Four Corners region of Arizona and New Mexico (Bailey 1980). Grazing by Acoma and Laguna sheep may have had the greatest impact on the malpais and surrounding grasslands due to the close proximity of the two pueblos. The Zuni influence was minimal, as they primarily grazed sheep on the plains and mesas west of the monument (Grissino-Mayer 1995). Despite the presence of Native herders and the passage of Hispanic *carneradas* (massive sheep drives) to markets in Chihuahua and California during the 18th and early 19th centuries, it is unlikely that early livestock populations significantly impacted the landscape that is today EMNM (Baxter 1987; Grissino-Mayer 1995).

2.6.2 Anglo Land-Use History

The Mexican-American War (1846–1848) brought major cultural and economic changes to New Mexico and the surrounding region. The United States of America took possession of New Mexico from Mexican loyalists on 19 August 1846. Two years later the Treaty of Guadalupe Hidalgo ended the war. The treaty confirmed an American victory and gave most of Mexico's northern frontier to the United States (Meyer *et al.*

2003). Almost immediately, American military and survey expeditions began to chart and settle lands in the western portion of the territory. The ultimate goal of the American advance was to drive the Navajo and other tribes from the most suitable rangeland and secure the region for expanded agriculture, industry, and infrastructure (Mangum 1990).

The Atlantic and Pacific Railroad reached the malpais country in 1881. A coal depot was constructed at Grant Station (the modern town of Grants) near the northern terminus of the malpais (Mangum 1990). The establishment of Fort Wingate near San Rafael during the 1860s preceded construction of the railroad. Fort Wingate was part of the U.S. Army effort to subjugate the Navajo. These two developments elevated the Anglo-American presence in west-central New Mexico (Mangum 1990; 1997) and greatly increased the flow of livestock into the area.

San Rafael, which was once merely one of several New Mexican herding communities near the malpais, emerged as the sheep capital of the region (Figure 2.9). By the 1880s, thousands of sheep grazed the area around San Rafael, including the foothills of the Zuni Mountains and areas that are now part of EMNM (Mangum 1990; Grissino-Mayer 1995). Heavy sheep grazing greatly reduced groundcover, which acted as an early form of fire suppression and constituted the first major anthropogenic disruption of the natural fire regime at EMNM (Grissino-Mayer and Swetnam 1997). Cattle companies also began to operate in the malpais country during the 1880s and 1890s (Mangum 1990). However, a drought between 1891 and 1893 devastated sheep and cattle populations across the Southwest, effectively ending the livestock boom of the late 19th century (Allen 1989; Grissino-Mayer 1995).



Figure 2.9 Sheep grazing in the ponderosa parkland near Cerro Bandera *ca.* 1920 (Photo taken by W.T. Lee. Credit: United States Geological Survey Photographic Library, Denver, Colorado).

Industrial logging was the next commercial enterprise to exploit the malpais region. Timber companies were drawn to the area by virgin stands of ponderosa pine. Logging operations began in 1891 after businessmen from Michigan purchased large tracts of land within the Zuni Mountains (Mangum 1990). Economic difficulties slowed logging efforts during the late 1890s, but harvesting intensified shortly after the turn of the 20th century. The first company to heavily log the malpais country was the American Lumber Company. In 1910, the American Lumber Company processed 60 million board feet of timber from the Zunis and surrounding areas, which was nearly double the amount of their average harvest during 1903–1913 (Mangum 1990).

The American Lumber Company, and later the Breece Lumber Company, built 55 miles of narrow-gauge railways in the Zuni Mountains (Glover and Hereford 1986). Many of the rail lines initially served the northern slopes of the Zunis where the logging was most intense (Grissino-Mayer 1995). However, during the 1920s and 1930s the timber companies shifted their focus south to the lucrative stands of ponderosa pine on lands immediately surrounding the malpais lava flows. Trees harvested from these areas could now be easily transported to Grants by truck. Research by Grissino-Mayer (1995) showed that many of the trees harvested from the periphery of the malpais during this period were hundreds of years old and > 1.5 m in diameter. Most locations on the malpais interior were not logged due to the unmarketable timber and inaccessible terrain, yet at least one rail line was built across the lava to access pines on Lost Woman Cinder Cone. Logging was likely more intense in the ponderosa parklands surrounding El Calderon and in the vicinity of Cerro Bandera, Cerro Rendija, and Cerritos de Jaspe (Grissino-Mayer 1995).

The United States government began to establish Forest Reserves (precursors to National Forests) during the 1890s. This development was one of the first non-military efforts by the federal government to manage the resources of west-central New Mexico (Grissino-Mayer 1995; Mangum 1990). Much of the Zuni Mountains were designated as Zuni National Forest in 1909. The property was later incorporated into Manzano National Forest in 1914, before a final designation as Cibola National Forest in 1931 (Grissino-Mayer 1995). Meanwhile, the BLM was granted control of the malpais lava flows, mesas, and open plains south of the Zuni Mountains (Grissino-Mayer 1995). Both the USFS and the BLM aggressively suppressed all fires in the region during most of the 20th century. Fire was viewed as a threat to timber resources, and managers used new technologies (*e.g.*, aircraft and airborne firefighters) to extinguish all fires. Low-impact surface fires, which had occurred regularly in the ponderosa forests and other woodland habitats of the malpais, were virtually eliminated (Grissino-Mayer and Swetnam 1997; Lewis 2003; Trader 2009).

The establishment of EMNM in 1987 led to a departure from decades of fire suppression policy. The new monument shifted administration of the malpais and surrounding forests to the NPS. A central objective of the NPS at EMNM is to restore "the natural function of fire within the ecosystems of the park to the greatest extent possible" (NPS 2000). To achieve this goal, NPS officials reconsidered strict fire suppression tactics and moved toward management policies more tolerant of fire. Recent prescribed burns (1999, 2003, 2006, and 2008) within EMNM significantly reduced fuel loads, and subsequently, wildfire danger (Trader 2009). EMNM officials also use mechanical clearing to periodically thin dense stands of "dog-hair ponderosa pine" that

emerged during the era of fire suppression (Gary Luce, NPS, personal communication 2009). Mechanical clearing reduces wildfire risk at the monument. Successful fuels management and continued fire-science research will remain key in mitigating impacts from past fire suppression and restoring a functional fire regime at EMNM.

2.7 The Future

The natural and land-use histories of the malpais country are incomplete. The dynamic natural history of the region suggests that the contemporary malpais is merely an ephemeral landscape when placed in the context of geologic time. Future volcanic eruptions, climatic shifts, regional uplift, or biological controls would likely bring significant changes to the malpais. Interactions between humans and the malpais will also continue to influence the appearance and vitality of this unique landscape. While exploitive logging and grazing operations diminished across the region during recent decades, resource managers must always consider the potentially negative impacts caused by the promotion of tourism and outdoor recreation on the malpais. Hopefully, as appreciation for the aesthetic qualities of the malpais increases, so too will the attention directed to the scientific and cultural value of this resource.

Chapter Three

COMPARING MIXED-CONIFER WOODLAND DYNAMICS ON THE BANDERA LAVA FLOW (1948–2010), EL MALPAIS NATIONAL MONUMENT, NEW MEXICO, U.S.A.

Portions of this chapter that refer to drought and land-use history in the American Southwest were taken from Chapters 1 and 2 of this dissertation. The use of "we" in this chapter refers to Mark Spond, Dr. Henri Grissino-Mayer, and Grant Harley, all of whom will be coauthors on a manuscript, taken from this material, to be submitted for peer-reviewed publication.

Abstract

Previous studies showed that many trees growing on the Quaternary lava flows at El Malpais National Monument, New Mexico (EMNM) live to very old ages, suggesting that the volcanic badlands insulate vegetation from environmental impacts (*i.e.*, drought and anthropogenic activity) that cause tree mortality and changes in plant density. In contrast, the edge of the expansive basalt formations sharply transitions into weathered substrate where moisture is quickly lost to evaporation and the effects of human land use are more pronounced. Our goal was to compare stand inventory data collected from the mixed-conifer woodland on the interior of the Bandera Lava Flow with repeat photographs of the vegetation at a nearby location on the edge of the Bandera Lava Flow. This approach provided concurrent vegetation-dynamics data from two ecologically different locations on the Bandera Lava Flow. We hypothesized that vegetation changes would be apparent at the lava-substrate interface, while minimal structural changes would be detected at our sample site on the lava interior.

We used repeat historical photographs (summer 1948 and summer 1981) taken by the late ecologist Alton A. Lindsey of the basalt-substrate interface at the western edge of

the Bandera Lava Flow. Two adjacent scenes were rephotographed a third time during summer 2010. The three-part rephotography sequences were analyzed in horizontal scans using a digital loupe at 2x magnification. Living and dead trees, groundcover, and tree species composition were compared among the photographs to elucidate fine-scale woodland dynamics at the boundary between the basalt badlands and the surrounding substrate. Our visual analyses were then compared with stand-structure data from the lava interior, where human activity is minimal and the porous lava retains precipitation during dry periods.

Substantial changes in woodland structure and groundcover were visible in the repeat photography sequences from the lava edge (1948, 1981, and 2010). Some of the trees we observed in the 2010 images were not visible in the earlier photographs, while several trees prominently featured in Lindsey's initial photographs appeared dead in the most recent scenes. Trees within our interior study plot were old and there was little evidence of regeneration or mortality within the stand. Within the plot, 89% of stems > 10 cm diameter at ground level persisted throughout the period covered by our repeat photographs (1948–2010), including the drought of the mid-20th century and the current Southwestern drought (*ca*. 2000–2010). We concluded that despite the insular qualities of the volcanic malpais and drought adaptations of its plant species, noticeable vegetation changes occurred during the 20th and early 21st centuries at the periphery of the Bandera Lava Flow. Vegetation changes at the lava-substrate interface could be linked to human activity, resource management, or episodes of drought. Our repeat-photography sequences and woodland-inventory data may suggest patterns of tree mortality and persistence at larger spatial scales within EMNM.

3.1 Introduction

Significant land-use changes occurred in western New Mexico during the 20th century, particularly in areas now controlled by the United States government (Mangum 1990). Many government lands are managed to restore the function and appearance of the resource prior to European settlement (*ca*. 1880), allowing visitors to experience a landscape void of human disturbance (NPS 2010). The residual effects of past industrial logging, livestock grazing, and fire suppression complicate this management strategy. Ecosystem restoration efforts are made even more challenging by the persistent drought that has plagued the Southwest for more than a decade. Instrumental records and proxy-based drought reconstructions indicate that this drought is among the most severe in recent history (Cook *et al.* 2007; Stahle *et al.* 2007). The current drought and projections of regional "drying" through the remainder of the 21st century (Seager *et al.* 2007; Hughes and Diaz 2008) have raised questions concerning the future effects of climate change in Southwestern ecosystems (Baron *et al.* 2009). Existing studies suggest that the ongoing "global-change type drought" has already increased mortality rates in some Southwestern conifer species (Breshears *et al.* 2005; Allen *et al.* 2010). However, the impacts of climate change on vegetation dynamics in old-growth woodlands that are highly resistant to moisture stress are uncertain (Shields and Crispin 1956; Grissino-Mayer 1995; McDowell *et al.* 2008).

Numerous studies have analyzed repeat historical photographs to provide evidence of environmental and anthropogenic changes to western landscapes (Hastings and Turner 1965; Veblen and Lorenz 1991; Allen *et al.* 1998; Butler and DeChano 2001; Noel and Fielder 2001; Hutchinson 2000; Turner *et al.* 2003; Griffin *et al*. 2005). Repeat

photography (rephotography) analysis compares two or more photographs, depicting the same subject, captured at specified times (Rogers *et al*. 1984). Although not as spatially comprehensive as aerial photographs and satellite imagery, repeated ground-based photographs provide finer scale assessment of vegetation changes and anthropogenic activity. Ground-based photography also predates remotely sensed data in many locations (Turner *et al*. 2003). Repeat historical photographs provide a visual assessment of environmental effects on tree establishment, tree growth, and tree mortality. Rephotography may also permit unique analyses and inferences, especially regarding vegetation fragmentation, changes to plant morphology, species composition, and stand structure. Differences among featured species at photography sites is sometimes apparent, allowing land managers to allocate rehabilitation resources where needed most (Turner *et al.* 2003; Baron *et al.* 2009).

Mixed-conifer woodlands cover much of the lava flows at El Malpais National Monument (EMNM). The basalt abruptly transitions into a highly-weathered substrate that supports a community of grasses, shrubs, and trees (Bleakly 1997). Research by Grissino-Mayer (1995; 1996) identified hundreds of ancient conifers and pieces of remnant wood on the basalt formations at EMNM. His findings suggested that ecosystem disturbances (both natural and anthropogenic) and subsequent vegetation changes occur infrequently on the rugged lava flows. However, much of the land surrounding the basalt formations was heavily impacted by industrial logging and grazing during the late 19th and early 20th centuries (Mangum 1997).

The stark contrast in land use at EMNM provides the opportunity to investigate fine-scale vegetation dynamics at two land-use extremes: the malpais interior, which is

difficult to access, and the more accessible lava edge. The famed ecologist Alton A. Lindsey initiated this research during the 1940s by producing a collection of photographs that detailed the flora and geology of the malpais. Lindsey repeated many of his photographs during the summer of 1981. He noticed changes in some scenes, while other subjects remained essentially the same (Lindsey 1997). Our objective was to augment the work of Lindsey by photographing a selection of the scenes a third time during summer 2010. The goals of our study were to: (1) assess vegetation dynamics in historical and repeat photographs taken at the lava-substrate interface; (2) investigate woodland stand dynamics on the protected interior of a lava flow; and (3) compare contemporaneous vegetation dynamics at the two locations. We hypothesized that vegetation changes would be apparent at the lava-substrate interface, while minimal changes would be detected at our sample site on the lava interior.

3.2 Study Area

EMNM was established 31 December 1987 (Mangum 1990). The monument is located on the Datil Section of the Colorado Plateau, which stretches across parts of west-central New Mexico and east-central Arizona. Elevations at EMNM range from 1,950–2,400 m. The Köppen Climate Classification System categorizes much of the region as a hot steppe (BSh). Local weather is characterized by hot summers (average maximum July temperature > 30 °C), cold winters (average minimum January temperature < –10 °C), and relatively low precipitation. Average annual precipitation at EMNM is approximately 400 mm, much of which can be attributed to the summer rains that accompany the North American Monsoon (Sheppard *et al.* 2002; Lewis 2003; Stahle *et al.* 2009).

The Zuni-Bandera volcanic field is the most prominent landscape feature at EMNM. Thousands of hectares of EMNM and surrounding areas are covered with undulating basalt formations deposited during the Quaternary Period (Laughlin *et al.* 1993; Laughlin and Wolde-Gabriel 1997). One of the major basalt features at EMNM is the Bandera Lava Flow. The Bandera Lava Flow originates from Bandera Crater and extends along the western boundary of EMNM. Radiometric dating indicates that the Bandera Lava Flow was deposited during eruptions that occurred between 10,000–11,000 years before present (Laughlin and Wolde-Gabriel 1997).

The basalt flows and volcanic craters at EMNM support a patchwork of shrubs, herbs, and grasses. The malpais also harbors one of the best-preserved old-growth woodlands in the western United States (Grissino-Mayer 1995; Grissino-Mayer *et al*. 1997; Lewis 2003). The old-growth woodlands at EMNM are primarily composed of mixed-conifer species. Douglas-fir (*Pseudotsuga menziesii* (Mirb.) Franco), ponderosa pine (*Pinus ponderosa* Dougl. ex Laws.), Rocky Mountain juniper (*Juniperus scopulorum* Sarg.), one-seed juniper (*Juniperus monosperma* (Engelm.) Sarg.), and piñon pine (*Pinus edulis* Engelm.) are the dominant tree species. Quaking aspen (*Populus tremuloides* Michx.) is also present on some basalt formations. Despite poor soil development and heavy precipitation run-off, a mosaic of grasses, shrubs, and herbs inhabit the jagged lava flows, including: wax current (*Ribes cereum* Douglas), Apache plume (*Fallugia paradoax* (D. Don) Endl. ex Torr.), skunkbrush (*Rhus trilobata* Nutt.), rockspirea (*Holodiscus dumosus* (Nutt.) ex. Hook.), wild buckwheat (*Eriogonum jamesii* Benth.), skyrocket (*Ipomopsis tenuifolia* (A. Gray) V.E. Grant), and mountain muhly (*Muhlenbergia montana* (Nutt.) Hitchc.) (Bleakly 1997).

Trees growing on the malpais are primarily non-commercial timber characterized by irregularly-shaped stems, sparsely-foliated crowns, and other diagnostic old-growth features (Schulman 1954; Stahle and Chaney 1994). The highly-fractured basalt effectively stores surface run-off like a sponge, allowing deep-rooted conifers to endure sustained periods of minimal precipitation (Shields and Crispin 1956; Grissino-Mayer 1995). Therefore, the volcanic malpais often exhibit more tree species and greater stem density than the weathered basalt and sedimentary rock that form the surrounding substrate (Bleakly 1997). Poor timber quality and the inhospitable terrain serve as a deterrent to anthropogenic disturbances on the lava flows (*e.g.*, livestock grazing and logging), allowing many conifers to live for centuries. Trees growing on the malpais are also more protected from natural phenomena (*e.g.,* wildfires and pathogens) due to the isolating effects of life on the basalt (Grissino-Mayer and Swetnam 1997; Lewis 2003).

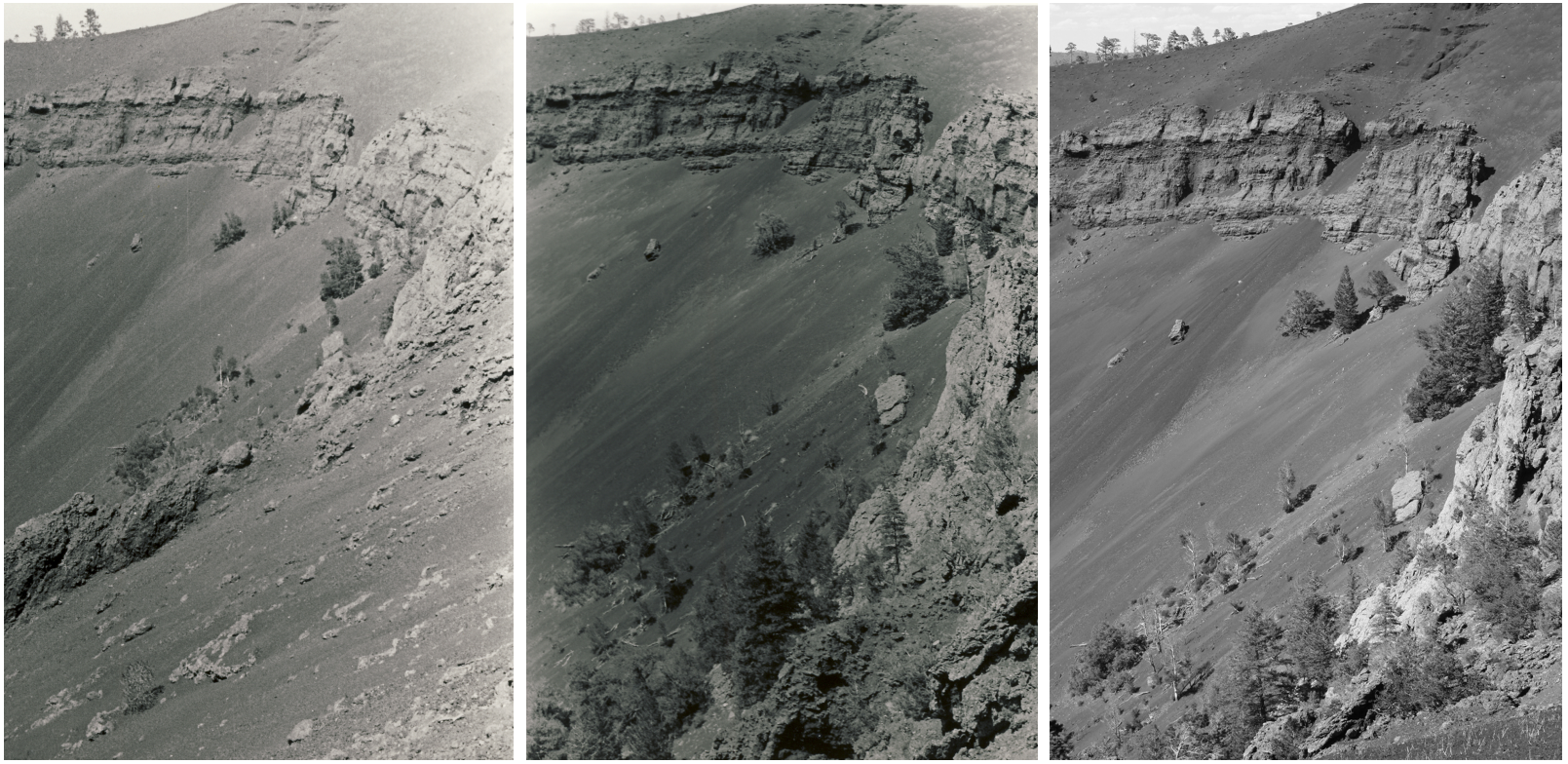
3.3 Methods and Materials

We examined > 200 historical photographs, taken by Alton A. Lindsey, of ecological communities and geologic formations on the volcanic badlands in and around EMNM. The images are archived as 10.60 x 15.24 cm black and white photographic plates at the EMNM headquarters in Grants, New Mexico. The collection consists of initial photographs paired with subsequently repeated images of the same scenes photographed more than 30 years later. The first set of photographs was taken during the summers of 1947 and 1948, while the repeated set was produced during the summer of 1981. Notes that Lindsey prepared for an unpublished report to the Bureau of Land Management accompany the photographs (Lindsey 1981). The majority of Lindsey's

photographs were excluded from our study because they did not show the lava-substrate interface (Figure 3.1 and 3.2), or they featured scenes that we could not relocate (Figure 3.3–3.6). Others were excluded due to inconsistencies caused by Lindsey's use of different camera lenses (*i.e*., focal lengths) during his 1947, 1948, and 1981 field seasons (Lindsey 1981).

We chose to work with two rephotographed scenes that showed conditions at the edge of the Bandera Lava Flow in an area of EMNM known as the Big Tubes (Figure 3.7). The images we selected were among the few in Lindsey's collection that featured distinguishable vegetation at the lava-substrate interface. The photographs showed adjacent locations with an approximately 0.5 ha combined field of view. Historical photographs used in this study were digitized in grayscale at 236 dots per centimeter, cropped for uniformity, and saved as TIFF (Tagged Image File Format) files (Griffin *et al*. 2005). We produced a third photograph of the selected scenes on 10 August 2010. The new images were produced with a hand-held, digital single-lens reflex camera at a focal length of approximately 55 mm and a cropping factor of 1.6x. Camera location and azimuth were recorded with a GPS receiver and a digital compass. Digital images were saved as JPEG (Joint Photographic Experts Group) files, which were later cropped and edited with Adobe Photoshop. The 2010 pictures completed a 3-part, > 70-year visualization of vegetation dynamics along this section of the lava edge.

We visually identified changes in stand structure among the repeated photographs to chronicle 20th century woodland dynamics at the margin of the Bandera Lava Flow.



1948 **1981** **2010**

Figure 3.1 Photo sequence shows the interior of the Bandera Crater (N 34º 59.882, W 108º 04.986). The camera faces north (*ca*. 0º). Although vegetation changes are noticeable among the photographs, the images do not show the edge of a lava flow.



1948



1981



2010

Figure 3.2 Photo sequence shows the sandstone bluffs, grasslands, and the eastern edge of the malpais along New Mexico State Highway 117 (N 34º 55.457, W 107º 50.604). The camera faces north-northeast (*ca.* 15º). While the lava-substrate interface is visible in the images, the distance between the camera and edge of the lava prohibits the accurate assessment of potential vegetation changes at the lava margin.



1948



1981

Figure 3.3 Lindsey described the ponderosa pines growing near New Mexico State Highway 117 as a “pygmy” forest. We were unable to relocate this site due to the homogeneous landscape.



1948



1981

Figure 3.4 Lindsey noted little change in many scenes within the "pygmy forest" between 1948 and 1981. We were unable to relocate this site.



1948



1981

Figure 3.5 Photo pair shows gnarled ponderosa pines growing near the eastern boundary of what is today EMNM. We were unable to relocate this site.



1948



1981

Figure 3.6 Photo pair shows "pygmy" ponderosa pines growing near the eastern boundary of what is today EMNM. Lindsey recognized little change at this location between 1948 and 1981. He noted that many of the trees on the horizon persisted during the period. We were unable to relocate this site.

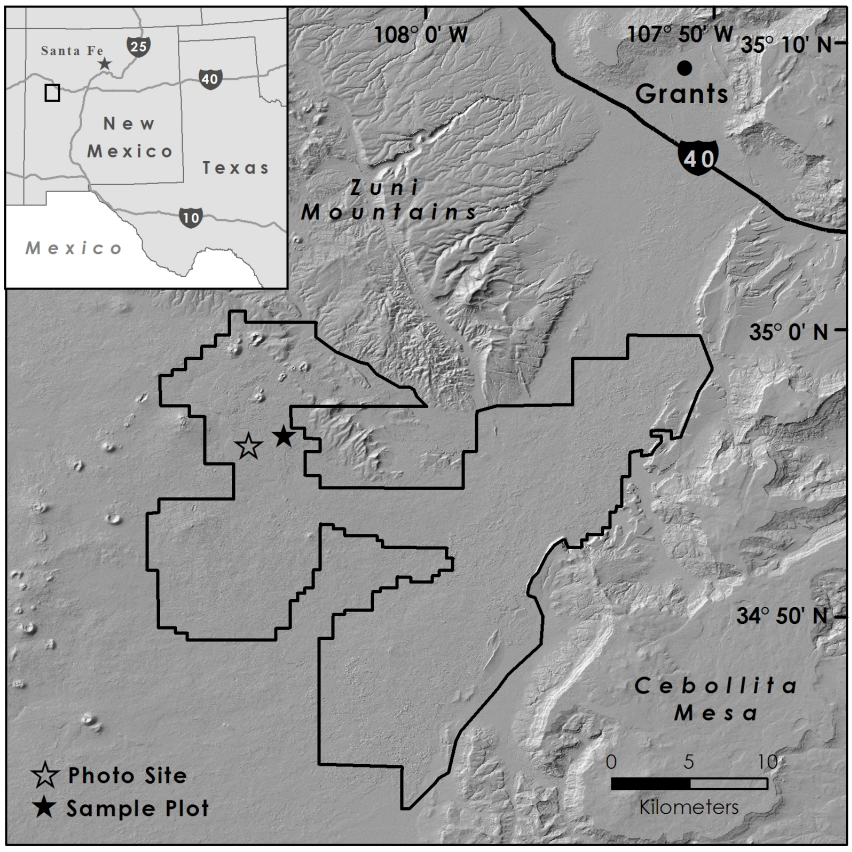


Figure 3.7 The black polygon indicates the boundary of EMNM. The black star shows the approximate location of our 0.5 ha sample plot on the interior of the Bandera Lava Flow. The gray star marks the approximate location of our repeat-photography sites along the edge of the Bandera Lava Flow near the area known as Big Tubes.
(Map by Grant Harley)

Horizontal scans across the images were performed with the digital loupe tool (2x magnification) included with Apple Aperture computer software. We looked for tree mortality and regeneration, changes to tree species composition, and changes to substrate groundcover. Changes among the photographs were listed and collectively analyzed as a visual time series of vegetation dynamics at the boundary between the Bandera Lava Flow and the surrounding substrate.

Woodland structure data were collected at a 0.5 ha rectangular plot to provide comparisons between repeat-photo sequences taken at the periphery of the Bandera Lava Flow and observations from a comparably sized area on the interior of the lava. The 0.5 ha plot was established approximately 1 km northeast of the Big Tubes camera location. All living trees within the plot > 10 cm diameter at ground level (D_{GL}) were identified by species, inventoried, and cored with an increment borer. Dead trees were identified and photographed. Additional attention was directed to recording the presence of tree saplings and other groundcover. Tree-ring samples were mounted, surfaced (Orvis and Grissino-Mayer 2002), and aged using standard forestry methods (Yamaguchi 1991). Age data from the plot were used to quantify stand dynamics at the interior location using observation intervals that matched our three-part rephotography sequences.

3.4 Results

Stand structure changes were apparent in the repeat photo sequences produced at the edge of the Bandera Lava Flow. Several ponderosa pines that appeared alive in the 1948 images were dead in later photographs, while a prominent ponderosa on the foreground substrate matured during the same period and appeared healthy in 2010

(Figure 3.8). Lindsey's 1981 photographs recorded the emergence of quaking aspen that we found dead in 2010. Multiple conifers persisted through the entire rephotography period, including Rocky Mountain junipers, piñon, and the old-growth ponderosa pine at the southern margin of the photography site (Figure 3.9). The repeat photography sequences also showed increased vegetative cover in the foreground of the images. Continuous grass cover replaced the patchy substrate groundcover visible in Lindsey's earlier images prior to our return in 2010.

Aging the trees within our interior study plot allowed us to determine which of the 80 stems identified as > 10 cm D_{GL} during 2009 persisted throughout the period included in our repeat photography sequence. Only 9 of the 80 trees (11%) in our plot that were > 10cm D_{GL} during 2009 established after 1948 (Table 3.1). In fact, many of the trees growing within the plot were > 300 years old. We also identified 3 standing dead trees in the plot (2 ponderosa pine and 1 Rocky Mountain juniper) and 2 downed dead trees (both ponderosa pine). Tree seedlings were almost non-existent within the 0.5 ha plot. We identified only several piñon and ponderosa pine seedlings, as well as a coppice of young aspen stems. Although the mixed-conifer woodland within our plot experienced some changes between 1948–2009, the dynamics appear to be less pronounced than those observed at the lava-substrate interface.

3.5 Discussion

Historical photographs are valuable archives of fine-scale environmental dynamics. Rephotography sequences presented in this study show vegetation at the interface of the Bandera Lava Flow and surrounding substrate at EMNM. Visual



1948



1981



2010

Figure 3.8 Photo sequence shows the edge of the Bandera Lava Flow near the Big Tubes (N 34°57.466, W 108°06.875). The camera faces northeast (*ca*. 65º).



1948



1981



2010

Figure 3.9 Photo sequence shows the area adjacent (south) to the location featured in Figure 3.7. The site is positioned along the same edge of the Bandera Lava Flow near the Big Tubes (N 34°57.465, W 108°06.875). The camera faces northeast (*ca*. 70º).

Table 3.1 Our sample plot was located at an interior location of the Bandera Lava Flow (N 34° 57.448, W 108° 06.404), approximately 1 km northeast of the Big Tubes repeat-photography site. Stars indicate that one Rocky Mountain juniper (34cm D_{GL}) was not cored due to rot. However, we are confident that the tree recruited to >10cm D_{GL} prior to 1948, based on abundant old-growth characteristics.

D_{GL} = tree diameter at ground level

Tree Species	Stems > 10cm D_{GL} 1948	Stems > 10cm D_{GL} 1981	Stems > 10cm D_{GL} 2009
Ponderosa Pine	27	29	29
Douglas-Fir	7	13	13
Rocky Mountain Juniper	32*	32*	32
Piñon Pine	5	6	6
Total	**71**	**80**	**80**

analyses of the photographs were then assessed together with stand-structure and age data collected within a comparably sized area (*ca*. 0.5 ha) on the interior of the Bandera Lava Flow. Our goal was to compare and contrast changes in woodland structure between 1948–2010 at two site extremes on the Bandera Lava Flow.

Vegetation changes visible in our repeat-photography sequences correspond with episodes of regional drought during the past 70 years. Lindsey's initial photographs were taken during one of the worst droughts in western New Mexico in over 1,000 years (Grissino-Mayer *et al.* 1997; Stahle *et al.* 2009). The earliest pictures in our rephotography sequence do not show quaking aspen growing at the lava edge. Aspens are not as drought-tolerant as the conifer species that inhabit the woodlands at EMNM (Burns and Honkala 1990). The absence of aspen in the 1948 photographs could be the result of lower moisture availability at the lava-substrate interface during that time due to reduced precipitation. Aspen establishment at the edge of the Bandera Lava Flow prior to Lindsey's 1981 photographs may be linked to increased precipitation during preceding years (Grissino-Mayer 1995). The same aspens appear dead in our 2010 photographs, suggesting that the trees succumbed to the current drought in the American Southwest (Stahle *et al.* 2009).

In addition to the potential effects of precipitation variability at our repeat photography location, human activities and management policies (*e.g.*, logging, livestock grazing, and fire suppression) may have contributed to the vegetation changes we observed (Mangum 1990; NPS 2000). A gradual increase in grasses and other groundcover is visible in the foreground of the 1981 and 2010 photographs. The noticeable expansion of surface vegetation that occurred before the 2010 photographs is

consistent with the decline of industrial livestock grazing during the 20th century at what is today EMNM. Livestock grazing ceased completely across much of the area after the establishment of EMNM in 1987 (Mangum 1990), which may partially explain the increase in groundcover on the substrate surrounding the Bandera Lava Flow.

Recent vegetation dynamics at the edge of the Bandera Lava Flow might also be associated with anthropogenic disruptions to the local fire regime during the second half of the 20th century (Grissino-Mayer and Swetnam 1997; Lewis 2003; Rother 2010). Lindsey's 1948 and 1981 photographs may show regeneration (*e.g.*, recovering ground cover off the lava and the recent establishment of aspen trees at the lava edge) after low-intensity surface fires that occurred before the implementation of fire-exclusion management practices. The contiguous groundcover off the lava visible in the 2010 photographs, and the persistence of fuels (*e.g.*, logs) and young trees on the edge of the lava, is consistent with the diminished role of fire at this site during recent decades.

Our methods produced woodland structure data for a 0.5 ha study plot located on the interior of the Bandera Lava Flow, approximately 1km from the Big Tubes repeat-photography site. The inaccessibility and ruggedness of this interior woodland make it unlikely that the location was ever logged, grazed, or inhabited by European Americans. Drought-tolerant conifers within the plot were larger and displayed more old-growth features (*e.g.*, twisted stems, strip bark, spiked tops) than those at the lava edge. Several small aspen stems growing within the plot might indicate sufficient moisture availability on the interior malpais, despite the recent drought. A solitary, lightning-struck ponderosa pine, surrounded by living trees, suggests that fire does not spread easily across the broken surface of the interior Bandera Lava Flow.

3.6 Conclusions

Lindsey's photographs of the mixed-conifer woodlands at EMNM are important tools for investigating vegetation changes across the spatial and ecological gradients of this unique landscape. The photographs provide a visual record of past conditions that can be used to complement forest-inventory analysis, dendrochronology, Geographic Information Systems, and other methods used for ecological monitoring. Although the photographs used in this study were subjectively chosen and do not represent all locations at EMNM, our results agreed with previous studies that suggested the interior of the malpais insulates against drought and anthropogenic activities that alter stand structure and composition (Grissino-Mayer *et al*. 1997; Grissino-Mayer and Swetnam 1997; Lewis 2003).

The repeat-photography sequences produced by this study provide a record of fine-scale vegetation dynamics at one location within EMNM and may suggest changes at other locations within the monument. The dynamics we observed at our repeat-photography site perhaps indicate vegetation changes at additional locations along the boundary between the Bandera Lava Flow and surrounding substrate. Our findings also indicate that the old-growth woodlands on the interior of the Bandera Lava Flow experienced minimal mortality during drought events that occurred between 1948–2010. The resistance of interior trees to periods of moisture stress suggests that the mixed-conifer woodlands of EMNM may persist on the porous, relatively inaccessible lava flows despite a potential increase in regional aridity during future decades. The continued use of repeat photography, complemented by additional vegetation inventories and dendroclimatological analysis, could clarify contemporary relationships among drought,

human activity, and vegetation dynamics on the malpais of western New Mexico and throughout the greater Southwest.

Chapter Four

DENDROCLIMATIC POTENTIAL OF ROCKY MOUNTAIN JUNIPERS (*JUNIPERUS SCOPULORUM* SARG.) ON THE VOLCANIC BADLANDS OF CIBOLA NATIONAL FOREST, NEW MEXICO, U.S.A.

Portions of this chapter that refer to the natural history and dendroclimatic record of western New Mexico were taken from Chapters 1 and 2 of this dissertation. The use of "we" in this chapter refers to Mark Spond, Dr. Henri Grissino-Mayer, and Dr. Saskia van de Gevel, all of whom will be coauthors on a manuscript, taken from this material, to be submitted for peer-reviewed publication.

Abstract

We sampled Rocky Mountain juniper to produce a multi-century tree-ring chronology from a relict lava flow, the Paxton Springs Malpais (PAX), in the Zuni Mountains of western New Mexico. Our objective was to assess crossdating potential for Rocky Mountain junipers growing on the volcanic badlands of the region, investigate potential relationships between local climate and Rocky Mountain juniper growth on the malpais, and investigate temporal variability in relationships identified between local climate and Rocky Mountain junipers growing at our site. We hypothesized that, like the other drought stressed-conifers growing on the lava flows, Rocky Mountain juniper responds to climate factors that influence and indicate moisture availability.

A high average mean sensitivity value (0.53) indicated that the PAX chronology exhibits enough annual variability to capture fluctuations in environmental conditions. The PAX average interseries correlation (0.74) indicates confident crossdating, and a strong association of annual growth among trees within the stand. The positive correlation between the PAX chronology and total precipitation for the local water year

was statistically significant ($r = 0.53$; $P < 0.001$). Significant positive correlations were identified between monthly PDSI (previous August–current December) and Rocky Mountain juniper growth. We also identified a positive relationship between the PAX chronology and monthly total precipitation for the previous October to current May. An inverse relationship was identified between radial growth and monthly mean temperature during periods of the preceding year and current growing year. Analyses of temporal stability indicated that the positive relationship between Rocky Mountain juniper growth at the PAX site and monthly PDSI was the most stable relationship during the period of analysis (1895–2007). Our results confirm that Rocky Mountain juniper samples collected on the Paxton Springs Malpais are sensitive to climate factors that affect moisture availability. Our findings also suggest that Rocky Mountain juniper may be suitable for use in dendroclimatic research at additional locations across the broad distribution of the species.

4.1 Introduction

4.1.1 Purpose

Rocky Mountain juniper (*Juniperus scopulorum* Sarg.) is one of the most widely distributed juniper species in North America (Figure 4.1). The species is closely related to eastern red cedar (*Juniperus virginiana* L.), a common tree in eastern North America (Burns and Honkala 1990). Rocky Mountain juniper grows at low to middle elevations (1,500–2,700 m) within the Western Cordillera. Rocky Mountain juniper is successful in a range of environments, but is particularly suited for arid, high-light conditions (Burns and Honkala 1990). The species range of Rocky Mountain juniper includes multiple ecosystems (*e.g.*, mixed-conifer woodlands and montane forests) across the western United States and Canada (Burns and Honkala 1990). Despite a broad distribution, the species has rarely been used in dendrochronological studies (Sieg *et al.* 1996). Dendrochronologists often favor co-dominant species (*e.g.*, ponderosa pine (*Pinus ponderosa* Douglas ex C. Lawson), Douglas-fir (*Pseudotsuga menziesii* (Mirb.) Franco), and piñon (*Pinus edulis* Engelm.)) that produce more-clearly defined growth rings and have fewer locally-absent growth rings.

Currently, only three Rocky Mountain juniper chronologies are archived in the International Tree-Ring Data Bank (ITRDB), and none of the chronologies were produced on the Colorado Plateau (Sieg *et al.* 1996; ITRDB 2011). Grissino-Mayer briefly addressed the growth history of Rocky Mountain junipers living on the volcanic badlands of west-central New Mexico (Grissino-Mayer 1995; Grissino-Mayer *et al.* 1997). He suggested that Rocky Mountain juniper was likely the longest-lived tree species on the lava flows of El Malpais National Monument (EMNM). However,

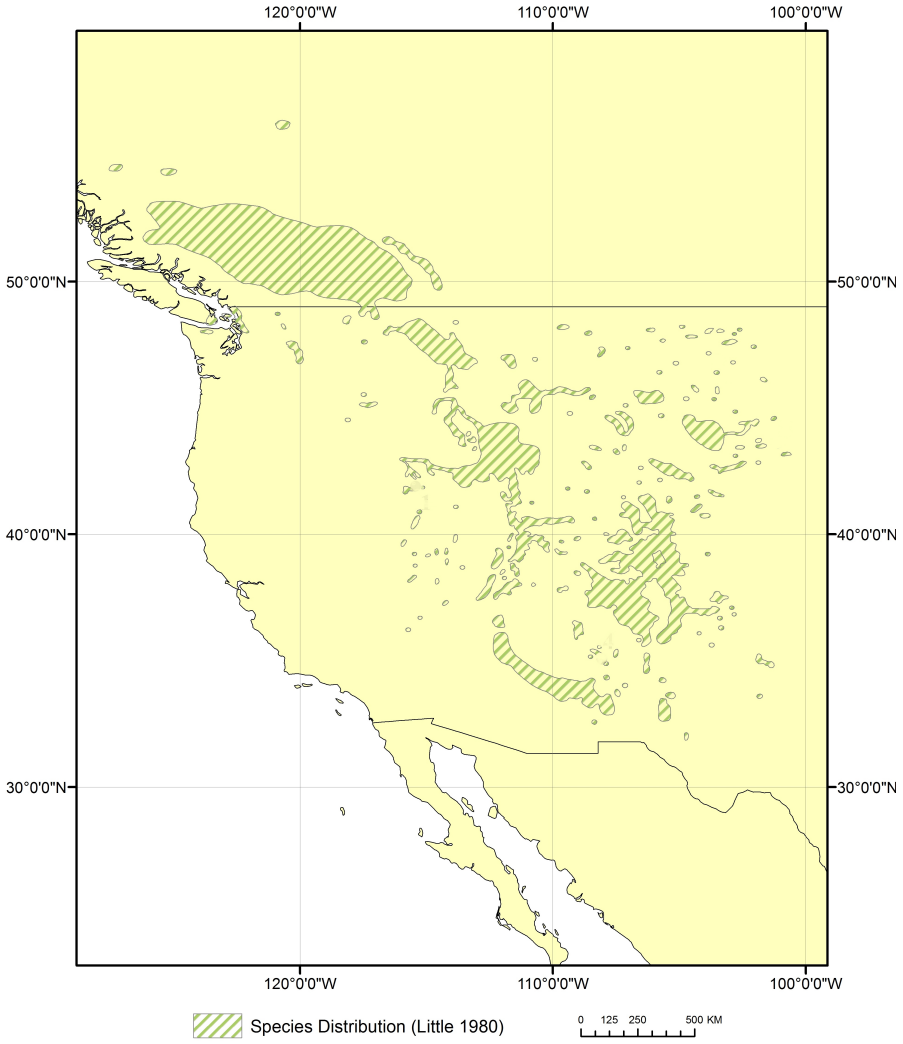


Figure 4.1 Distribution of Rocky Mountain juniper. (Map by Andi Cochran)

comparatively little attention was directed toward the ancient junipers at EMNM. Grissino-Mayer avoided sampling Rocky Mountain juniper due to the contorted growth forms and irregular ring patterns characteristic of the species. His preliminary dendrochronological analysis of the species did not investigate potential relationships between local climate and the annual radial growth of Rocky Mountain junipers on the lava flows.

Our purpose was to address the following question: Are the Rocky Mountain junipers growing on the basalt badlands of west-central New Mexico sensitive to climate? To investigate this question, we pursued the following objectives: (1) assess crossdating potential for Rocky Mountain junipers growing on the volcanic badlands of west-central New Mexico; (2) investigate potential relationships between local climate and Rocky Mountain juniper growth on the badlands; and (3) elucidate temporal variability in relationships identified between local climate and Rocky Mountain juniper. We hypothesized that, like the other drought-stressed conifers growing on the lava flows, Rocky Mountain junipers respond to climate factors that influence and indicate moisture availability. Our results are intended to augment the robust tree-ring research previously conducted on the malpais with other conifer species. An improved perspective of the dendroclimatic potential of Rocky Mountain juniper would enhance our understanding of climate effects in multiple ecosystems and strengthen the spatial and temporal resolution of the tree-ring record in western North America.

4.1.2 Dendrochronology on the Volcanic Badlands of Western New Mexico

Previous dendroclimatic studies conducted in western New Mexico used non-destructive techniques (*i.e.*, increment borers and partial chainsaw sampling) to sample

moisture-stressed conifers, producing a 2,000-year proxy record of regional climate that contained evidence of broad-scale climate oscillations (D'Arrigo and Jacoby 1991; Grissino-Mayer 1995; Grissino-Mayer 1996; Grissino-Mayer *et al.* 1997; Stahle *et al.* 2009). Grissino-Mayer (1995) used tree-ring data from Douglas-fir and ponderosa pine collected at EMNM (The Malpais Long Chronology) to reconstruct annual precipitation for the period 136 B.C.–A.D. 1992. The reconstruction showed significant fluctuations in precipitation for western New Mexico during the past two millennia. Seven periods of sustained wetness or dryness appear in the reconstruction. The reconstruction showed short-term fluctuations within these long-term patterns, including the "Great Drought" (A.D. 1271–1296) that likely influenced the abandonment of population centers and the subsequent migration of Ancestral Puebloan peoples on the Colorado Plateau (Dean *et al.* 1985). Grissino-Mayer (1995) also showed decreased growth during the 16th century megadrought (1559–1582) (Stahle *et al.* 2007). The American Southwest experienced shorter intervals of severe drought during the instrumental record (*e.g.*, the middle of the 20th century and the early 21st century) (Cook *et al.* 2004; Stahle *et al.* 2007). However, Grissino-Mayer (1995) identified the 200 years prior to 1992 as one of the wettest periods in western New Mexico during the past 2,000 years.

Recent work by Stahle *et al.* (2009) analyzed the intra-annual ring anatomy of Douglas-fir and ponderosa pine to reconstruct cool season (November-May) and early warm season (July) precipitation at EMNM over the length of Grissino-Mayer's initial reconstruction of total annual precipitation. The resulting earlywood and latewood chronologies suggest that above average winter/spring precipitation is influenced by the positive (warm) phase of the El Niño-Southern Oscillation (ENSO) and the positive

(warm) phase of the Pacific Decadal Oscillation (PDO). ENSO and PDO are both quasi-cyclical, atmospheric-oceanic phenomena that involve sea-surface temperature (SST) and pressure oscillations in the Pacific Ocean. Stahle *et al.* (2009) linked heavy July precipitation to the onset of the North American Monsoon. Their reconstructions did not indicate interannual correlation between cool-season and warm-season precipitation totals. However, they observed that the wettest cool seasons tended to be followed by early summer dryness, while the driest winters were often associated with wet conditions the subsequent July. This antiphasing of precipitation extremes could be caused by large-scale ocean-atmospheric forcing, land-surface feedbacks, or the interactions of climate forces at multiple spatial scales (Stahle *et al.* 2009).

Fire-history studies conducted at EMNM suggest that fires occurred regularly at the monument for hundreds of years prior to European settlement (Grissino-Mayer and Swetnam 1997; 2000; Lewis 2003). The fires were typically low-severity surface burns that maintained park-like conifer stands. Fire-interval data suggest differences in natural fire regimes among the vegetation communities at EMNM (Grissino-Mayer and Swetnam 1997). Rother (2010) showed that ENSO values were often above average (warm phase) during the year before fire events and below average (cool phase) the year that the fire occurred. However, she found no significant patterns in local fire activity that could be attributed to a particular phase combination of ENSO and PDO. Fire-history reconstructions at EMNM (Grissino-Mayer and Swetnam 1997; Lewis 2003) and in the Zuni Mountains (Rother 2010) also indicated pronounced decreases in fire events *ca.* 1880 and *ca.* 1940. The initial suppression was likely the result of a decrease in fuels (*e.g.*, grasses) caused by the expansion of the sheep grazing industry in western New

Mexico. The second decrease in fire frequency in the malpais region can be attributed to clear-cutting, and improved fire-fighting technologies that emerged during the middle of the 20th century (Swetnam and Baisan 1996; Mangum 1990; Grissino-Mayer and Swetnam 1997; Rother 2010).

4.2 Study Area

4.2.1 The Volcanic Landscape of Western New Mexico

The Zuni-Bandera field is a region of geologically recent volcanism in the American Southwest, located near Grants, New Mexico. The field is part of the larger Jemez Lineament, which stretches from central Arizona to northeastern New Mexico (Laughlin and Wolde-Gabriel 1997). The Zuni-Bandera volcanic field contains cinder-cone volcanoes, shield volcanoes, stratovolcanoes, and relict lava flows. EMNM was established 31 December 1987 to protect the unique volcanic landscape. The monument is managed by the United States Department of the Interior National Park Service (NPS). Much of the surrounding landscape is administered by the United States Department of the Interior Bureau of Land Management (BLM), the United States Department of Agriculture Forest Service (USFS), and Native communities.

EMNM preserves over 46,000 ha of the Colorado Plateau in western New Mexico. The monument protects unique geologic features, Native cultural sites, and rich biological diversity. *Malpais* is Spanish for "bad country" (badlands), a reference to the inhospitable, disorienting lava flows of the Zuni-Bandera volcanic field. Ironically, the harsh terrain harbors one of the most celebrated old-growth woodlands on the Colorado Plateau (Grissino-Mayer 1996; Grissino-Mayer *et al*. 1997; Lewis 2003). Trees at

EMNM are primarily non-commercial timber characterized by irregularly shaped stems, sparsely foliated crowns, and other diagnostic old-growth features (Schulman 1954; Stahle and Chaney 1994).

The Köppen Climate Classification System categorizes much of western New Mexico as a hot steppe. The malpais region is located near the boundary of New Mexico Climate Division 1 (Northwestern Plateau) and Climate Division 4 (Southwestern Mountains) (NOAA 2011). Most of the Zuni Mountains are included in New Mexico Climate Division 1 (NOAA 2011). Summers are typically hot (average maximum July temperature > 30 °C) and winters are cold (average minimum January temperature < –10 °C) (NPS 2011). Precipitation is bi-modally distributed, with a pronounced maximum during July, August, and September and a secondary peak between December and March. Average annual precipitation at El Morro National Monument, one of the closest weather stations to our study area, is 406 mm (NPS 2011). A large percentage of regional precipitation is associated with the North American Monsoon during the summer months (Sheppard *et al.* 2002; Stahle *et al.* 2009).

4.2.2 The Paxton Springs Malpais Site (PAX)

Our study analyzed an old-growth stand of Rocky Mountain juniper living on a small section of the Paxton Springs Lava Flow *ca.* 10 km north of EMNM (Figure 4.2). The site is *ca.* 150 m north of the Paxton Springs Crater, a cinder cone volcano located in the Zuni Mountains of Cibola National Forest. The Zuni Mountains are not a jagged escarpment, but rather a complex of gentle slopes that rise *ca.* 300 m above the highest

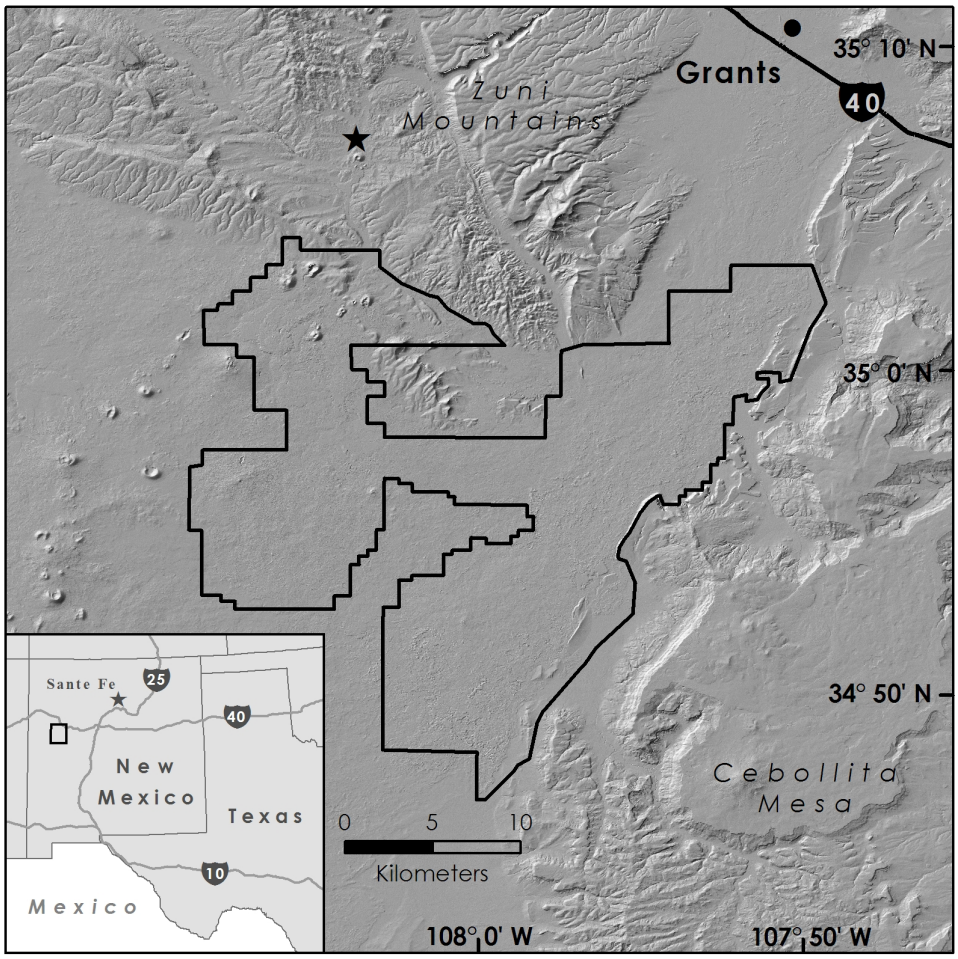


Figure 4.2 The black star indicates the approximate location of our study site (2,375 m) on the Paxton Springs Lava Flow (35.066997 N, 108.060219 W). Paxton Springs Crater is the volcanic cone immediately south of the study site. The black outline indicates the boundary of EMNM. (Map by Grant Harley)

portions of EMNM. Elevations in the Zunis range between *ca.* 2,000 m and 2,820 m. The Zunis differ from other mountains in the area in that they formed by geologic uplift rather than volcanism (Chronic 1987). The Zuni Mountains initially consisted of a Precambrian core of igneous and metamorphic rocks, overlain by sedimentary strata that were deposited during subsequent periods. As the Zunis were uplifted, the sedimentary rock was eroded away, exposing the underlying core rock (Chronic 1987). However, the abundant volcanism in the region left its mark on the Zuni Mountains. Volcanic vents are located in the Zunis along Oso Ridge and at the Paxton Springs Crater. Basalt malpais, formed from lava that flowed out of the Paxton Springs Crater, covers part of Zuni Canyon and much of the surrounding area.

Although the eruption that produced the basalt formation at the study site has not been absolutely dated, the basalt, which originated from the Paxton Springs Crater, is older than the nearby Bandera Lava Flow (*ca.* 10,000–11,000 years before present) and younger than the neighboring Bluewater Lava Flow (*ca*. 79,000 years before present) (Laughlin *et al.* 1993). Elevation at the Paxton Springs Malpais study site (PAX) is approximately 2,375 m. The elevation gradient within the site is minimal; however, the rugged basalt surface is jagged and uneven. Tree species diversity in the vicinity of the PAX site is greater on the basalt formations than in adjacent areas not covered by the ancient lava flows. Rocky Mountain juniper, quaking aspen (*Populus tremuloides* Michx.), and Douglas-fir inhabit the basalt formations, while off of the lava, the forest consists almost entirely of ponderosa pine.

Much of the area that surrounds the Paxton Springs Crater was heavily logged and grazed during the late 19th and early 20th centuries (Rother 2010). The ponderosa harvest

from the Zuni Mountains was one of the most prolific in the West (Mangum 1990). Today, the proximity of the PAX site to USFS roads allows easy access for tree-ring sampling, but also provides persons gathering firewood an ideal location for collecting juniper and other tree species. The mixed-conifer woodlands at the PAX site appear to have suffered less from recent anthropogenic activity than the ponderosa pine forest that surrounds them, but cut stumps, severed branches, and small amounts of human refuse indicate that the PAX site is not pristine.

4.3 Methods

4.3.1 Increment Core Recovery and Preparation

Research teams from the University of Tennessee Laboratory of Tree-Ring Science recovered *ca.* 100, 5 mm diameter increment cores at PAX during July 2008 (Figure 4.3). The samples were taken from 60 living Rocky Mountain juniper trees. All Rocky Mountain junipers > 10 cm diameter at breast height were cored for dendroclimatological analyses. Each tree was cored between 1 and 3 times. Some cores extended across the diameter of the entire tree, producing two visible radii. After cores were air dried in storage straws, we glued the specimens to wooden core mounts. The mounted cores were set in place so that the cells would remain vertically aligned to ensure a transverse view of the growth rings (Stokes and Smiley 1996). Core identifications were printed on the mounting board using the exact identifications labeled on the storage straws. Next, the cores were surfaced using progressively finer sandpaper, beginning with ANSI 100-grit and finishing with ANSI 400-grit (Orvis and Grissino-Mayer 2002). The polishing produced a wood surface with clearly defined cellular



Figure 4.3 Old-growth Rocky Mountain junipers growing at the Paxton Springs Malpais study site (PAX) were cored for dendroclimatic analysis (Photo by Mark D. Spond 2008). Many of the trees at the site exhibited key characteristics of old-growth conifers living on the malpais of western New Mexico (Grissino-Mayer 1995; Grissino-Mayer *et al.* 1997).

features. Annual growth rings were visible on the core surfaces without magnification.

4.3.2 Core Selection

Increment cores were sampled from living trees during the middle of the 2008 growing season. Therefore, when bark was present, we were able to "anchor" the incomplete, outermost growth ring as 2008. All cores were analyzed under 7–35x continuous zoom magnification using a Leica stereozoom, boom-arm microscope with crosshair reticule and a Nicholas Illuminator artificial light source. Although over 100 cores were collected at PAX, some cores could not be included in our dendroclimatological analyses due to ring anomalies associated with the lobate growth form and twisted stems of the Rocky Mountain junipers. Few trees produced more than one sample suitable for tree-ring dating. Other cores were excluded due to fractures and decay that prohibited accurate dating. We selected 60 cores from 45 trees for visual and statistical crossdating. The selected cores had attached bark and contained minimal ring abnormalities (*e.g.*, reaction wood) that could complicate tree-ring dating and subsequent dendroclimatological analyses.

Select Rocky Mountain juniper samples from the PAX site were scanned with a high-resolution digital scanner (EPSON, Expression 10000XL) at 1,200 dpi and measured using WinDENDRO^{TM} computer software (version 2009C, Regent Instruments, Canada). Ring widths were measured to the nearest 0.001 mm. Measurement began with the inner date and moved toward the outermost complete ring (2007) on the cores. Cores were visually crossdated using the list method (Yamaguchi 1991) and statistical output from COFECHA (Holmes 1983; Grissino-Mayer 2001) for

the El Malpais Long Chronology (Grissino-Mayer 1995). The measuring process precisely quantified the ring widths of all the series in this study, allowing us to further test our visual dating with quality-control software used in dendrochronology.

4.3.3 Statistical Crossdating Using Program COFECHA

We confirmed and improved our initial visual crossdating using COFECHA, a quality-control program that uses segmented time-series correlation techniques to assess the temporal placements of dated and undated tree ring sequences (Holmes 1983; Grissino-Mayer 2001). COFECHA removes all low-frequency growth and disturbance trends using both spline-fitting algorithms and autoregressive modeling (Grissino-Mayer 2001). Each measured radius was processed by COFECHA as an individual time series. During processing, COFECHA subdivided the time series into 40-year segments, which were then sequentially overlapped by 20 years (Grissino-Mayer 2001). The 40-year segments (with 20-year overlaps) were then tested for correlation with a PAX master chronology created from all other series (*i.e.*, an average derived from all series from the PAX site, minus the series in question).

4.3.4 Standardization of Tree-Ring Data

We standardized all series to remove the adverse growth effects from age-related growth trends, autocorrelation, and possible natural or anthropogenic influences that could interfere with the macroclimate signal within the growth rings using the program ARSTAN (Cook 1985). Each ring measurement was divided by a predicted annual value of growth based on a negative-exponential curve fit to the measurement data. This produced a dimensionless index of growth for that year in which a value of 1.0 was

"average." After standardizing each individual series, a detrended master chronology was created from the PAX data by averaging all indices of tree growth for each year (Cook 1985). ARSTAN created three index chronologies from the PAX measurements: standard, residual, and ARSTAN. Preliminary correlation analysis between monthly temperature and precipitation records for New Mexico Climate Division 1 revealed that the standard chronology produced the strongest correlations between annual radial growth and our selected climate variables, prompting us to use the standard chronology for all additional analyses.

4.3.5 Dendroclimatic Analyses

We used DENDROCLIM2002 (Biondi 1997; Biondi and Waikul 2004) to investigate relationships between local climate variables and the annual radial growth of Rocky Mountain junipers sampled at the PAX site (Fritts 1976). DENDROCLIM2002 was used because the program calculates correlation coefficients and response function coefficients with bootstrapped confidence intervals, which increases the accuracy of results (Biondi 1997). Divisional climate data are available for much of western New Mexico beginning in 1895 (NOAA 2011). We selected monthly mean temperature, monthly total precipitation, and monthly Palmer Drought Severity Index (PDSI) values for New Mexico Climate Division 1 (composite data from 72 weather stations in western New Mexico) for our analyses. PDSI is a drought index based on temperature, precipitation, and soil moisture. PDSI values range between –6 (very dry) and +6 (very wet) (Palmer 1965). Instrumental temperature, precipitation, and PDSI values were

obtained from the National Climatic Data Center for the period 1895 to 2007 (NOAA 2011).

We conducted correlation analyses to test the strength of association between climate variables and annual radial growth. Correlation analysis tests the linear relationship between two variables, producing values ranging between +1 and –1. Positive correlations indicate that measures of both variables simultaneously increase, while negative correlations indicate that as a measure of one variable increases, the other decreases. The association between the variables strengthens as the correlation approaches +1 or –1. Data analyzed in DENDROCLIM2002 are assumed to be normal, which allows the program to generate Pearson product-moment correlation coefficients between monthly climate variables and our PAX ring-width index. Correlation coefficients were deemed statistically significant at the $P < 0.05$ level as shown by the DENDROCLIM2002 bootstrapped-confidence intervals. Our window of analysis spanned between the previous May and current December (20 months) to include the effects of climate during the previous year on current radial growth (Fritts 1976; Grissino-Mayer 1995).

To complement the correlation analysis, we used DENDROCLIM2002 to conduct response function analysis between annual radial tree growth and climate at the PAX site. Response function analysis uses principal components multiple regression to estimate indexed values of annual radial growth. Regression coefficients and principal components are calculated to produce adjusted regression coefficients related to the initial climate data (Fritts 1976; Briffa and Cook 1990; Biondi and Waikul 2004).

Response function analysis differs from correlation analysis in that it removes potential influences of interdependence among the selected climate variables (Fritts 1976).

Following the correlation and response function analyses, we used DENDROCLIM2002 to conduct forward evolutionary interval analysis and moving interval correlation analysis. Both analyses were used to provide two perspectives of the temporal stability of the data. Our objective was to elucidate temporal variability in the relationships identified between climate and Rocky Mountain juniper growth at the PAX site (Biondi 1997; Biondi and Waikul 2004). Moving interval correlation and forward evolutionary interval analyses begin with the earliest year in common to all variables. In moving interval correlation analysis, the constant base interval is shifted forward by one year at each iteration, while forward evolutionary intervals are progressively enlarged by adding one year to a base interval length at each iteration (Biondi and Waikul 2004).

Persistent relationships between climate variables and radial tree growth, as identified by moving correlation and forward evolutionary interval analyses, further substantiate the results of initial correlation and response function analyses. Such relationships may suggest the suitability of a dataset for use in dendroclimatic reconstructions. Grissino-Mayer (1995) reported that Douglas-fir and ponderosa pine growing at nearby EMNM respond strongly to total water year precipitation (previous 1 July–current 30 June), which ultimately allowed him to produce a > 2,000-year reconstruction of total annual precipitation at the monument. Similarly, we tested for relationships between the PAX chronology and total water year precipitation (1896–2007) for New Mexico Climate Division 1 using correlation analysis.

4.4 Results

4.4.1 The PAX Chronology

The master chronology for PAX consists of 24 tree-ring series (3,577 total annual rings) collected from 24 Rocky Mountain juniper trees at the Paxton Springs Malpais (Table 4.1). Samples from 21 trees that were selected for crossdating were ultimately excluded due to erratic growth rings. The chronology spanned between 1692 and 2007 (316 years) (Figure 4.4). Although many of the cores we collected at the PAX site could not be included in our chronology due to rot, fractures, or compressed growth, intact cores with the clear growth patterns dated very well against the El Malpais Long Chronology (Grissino-Mayer 1995). Confident dating was aided by several marker rings (very narrow or locally absent rings) identified by Grissino-Mayer (1995) and Stahle *et al*. (2009) including: 1761, 1782, 1819, 1847, 1876, 1900, 1925, 1951, 1971, 1996, and 2002. We also found the 2006 growth ring to be consistently narrow or locally absent. Missing rings complicated dating, but in every case the existence of a locally absent ring was indicated by intra-site crossdating and the persistent relationship to previously identified marker rings. Locally absent rings represented 2.8% of the total rings in the chronology. Density fluctuations within radial growth rings, commonly called "false rings," were distinguishable from actual annual ring boundaries by the careful identification of terminal latewood cells (Hoadley 1990).

Some of the cores taken from young trees (*i.e.,* < 60 total growth rings) were not included in the PAX chronology despite the presence of potentially datable marker rings. The cores were excluded from the master chronology because of erratic ring widths, which substantially lowered key statistical measures of crossdating. Sample depth was 1

Table 4.1

PAX Chronology Description	Value
Number of Dated Series[1]	24
Master Chronology (1692–2007)	317 years
Total Rings	3577
Average Interseries Correlation	0.74
Average Mean Sensitivity	0.53
Flagged Segments[2]	4
Total Segments	177
Percent of Flagged Segments	2.26
Mean Length of Series (years)	149

[1] Dated series are crossdated cores.
[2] Flagged segments contained possible dating errors that were dismissed after additional visual inspection.

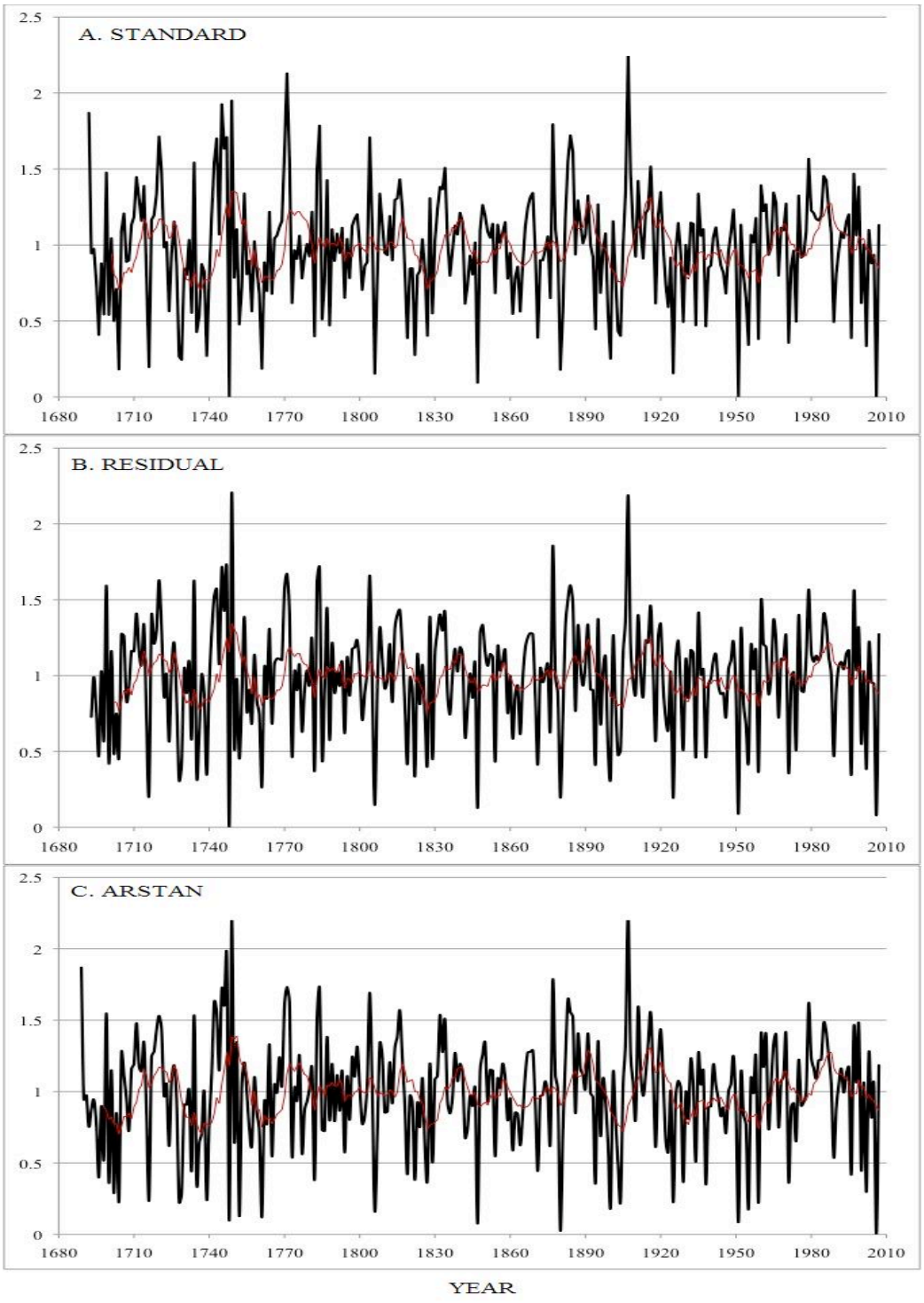


Figure 4.4 The computer program ARSTAN produced three index chronologies from our Rocky Mountain juniper data at the PAX study site: Standard (A), Residual (B), and ARSTAN (C). Values on the y-axis > 1 represent above average growth, while values < 1 represent below average growth. The red line is a 10-year moving average to show decadal trends.

series at 1692, 2 series at 1703, 6 series at 1780, 10 series at 1840, 18 series at 1890, and 24 series at 2007. The mean length of all series in the PAX master chronology was 149 years. All 24 series terminated in 2007, however the inner rings on some cores were not dated due to fractures or ring distortion.

Crossdating quality was assessed by two statistical descriptors, average mean sensitivity and average interseries correlation. Average mean sensitivity measures the annual ring-width variability required for accurate crossdating. Average mean sensitivity for the PAX master chronology was 0.53. Average interseries correlation is the mean of the interseries correlations for all series included in the chronology and is a measure of shared growth fluctuations within the sample (Grissino-Mayer 2001). The average interseries correlation for the PAX chronology was 0.74. The PAX chronology consisted of 177, 40-year dating segments. COFECHA flagged only four of the segments (2.25%) for possible dating errors. Careful inspection of the flagged cores and the presence of strong crossdating within other segments of the suspect series suggested that the potential dating errors were the result of a reduced climate signal, not misdating.

4.4.2 Relationships Between Climate and Tree Growth

Significant relationships were identified between climate data from New Mexico Climate Division 1 and the annual radial growth of Rocky Mountain juniper sampled at the PAX site. The relationships indicated that local climate influences the formation of radial growth rings. However, no monthly response function coefficients generated for monthly mean temperature and monthly total precipitation were significant (Figure 4.5). Only current April PDSI and current May PDSI produced significant response function

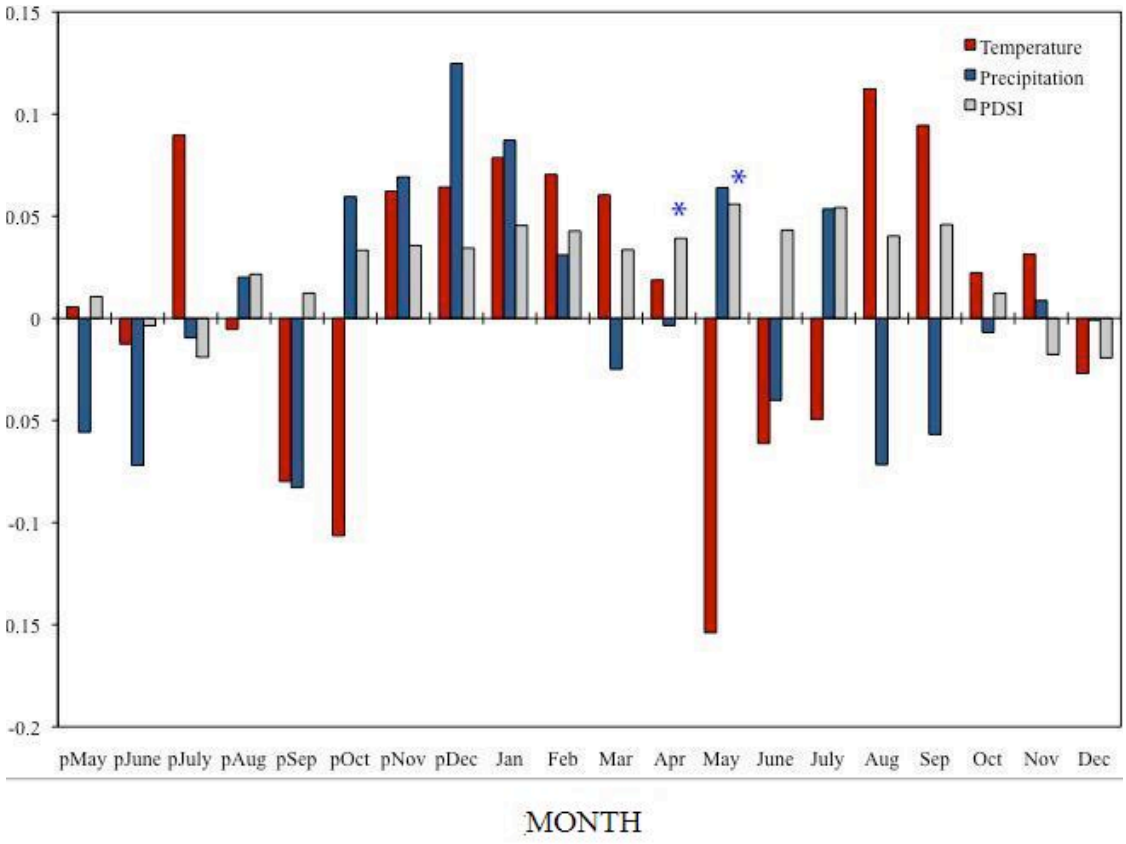


Figure 4.5 Response function coefficients (y-axis) showing the relationship between the PAX Rocky Mountain juniper chronology and monthly mean temperature, monthly total precipitation, and monthly PDSI from the previous May (pMay) to the current December (Dec) (1895–2007). Asterisks indicate significant relationships ($P < 0.05$).

results. Correlation analysis produced many more significant relationships than response function analysis (Figure 4.6). Significant negative correlations were identified between the PAX standard chronology and monthly mean temperature for the previous August, previous October, previous November, and current April–current July. Significant positive correlations were identified between indexed growth at the PAX site and monthly total precipitation for October–December of the previous year and January–May of the current year. PDSI was the climate variable that produced the greatest number of statistically significant monthly correlations. PDSI values were positively correlated with indexed growth at the PAX site between the previous August and current December. The PAX chronology was also positively correlated ($r = 0.53$; $P < 0.001$) with total precipitation for the local water year (previous 1 July–current 30 June) (Figure 4.7).

4.4.3 Temporal Stability of Climate-Tree Growth Relationships

Our initial correlation analyses prompted us to investigate the temporal stability of climate-growth relationships at the PAX site. For monthly mean temperature and PDSI, moving interval correlation analyses were performed at 34-year intervals and forward evolutionary interval analyses were performed with a 34-year base interval. The analyses were conducted with 30-year moving and base intervals for monthly total precipitation. We selected moving interval lengths and base interval lengths that were twice the number of predictor months used for each climate variable (Biondi and Waikul 2004) as indicated by the results of our initial correlation analyses.

We tested the period between the previous August and current December (17 months) for monthly mean temperature and PDSI. Monthly total precipitation was

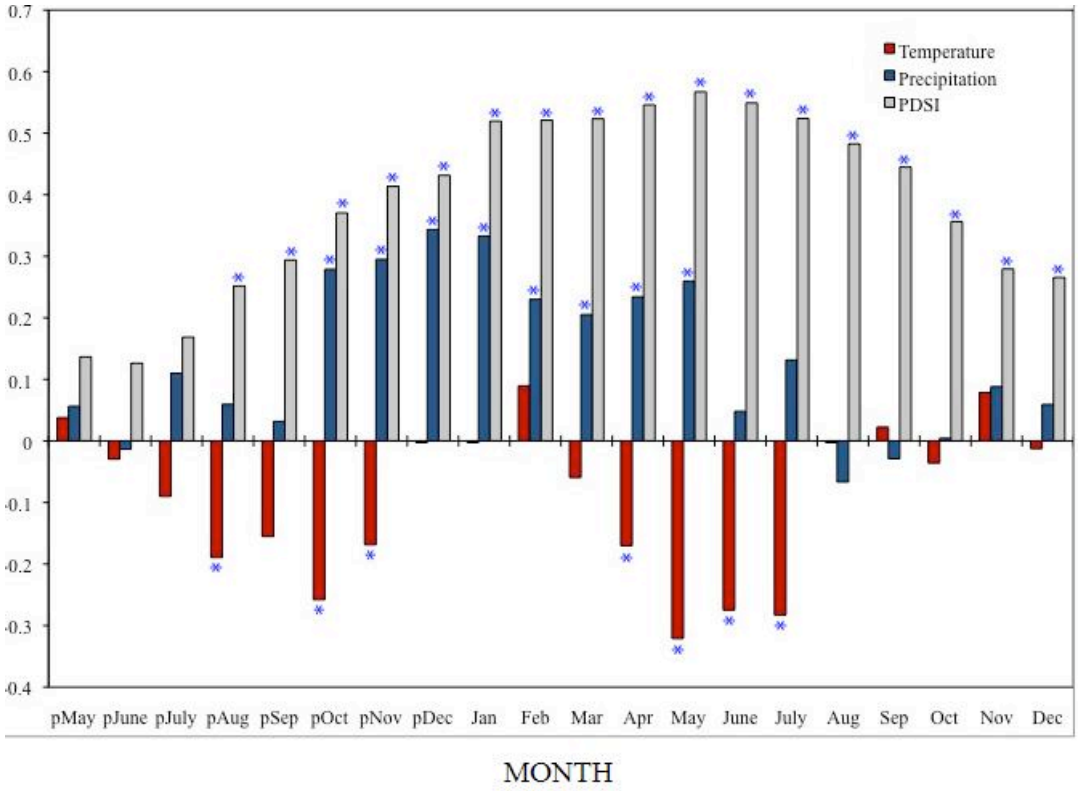


Figure 4.6 Pearson's correlation coefficients (y-axis) showing the relationship between the PAX Rocky Mountain juniper chronology and monthly mean temperature, monthly total precipitation, and monthly PDSI from the previous May (pMay) to the current December (Dec) (1895–2007). Asterisks indicate significant relationships ($P < 0.05$).

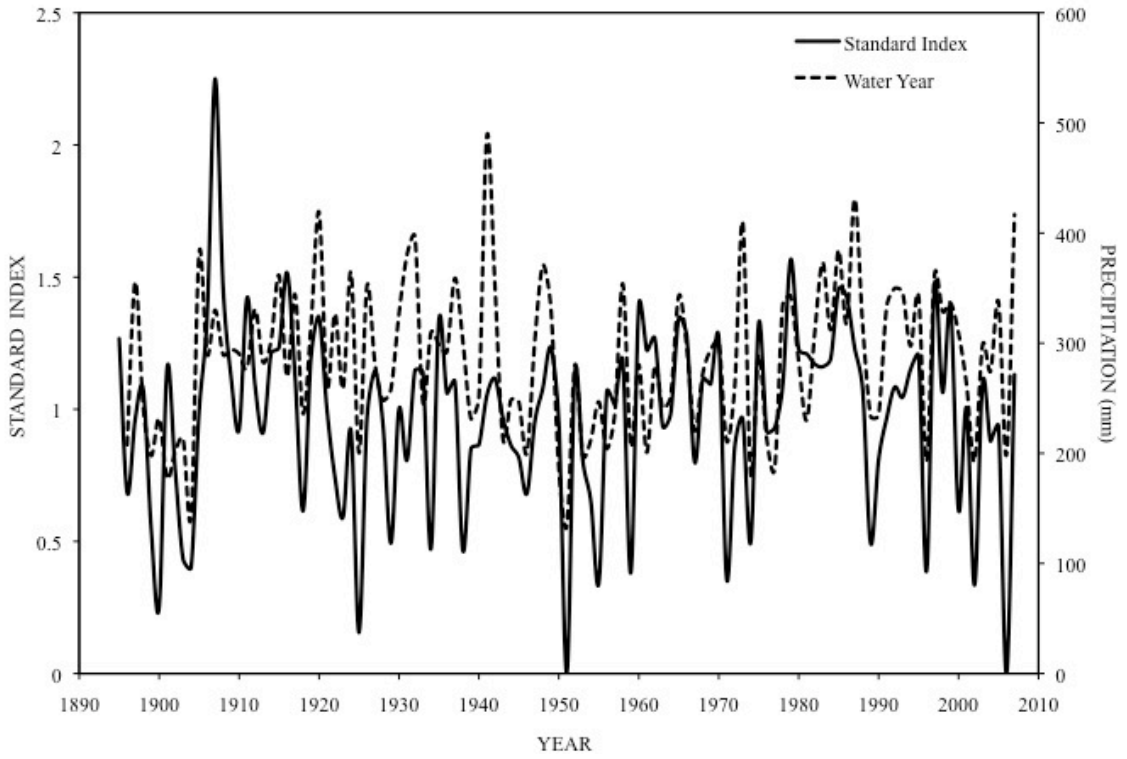


Figure 4.7 Relationship between the PAX standard chronology and previous 1 July–current 30 June total precipitation (local water year) for New Mexico Climate Division 1 ($r = 0.53$; $P < 0.001$). The time series indicate that Rocky Mountain junipers growing at the PAX site produced narrow growth rings during the current Southwestern drought and the severe drought that affected much of the region during the middle of the 20th century.

analyzed between the previous October and current December (15 months). The period of analysis for all three climate variables was 1896–2007. For our monthly analysis, we selected observation periods that began with the first month identified as significantly related to tree growth ($P < 0.05$) during the previous year and continued through the entire current year. We did not test the temporal stability of the two monthly PDSI response function values that were significant because the correlation analysis provided more interpretable results.

Forward evolutionary interval and moving interval correlation analyses indicated different results for the relationships between indexed growth at the PAX site and monthly mean temperatures (Figure 4.8 and 4.9). Our initial correlation analysis identified values for the previous August, previous October, and previous November as negatively correlated with the PAX chronology, as were those for current April through July. The two analyses of stability appeared to show the most agreement with the strong negative correlations during current May–June for the earliest part of the record, and previous October during the middle of the 20th century. Our temporal analyses suggested that these relationships were not all persistent during the period of inquiry. However, forward evolutionary interval analysis indicated a more sustained relationship between indexed growth and current May–July monthly mean temperatures.

Results for forward evolutionary interval and moving interval correlation analyses were more complementary for monthly total precipitation, with notable exceptions (Figure 4.10 and 4.11). Our initial correlation analysis identified values for previous October–current May as positively correlated with the PAX chronology. Both analyses

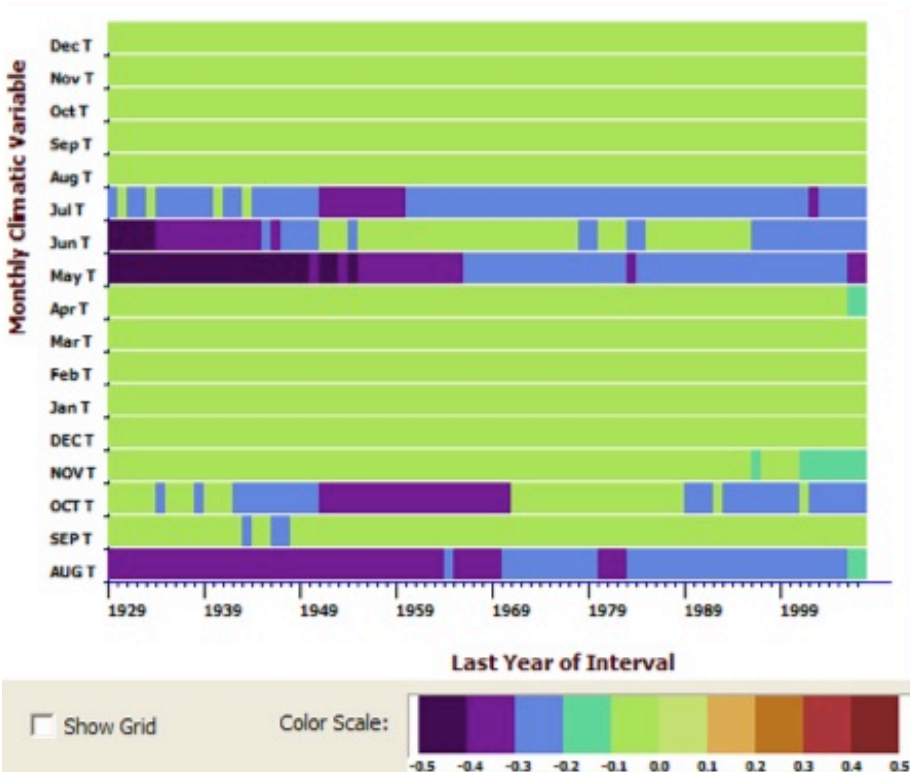


Figure 4.8 Results of forward evolutionary interval analysis (1896–2007) between monthly mean temperature and the PAX chronology, using a base 34-year interval. Monthly variables are shown on the y-axis, beginning with the previous August in the lower left corner and ending with current December in the upper left corner. The last years of forward intervals are listed on the x-axis. Periods during which a variable is significant are colored according to the strength of the correlation coefficient. Green shading shows periods that are not significantly correlated to tree growth.

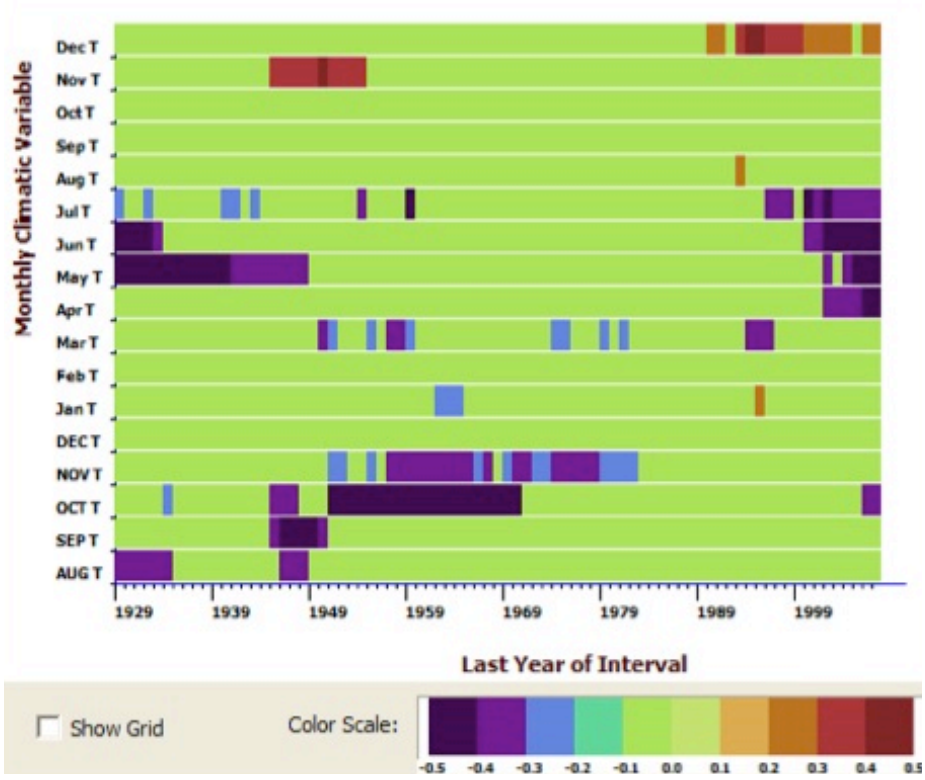


Figure 4.9 Results of moving interval correlation analysis (1896–2007) between monthly mean temperature and the PAX chronology, using 34-year moving intervals. Monthly variables are shown on the y-axis, beginning with the previous August in the lower left corner and ending with current December in the upper left corner. The last years of moving intervals are listed on the x-axis. Periods during which a variable is significant are colored according to the strength of the correlation coefficient. Green shading shows periods that are not significantly correlated to tree growth.

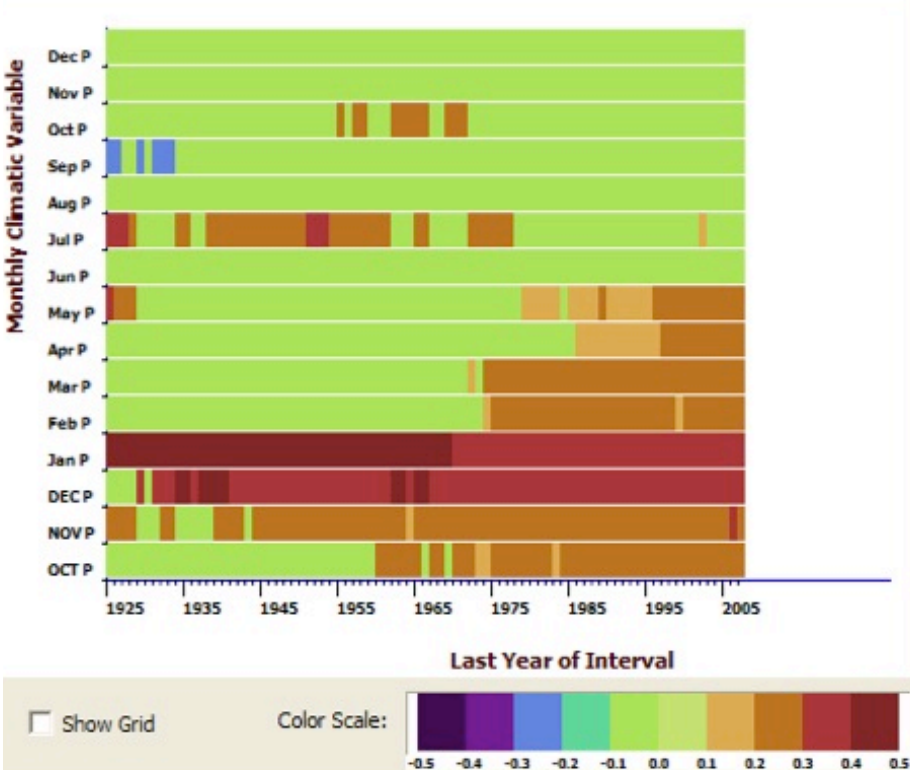


Figure 4.10 Results of forward evolutionary interval analysis (1896–2007) between monthly total precipitation and the PAX chronology, using a base 30-year interval. Monthly variables are shown on the y-axis, beginning with the previous October in the lower left corner and ending with current December in the upper left corner. The last years of forward intervals are listed on the x-axis. Periods during which a variable is significant are colored according to the strength of the correlation coefficient. Green shading shows periods that are not significantly correlated to tree growth.

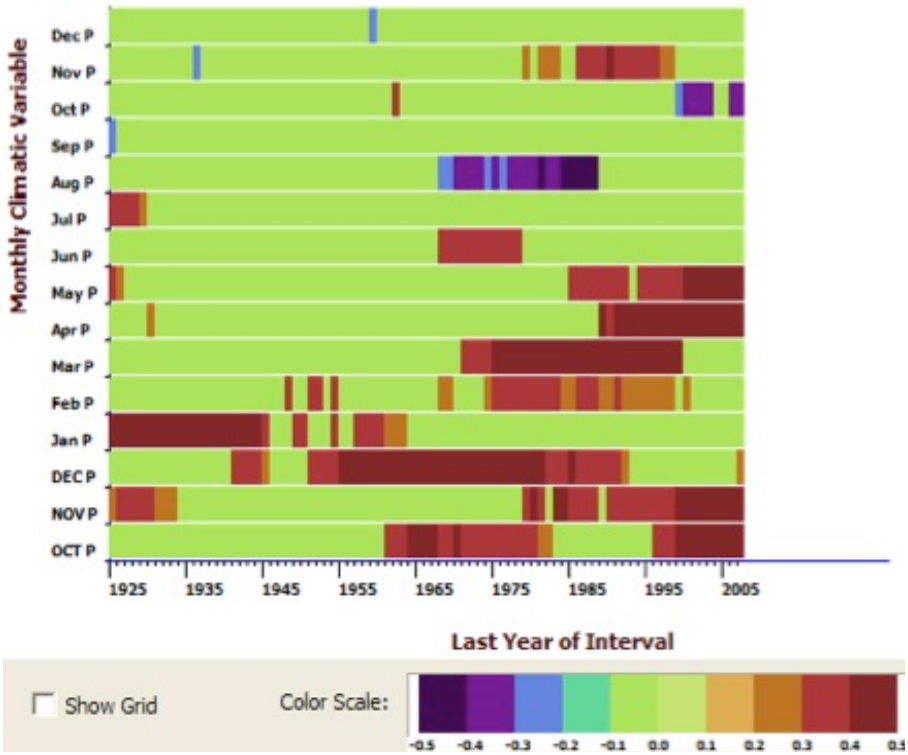


Figure 4.11 Results of moving interval correlation analysis (1896–2007) between monthly total precipitation and the PAX chronology, using 30-year moving intervals. Monthly variables are shown on the y-axis, beginning with the previous October in the lower left corner and ending with current December in the upper left corner. The last years of moving intervals are listed on the x-axis. Periods during which a variable is significant are colored according to the strength of the correlation coefficient. Green shading shows periods that are not significantly correlated to tree growth.

showed significant positive correlations for these months during at least part of the record; however, relationships appeared more persistent using the forward evolutionary interval analysis, especially for previous November–current January.

The greatest agreement between the two analyses of temporal stability was for monthly PDSI (Figure 4.12 and 4.13). Our initial analysis indicated significant positive correlations between the PAX chronology and monthly PDSI between previous August and current December. Both analyses of temporal stability indicated persistent significance between previous November and current September. Forward evolutionary interval analysis identified more persistent relationships during August–October of the previous year and October–December of the current year. In fact, moving interval correlation analysis indicated that previous August–September correlations lost significance during the middle of the 20th century, and values for current November–December were insignificant for much of the period of analysis.

4.5 Discussion

4.5.1 Crossdating Rocky Mountain Junipers

Before we could conduct dendroclimatic analyses, we first needed to confirm visual and statistical crossdating among the sampled trees. Rocky Mountain junipers often exhibits twisted growth forms and lobate-ring formation (Figure 4.14–4.17), which makes the species difficult to sample and crossdate. We identified clear annual growth rings on many of the intact cores we recovered at the PAX site. However, compressed growth rings on many cores taken from what appeared to be the oldest trees and erratic ring widths on cores extracted from younger trees led us to exclude many specimens from

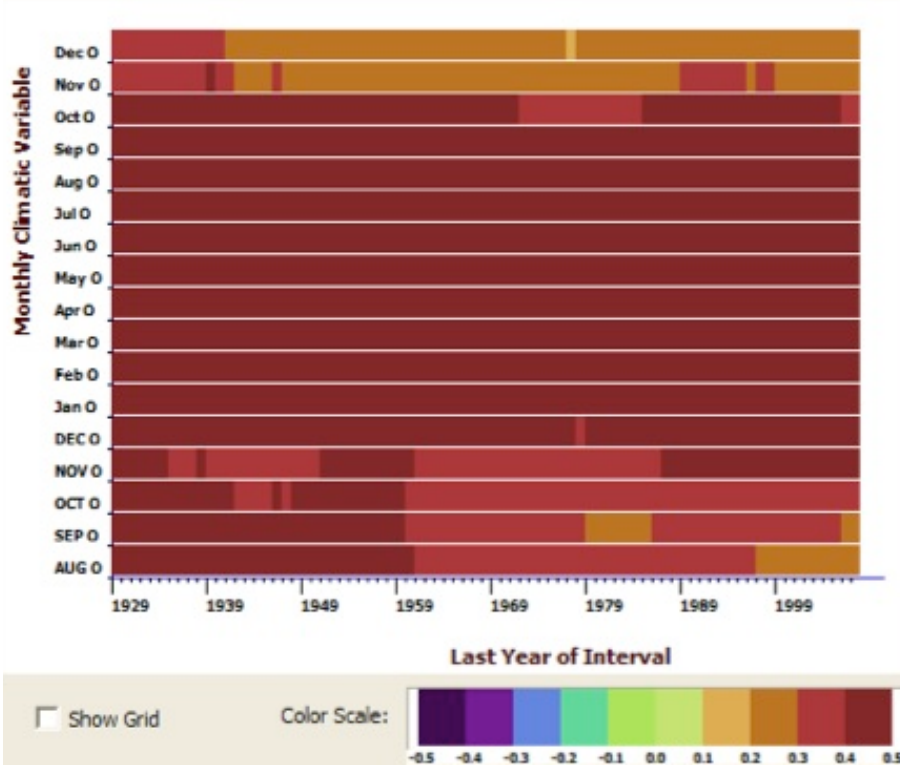


Figure 4.12 Results of forward evolutionary interval analysis (1896–2007) between monthly PDSI and the PAX chronology, using a base 34-year interval. Monthly variables are shown on the y-axis, beginning with the previous August in the lower left corner and ending with current December in the upper left corner. The last years of forward intervals are listed on the x-axis. For example a grid square marked 1950 represents the period between 1896 and 1950. Green shading shows periods that are not significantly correlated to tree growth.

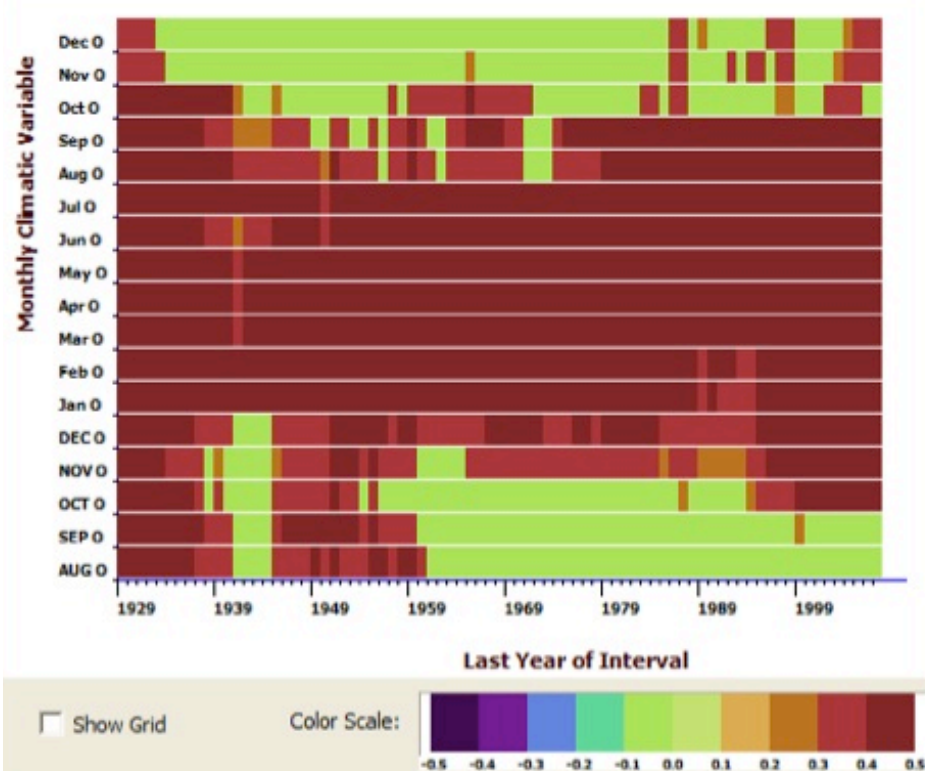


Figure 4.13 Results of moving interval correlation analysis (1896–2007) between monthly PDSI and the PAX chronology, using 34-year moving intervals. Monthly variables are shown on the y-axis, beginning with the previous August in the lower left corner and ending with current December in the upper left corner. The last years of moving intervals are listed on the x-axis. Periods during which a variable is significant are colored according to the strength of the correlation coefficient. Green shading shows periods that are not significantly correlated to tree growth.

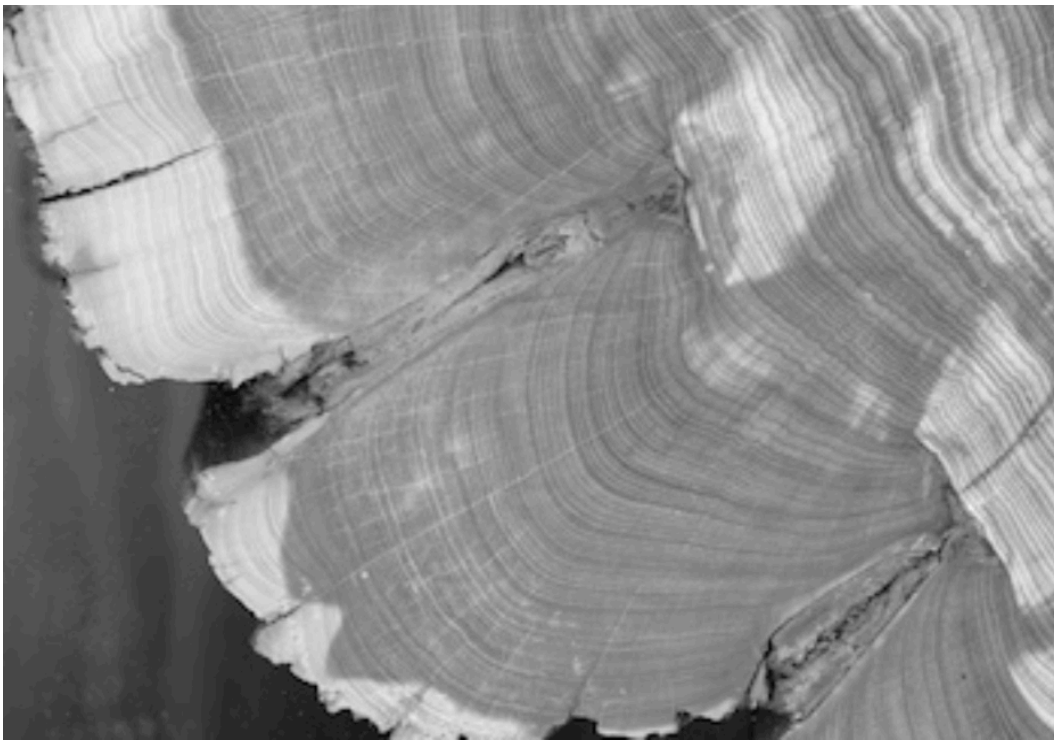


Figure 4.14 Image of a Rocky Mountain juniper cross-section taken from a relict log at PAX during July 2008. Rocky Mountain juniper stems generally exhibit pronounced lobes and furrows that obscure ring boundaries and complicate crossdating. In this image, lobes appear as pronounced bulges in the circumference of the tree, while furrows appear as indentations oriented toward the center of the tree (Photo by Mark D. Spond 2010).

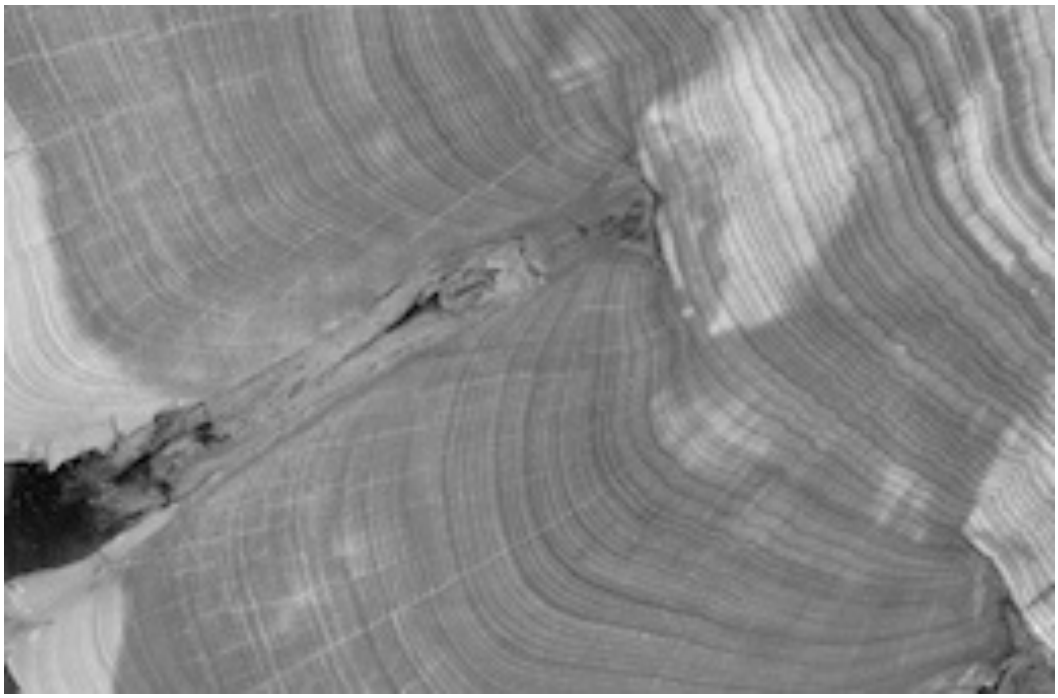


Figure 4.15 The left portion of this image shows pinched rings and a large branch scar on a cross-section taken from a Rocky Mountain juniper at PAX during July 2008. Branch scars and pinched growth rings complicated crossdating, which caused us to exclude many samples from our analyses.

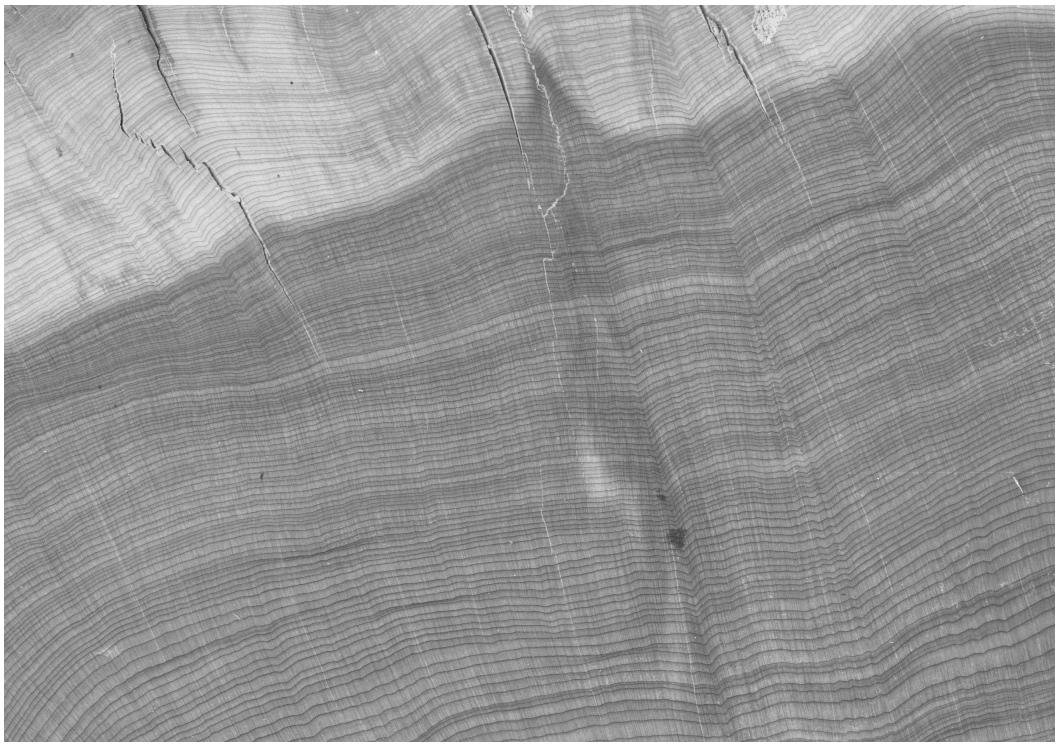


Figure 4.16 This photograph shows growth rings on a cross-section taken from a Rocky Mountain juniper log at PAX during July 2008. Although the growth rings are clearly visible, much of the bark and sapwood are not present on this sample. Missing bark and sapwood prevented us from dating recovered cross-sections against cores taken from living trees.

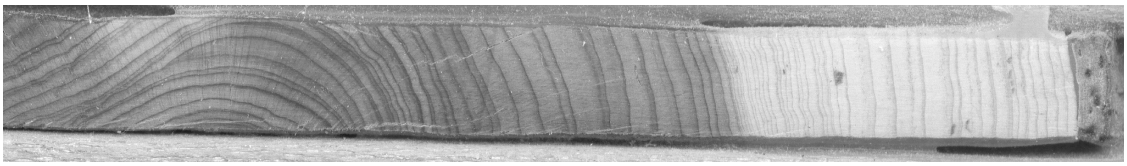


Figure 4.17 This photograph shows a core sample taken from a young Rocky Mountain juniper at PAX during July 2008. Erratic juvenile growth, particularly near the pith of the tree, weakened the average interseries correlation of the PAX chronology. The weak crossdating prompted us to ultimately exclude the core from the PAX master chronology.

our analyses. Visual dating was confirmed by the commonality of marker rings on the PAX cores that precisely matched those identified by previous dendroclimatic studies in the immediate area (Grissino-Mayer 1995; Stahle *et al.* 2009). Locally absent rings were linked with the most significant marker years on many of the samples included in the PAX chronology. Radial growth trends shared between Rocky Mountain junipers at the PAX site and other conifer species growing on the malpais indicate the regulating influence of local climate on tree growth.

Mean sensitivity values > 0.4 are necessary to confirm accurate crossdating in the southwestern United States (Grissino-Mayer personal communication 2007). Acceptable average interseries correlation values for high-quality conifer chronologies in the Southwest are typically > 0.7 (ITRDB 2011). The average mean sensitivity value for the PAX master chronology (0.53) is consistent with average mean sensitivity values for other studies conducted in the malpais region (Grissino-Mayer 1995; Stahle *et al.* 2009; Rother 2010). The average interseries correlation values (0.74) for the PAX chronology is lower than the average interseries correlation that Grissino-Mayer (1995) produced with ponderosa pine and Douglas-fir data collected at EMNM (0.86), but is still high enough to indicate a strong association among annual radial growth for the 24 trees in our sample. Comparing our chronology statistics with those from other Rocky Mountain juniper chronologies is complicated by the lack of available chronologies. However, the PAX chronology has a higher average interseries correlation and substantially higher average mean sensitivity than the three chronologies currently listed in the ITRDB (2011) (Table 4.2).

Table 4.2 Rocky Mountain juniper chronologies in the International Tree-Ring Data Bank (ITRDB) and the PAX chronology from the Paxton Springs Malpais.

Chronology	Location	Elevation (m)	Investigators	Dated Series	Period	Average Interseries Correlation	Average Mean Sensitivity
Cedar Butte, South Dakota, U.S.A	43.60 N, 101.12 W	785	Meko and Sieg	17	1691–1991	0.63	0.43
Jarbridge Canyon, Nevada, U.S.A.	41.90 N, 115.42 W	1,825	Holmes *et al.*	42	1334–1984	0.66	0.33
Theodore Roosevelt National Park, North Dakota, U.S.A.	46.92 N, 103.48 W	1,630	Meko and Sieg	42	1597–1991	0.68	0.40
Paxton Springs Malpais, New Mexico, U.S.A.	35.06 N, 108.06 W	2,375	Spond *et al.*	24	1692–2007	0.74	0.53

4.5.2 Influence of Climate on Radial Growth at PAX

Statistically significant correlations between the PAX chronology and monthly climate data for New Mexico Climate Division 1 support our hypothesis that Rocky Mountain junipers growing on the malpais of western New Mexico are suitable for dendroclimatic analyses. The strength of our crossdating ensures the necessary confidence to report climate-growth relationships. Correlation analysis did not reveal results identical to those identified in ponderosa pine and Douglas-fir at EMNM by Grissino-Mayer (1995) and ponderosa pine atop the Paxton Springs Crater (Rother 2010), but they did show similar seasonal trends.

Tree growth in the southwestern United States is strongly tied to moisture availability (Fritts 1976). The trees we sampled at the PAX site are most strongly correlated with monthly PDSI values, which can be used as a measure of soil moisture availability. A significant positive relationship between indexed growth at the PAX site and monthly PDSI emerges during August of the previous year and persists throughout the period of analysis. The relationship could indicate the importance of heavy rains produced by the North American Monsoon during the previous summer to recharge water stored in the porous basalt for use by trees during the drier phases of the subsequent growing season (Lindsey 1951; Grissino-Mayer 1995).

Statistically significant positive correlations exist between monthly total precipitation and indexed Rocky Mountain juniper growth at the PAX site during the previous October–current May. Clouds associated with increased precipitation during the previous fall could reduce evaporation loss, while higher levels of precipitation during this period would recharge the water supply stored in the basalt malpais for use by trees

during the next growing season. Increased precipitation during the winter months would likely produce more persistent snow cover on the basalt, which would prohibit large levels of insolation from reaching the lava surface and reduce the evaporation of water stored in the lava. Higher amounts of precipitation during the current spring might also reduce evaporation rates due to increased cloud cover, while recharging the porous basalt.

Statistically significant negative correlations exist between Rocky Mountain juniper growth at the PAX site and temperature during the previous August, previous October, and previous November. The inverse relationship between annual radial growth and monthly mean temperature is unique to the PAX chronology. Conifer chronologies from the Southwest typically respond to precipitation. The association between growth and monthly mean temperature is likely related to moisture availability. Evaporation increases as monthly mean temperature increases, restricting the amount of water available for photosynthesis, which may result in increased tree mortality (Fritts 1976; McDowell *et al.* 2008). Higher monthly mean temperatures during the previous late summer and previous fall would increase evaporation rates and decrease the amount of water stored in the basalt from summer rains. The decrease in available moisture the following growing season could decrease photosynthetic rates and cause trees to allocate fewer carbohydrates for radial growth (Fritts 1976; McDowell *et al.* 2008).

The negative correlation between monthly mean temperature and Rocky Mountain juniper growth at the PAX site resumes between April and July of the current growing season. Warm monthly mean temperatures during the early portion of this period (*i.e.*, current April) would likely melt any snow that accumulated during the previous winter, which would dramatically decrease surface albedo as the black basalt is exposed.

Decreased albedo would elevate evaporation rates and reduce the moisture available to trees growing on the malpais. High monthly mean temperatures during the late spring and early summer months of the current year would further reduce moisture available to trees on the malpais and restrict additional radial growth (Fritts 1976).

The strong positive correlation between radial growth at the PAX site and total water year precipitation was also interesting. Grissino-Mayer (1995) found a very strong, positive relationship ($r = 0.75$; $P < 0.0001$) between local water year precipitation (previous 1 July–current 30 June) and the annual radial growth of ponderosa pine and Douglas-fir at EMNM. He interpreted the relationship to suggest that the trees were responding more to hydrological constraints than climatic factors due to the tendency of the porous basalt to retain water throughout the year, including during annual precipitation minimums. The extended response allowed Grissino-Mayer to reconstruct total annual precipitation, rather than only seasonal or monthly rainfall. Our PAX chronology was also positively correlated ($r = 0.53$; $P < 0.001$) with total water year precipitation for the malpais region. The relationship between water year precipitation and Rocky Mountain juniper growth at the PAX site further suggests the ability of trees growing on the basalt malpais to record environmental data that would be unavailable from Southwestern conifers growing on less porous surfaces (Grissino-Mayer 1995).

4.5.3 Persistence of Climate-Growth Relationships

Our correlation analyses produced statistically significant relationships between monthly climate data for New Mexico Climate Division 1 and indexed Rocky Mountain juniper growth at the PAX site. However, emergent dendroclimatological evidence

suggests a need to test the temporal stability of climate-growth relationships (D'Arrigo *et al.* 2008). We tested the persistence of relationships between Rocky Mountain juniper at the PAX site and climate variables selected from New Mexico Climate Division 1 using moving interval correlation analysis and forward evolutionary interval analysis. The two methods did not produce identical results, nor did they indicate that all variables identified as significant in the initial correlation analyses persisted through the observation period.

Forward evolutionary interval analysis was more useful than moving interval correlation analysis. Results from forward evolutionary interval analysis provided a more continuous perspective of temporal stability. Despite noticeable discrepancies, the two tests of temporal stability did produce some agreement. Both methods indicated that monthly PDSI for the previous November to the current September was significantly correlated throughout the period of observation. In contrast, relationships between monthly mean temperature and monthly total precipitation appeared less stable.

Several possible explanations exist for the temporal instability of climate-growth relationships at the PAX site. First, climate data for New Mexico Climate Division 1 is less spatially comprehensive during the early part of the instrumental record (*i.e.*, 1895–1930). New Mexico Climate Division 1 currently consists of > 70 meteorological stations in western New Mexico. However, many of these stations were not established until the middle of the 20th century (NOAA 2011). Earlier records are based on far fewer recording stations. Quality-control issues might also negatively affect some early instrumental data. Early weather data were obtained with instruments that were less accurate than modern instruments. The potential for human error when recording data

was also greater prior to technological advances during the 20th century. The combined effects of poor spatial coverage and potentially inaccurate data during the early instrumental period may partially explain the temporal instability of climate-growth relationships at the PAX site.

Second, fluctuations in broad-scale atmospheric-oceanic oscillations may influence climate-growth relationships at the PAX site. Teleconnections are associations between oceanic-atmospheric oscillations and distinct meteorological and climatological effects in areas that are often thousands of kilometers away from the causative source (Caviedes 2001). Numerous studies have shown relationships between ENSO and PDO variability and precipitation patterns in the southwestern United States (Andrade *et al.* 1988; Swetnam and Betancourt 1990; D'Arrigo and Jacoby 1991; Seagar *et al.* 2005; Stahle *et al.* 2009). Temporal instability in climate-growth relationships at the PAX site may be linked to phase changes in ENSO, PDO, and other climate oscillations that could affect the timing and intensity of atmospheric conditions that facilitate tree growth.

Climate is not the only environmental variable that affects the widths of tree rings (Cook 1987; Fritts 1976). Biotic factors and fluctuations in nutrient availability are potentially a third explanation for temporal instability in climate-growth relationships at the PAX site. Physical and biological competition (*e.g.*, shading, water and mineral uptake, and allelopathy) from other plants that inhabit the site (*e.g.,* shorter-lived quaking aspen) potentially disrupted the climate signal of sampled Rocky Mountain juniper during portions of the period of analysis (Fritts 1976). It is possible that biological agents are also responsible for erratic-ring patterns that prevented the inclusion of many samples in the PAX chronology.

Fourth, anthropogenic activity (*e.g.*, logging and wood collection) may explain some of the temporal variability in the relationships between Rocky Mountain juniper growth and local climate. The PAX site is not pristine. Rother (2010) reported that the surrounding ponderosa-pine forests were heavily logged during the early 20th century. Hundreds of stumps still litter the area around the Paxton Springs Crater. Some of the trees may have suffered damage from logging crews that operated only a few meters off the lava. Crown removal or cambial damage could affect tree growth for years, reducing the influence of climate on ring formation (Fritts 1976). We noticed what appeared to be recent branch scars and wounds on some trees at the PAX site. Perhaps the injuries were the result of people gathering firewood or collecting building materials. Therefore, anthropogenic activity, past and present, may partially explain the temporal instability of climate-growth relationships at the PAX site.

4.6 Conclusions

We conclude that sufficient sampling and core inspection are needed to produce precisely dated tree-ring chronologies from Rocky Mountain juniper growing on the malpais of western New Mexico. Contorted growth forms and severely compressed growth rings complicated crossdating on most samples. However, 24 (40%) of the trees we sampled produced cores that were suitable for confident crossdating and chronology development. Dating was complicated by locally absent rings, which were typically contemporaneous with the narrowest rings on ponderosa pine and Douglas-fir samples used in the Malpais Long Chronology (Grissino-Mayer 1995).

Our results confirm that Rocky Mountain juniper samples collected on the Paxton Springs Malpais have potential for use in additional dendroclimatic analyses. We conclude that, like Douglas-firs and ponderosa pines growing on the volcanic badlands of nearby EMNM, Rocky Mountain junipers on the malpais are highly sensitive to climate factors that influence and indicate moisture availability during dry periods of the growing season. The inverse relationship we identified between annual radial growth and monthly mean temperature is uncommon among conifer chronologies from the Southwest. Climate-growth relationships are likely related to the ability of the porous basalt to store water during dry months, providing a sustained water supply for resident trees throughout the growing season. Positive correlations between monthly PDSI and radial growth at the PAX site persisted throughout the period of analysis. However, temporal variability in the relationships between radial growth, monthly total precipitation, and monthly mean temperature were less stable. Additional research is needed to investigate the potential role of broad-scale climate oscillations in changes to the relationships between local climate and tree growth.

Future dendroclimatic research should analyze the old-growth Rocky Mountain junipers growing on the lava flows at EMNM. Preliminary analysis of cores and cross-sections collected at EMNM suggests that many of the sampled trees are > 500 years old. It is very likely that Rocky Mountain junipers growing on the lava flows of EMNM are also sensitive to climate. Identifying relationships between climate and the radial growth of Rocky Mountain junipers at EMNM would further substantiate our findings at the PAX site and encourage future research at other locations within the wide distribution of the species. Capitalizing on the dendroclimatic potential of Rocky Mountain juniper,

especially the species' response to temperature, could advance our understanding of climate-growth relationships in multiple ecosystems and strengthen the spatial and temporal resolution of the tree-ring record in western North America.

Chapter Five

PACIFIC TELECONNECTIONS AND RADIAL GROWTH IN ROCKY MOUNTAIN JUNIPERS (*JUNIPERUS SCOPULORUM SARG.*) ON THE PAXTON SPRINGS MALPAIS, NEW MEXICO, U.S.A.

Portions of this chapter that refer to Rocky Mountain juniper and dendroclimatology on the malpais of New Mexico were taken from Chapters 1, 2, and 4 of this dissertation. The use of "we" in this chapter refers to Mark Spond, Dr. Henri Grissino-Mayer, and Dr. Saskia van de Gevel, all of whom will be coauthors on a manuscript, taken from this material, to be submitted for peer-reviewed publication.

Abstract

We used tree-ring data from Rocky Mountain junipers growing on the Paxton Springs Malpais (PAX) in western New Mexico to investigate relationships between annual radial growth and atmospheric-oceanic oscillations in the Pacific Ocean. The primary objectives of our research were to: (1) investigate relationships between sea-surface temperature (SST) in the El Niño 3.4 region of the central Pacific Ocean and radial growth trends in Rocky Mountain juniper; (2) investigate relationships between the Pacific Decadal Oscillation (PDO) and growth trends in Rocky Mountain juniper; (3) investigate relationships between the Pacific North American Oscillation (PNA) and growth trends in Rocky Mountain juniper; and (4) assess the temporal stability of relationships between radial growth in Rocky Mountain juniper and the three oscillations. We hypothesized that the PAX chronology is positively correlated with ENSO and PDO and negatively correlated with PNA.

The positive relationships we identified between ENSO and the PAX chronology agree with established teleconnections that affect atmospheric conditions favorable to tree

growth in the Southwest. Persistent positive relationships between annual radial growth and PDO during the cool months prior to the current growing season further indicate an association between SSTs in the Pacific Ocean and Rocky Mountain junipers at the PAX site. Positive relationships between monthly PNA index values and annual radial growth may result from the large distances between the PAX site and PNA centers of activity over the Pacific Northwest and southeastern United States. Unstable relationships between annual radial growth and monthly PNA data suggest the influence of ENSO, PDO, or other oceanic-atmospheric teleconnections. Our results further confirm the dendroclimatic potential of Rocky Mountain junipers at the PAX site and other locations on the volcanic badlands of western New Mexico. We recommend the development of additional Rocky Mountain juniper tree-ring chronologies to conduct tests for spatial and temporal patterns in the response of the species to oceanic-atmospheric teleconnections between the Pacific Ocean and western North America.

5.1 Introduction

5.1.1 Purpose

The broad-scale coupled dynamics of oceanic-atmospheric oscillations can affect short-term weather phenomena and long-term climate trends at the global scale (Ropelewski and Halpert 1987; Swetnam and Betancourt 1990; Caviedes 2001). Teleconnections are associations between oceanic-atmospheric oscillations and distinct meteorological and climatological effects in areas that are often thousands of kilometers away from the causative source (Caviedes 2001). ENSO is known to influence atmospheric conditions across much of North America (Ropelewski and Halpert 1986; Wu *et al.* 2005; Mo 2010). Numerous studies have shown relationships between ENSO variability and precipitation patterns in the southwestern United States (Andrade *et al.* 1988; Swetnam and Betancourt 1990; D'Arrigo and Jacoby 1991; Seagar *et al.* 2005). Additional research suggests an association between PDO, PNA, and precipitation in the region (Stahle *et al.* 2009; Frankze *et al.* 2011), and subsequently the amount of water that can be accessed by trees (McCabe and Detinger 1999; Larkin and Harrison 2005; Mo 2010). However, few studies have categorically analyzed the temporal stability of relationships among ENSO, PDO, PNA, and tree growth in the Southwest.

The primary objectives of our research were to: (1) investigate relationships between SST in the El Niño 3.4 region of the central Pacific Ocean and radial growth trends in Rocky Mountain juniper; (2) investigate relationships between the PDO and growth trends in Rocky Mountain juniper; (3) investigate relationships between the PNA and growth trends in Rocky Mountain juniper; and (4) assess the temporal stability of relationships between radial growth in Rocky Mountain juniper and the three oscillations.

We hypothesized that the PAX chronology is positively correlated with ENSO and PDO and negatively correlated with PNA, due to the influence of Pacific oscillations on cool-season precipitation in the Southwest.

5.1.2 ENSO

El Niño refers to episodes of anomalous warming in the tropical Pacific Ocean (Trenberth 1997; Caviedes 2001). During an El Niño event, warm water moves east from the western Pacific Ocean and eastern Indian Ocean as the easterly tradewinds and associated easterly ocean currents diminish. The absence of strong trade winds disrupts the "normal" upwelling of the cold Humboldt Current in the southeastern Pacific Ocean, resulting in a localized rise in the thermocline and increased SSTs. In contrast, La Niña refers to the intensification of deep-water upwelling and below normal SSTs in eastern portions of the tropical Pacific Ocean (Trenberth 1997; Caviedes 2001). El Niño and La Niña events typically last 16–18 months, with an average oscillation cycle of 2–7 years (Mantua and Hare 2002; Brown and Comrie 2004). Although the phenomena were initially identified by SST anomalies in the eastern equatorial Pacific off the coast of South America (Ropelewski and Halpert 1986; 1987; Trenberth 1997), subsequent studies suggested that ENSO-related temperature anomalies in the central Pacific Ocean (*i.e.*, El Niño Modoki) have significant impacts on atmospheric processes across much of the globe (Barsugli and Sardeshmukh 2002; Ashok *et al.* 2007). In fact, the central equatorial Pacific Ocean (*e.g.*, the El Niño 3.4 and El Niño 4 regions) is now regarded as a critical observation zone for monitoring SST anomalies associated with phase shifts between El Niño and La Niña conditions (Kao and Yu 2009; Di Lorenzo *et al.* 2010).

Oscillations between El Niño and La Niña conditions are viewed as the oceanic component of ENSO, while the Southern Oscillation is the atmospheric component. The Southern Oscillation refers to quasi-cyclical variations in atmospheric pressure over the tropical Pacific Ocean (Stahle *et al.* 1998). Surface pressure readings are compared between the western (Darwin, Australia) and eastern (Tahiti) equatorial Pacific Ocean to calculate the Southern Oscillation Index (SOI). Maximum pressure anomalies typically occur during the boreal winter (December, January, and February) (DJF) (Swetnam and Betancourt 1990). High SOI values indicate a strong pressure gradient between the eastern and western Pacific Ocean (*i.e.*, high pressure over the cool water of the eastern Pacific Ocean and low pressure over the warm water of the western Pacific Ocean), while low SOI values indicate opposite conditions. Low SOI values correspond with El Niño events and high SOI values are associated with episodes of La Niña (Swetnam and Betancourt 1990). ENSO teleconnections are largely responsible for interannual fluctuations in precipitation and temperature across much of western North America (Ropelewski and Halpert 1986; Brown and Comrie 2004; Mo 2010).

Dendroclimatological research in the western United States has addressed relationships between ENSO and tree growth (Woodhouse 1993; Stahle *et al.* 2009; Touchan *et al.* 2011). Previous tree-ring studies helped define the dipolar relationship between ENSO and precipitation in the southwestern and northwestern United States. El Niño conditions generally correspond with wet winters in the Southwest, while La Niña events typically cause high pressure and reduce precipitation in the Southwest during winter (Swetnam and Baisan 2003). ENSO effects on precipitation in the Northwest are

typically the opposite of those in the Southwest (Morgan *et al.* 2001; Swetnam and Baisan 2003).

Dendroclimatologists have also helped identify the influence of ENSO on disturbance regimes in the western United States. In particular, previous dendroclimatological studies showed relationships between ENSO variability and wildfires in the Southwest (Swetnam and Betancourt 1990; Swetnam and Baisan 2003). Existing studies identified a positive relationship between La Niña conditions and synchronized, regional fire events in the Southwest (Swetnam and Betancourt 1990; Swetnam and Baisan 2003). Increased fine-fuel growth during wetter periods (linked to El Niño events 1–3 years prior to major fires) might precondition the Southwest for broad-scale wildfires during the next La Niña event (Swetnam and Baisan 2003). As with precipitation, tree-ring research has identified a dipole between fire activity in the Southwest and Northwest (Morgan *et al.* 2001; Swetnam and Baisan 2003).

5.1.3 PDO

The PDO is a quasi-cyclical pattern of ocean-atmospheric variability in the northern Pacific Ocean (20–60° N) (Mantua *et al*. 1997; Mantua and Hare 2002). The oscillation was first described while investigating salmon production off the Pacific coast of North America (Mantua *et al.* 1997). The PDO is recognized as the leading mode of interdecadal SST variability in the North Pacific Ocean (Mantua *et al.* 1997; Newman *et al.* 2003). However, Newman *et al*. (2003) demonstrated that "the PDO is dependent upon ENSO on *all* timescales." The PDO is not a single mode of variability, but a combination of phenomena operating at multiple frequencies. The positive (warm) phase

is characterized by higher SSTs in the eastern North Pacific Ocean, while the negative (cool) phase is characterized by lower SSTs. Decadal variability of SSTs in the North Pacific Ocean is concentrated in the boreal winter and spring (Newman *et al*. 2003). PDO cycles typically last between 20 and 30 years. The most recent phase shifts occurred during 1925 (cool-warm), 1947 (warm-cool), and 1977 (cool-warm) (Mantua *et al.* 1997). The cool phase of the PDO is associated with reduced moisture advection into the American Southwest, particularly when in phase with ENSO (Kitzberger *et al.* 2007).

5.1.4 PNA

The PNA is an atmospheric circulation that influences interannual climate variability in North America (Wallace and Gutzler 1981; Trouet and Taylor 2009; Franzke *et al.* 2011). The PNA is observed as a sequence of Rossby waves with four centers of action (two of each sign) located between the northeastern Pacific Ocean and the southeastern United States (Franzke *et al*. 2011). The oscillation affects the position of Rossby wave trains and subsequently affects the mid-tropospheric geopotential height field over North America and portions of the North Pacific Ocean. The PNA is most pronounced during the boreal winter (Trouet and Taylor 2009). Although the PNA exhibits variability on interannual and interdecadal timescales, a typical PNA cycle lasts only two weeks (Franzke *et al.* 2011). The positive phase of the PNA is characterized by increased atmospheric pressure over the west coast of the United States and eastern portions of the tropical North Pacific Ocean, warmer winter temperatures across much of western North America, and decreased cool-season precipitation in the western United States. The negative phase of the PNA is characterized by negative geopotential height

anomalies in western North America and positive geopotential height anomalies in the southeastern United States and North Pacific Ocean (Trouet and Taylor 2009).

5.2 Study Area

Our study addressed an old-growth stand of Rocky Mountain juniper living on a small section of the Paxton Springs Lava Flow *ca.* 10 km north of El Malpais National Monument (EMNM) (Figure 5.1). The site is *ca.* 150 m north of the Paxton Springs Crater, a cinder cone volcano located in the Zuni Mountains of Cibola National Forest. The Zuni Mountains are not a jagged escarpment, but rather a complex of gentle slopes that rise *ca.* 300 m above the highest portions of EMNM. Elevations in the Zunis range between *ca.* 2,000 m and 2,820 m. The Zunis differ from other mountains in the area in that they formed by geologic uplift rather than volcanism (Chronic 1987). The Zuni Mountains initially consisted of a Precambrian core of igneous and metamorphic rocks, overlain by sedimentary strata that were deposited during subsequent periods. As the Zunis were uplifted, the sedimentary rock was eroded away, exposing the underlying core rock (Chronic 1987). However, the abundant volcanism in the region left its mark on the Zuni Mountains. Volcanic vents are located in the Zunis along Oso Ridge and at the Paxton Springs Crater. Basalt malpais, formed from lava that flowed out of the Paxton Springs Crater, covers part of Zuni Canyon and much of the surrounding area.

Although the eruption that produced the basalt formation at the study site has not been absolutely dated, the basalt that originated from the Paxton Springs Crater is relatively older than the nearby Bandera Lava Flow (*ca.* 10,000–11,000 years before present) and younger than the neighboring Bluewater Lava Flow (*ca*. 79,000 years before

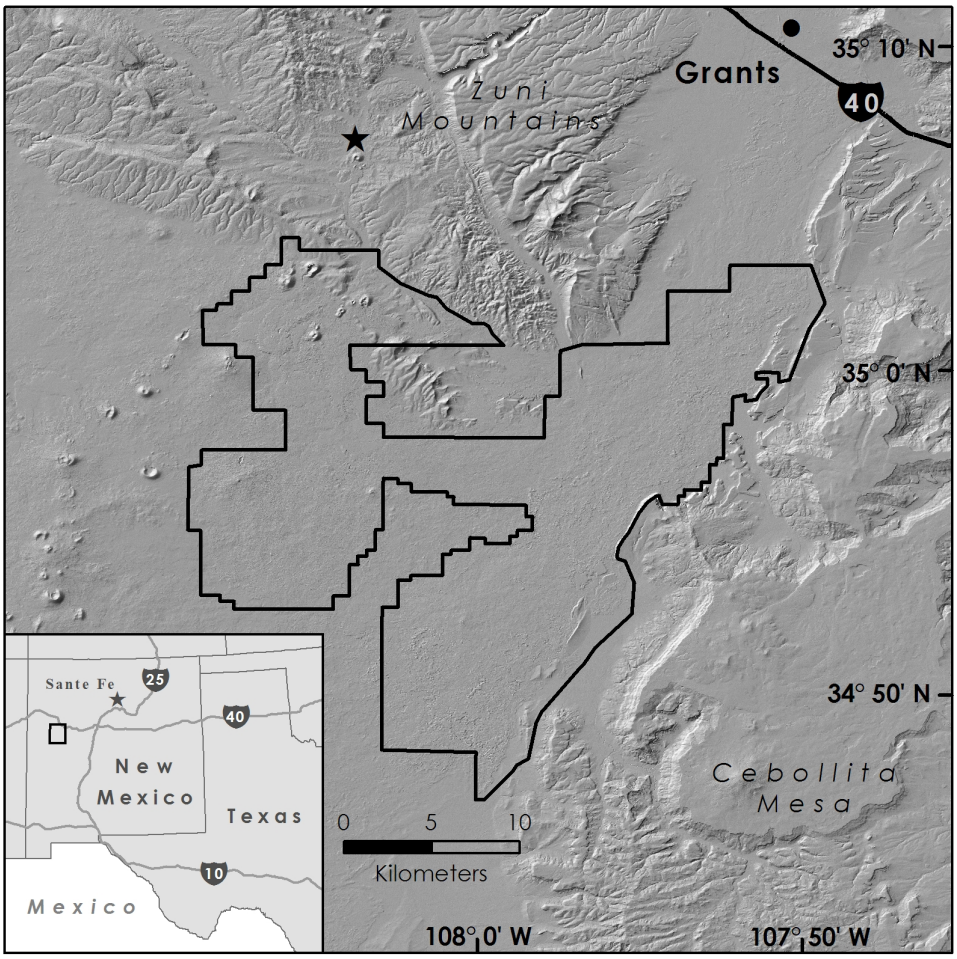


Figure 5.1 The black star indicates the approximate location of our study site (2,375 m) on the Paxton Springs Lava Flow (35.066997 N, 108.060219 W). Paxton Springs Crater is the volcanic cone immediately south of the study site. The black outline indicates the boundary of EMNM. (Map by Grant Harley)

present) (Laughlin *et al.* 1993). Elevation at the Paxton Springs Malpais study site (PAX) is approximately 2,375 m. The elevation gradient within the site is minimal; however, the rugged basalt surface is jagged and uneven. Tree species diversity in the vicinity of the PAX site is greater on the basalt formations than in adjacent areas not covered by the ancient lava flows. Rocky Mountain juniper, quaking aspen (*Populus tremuloides* Michx.), and Douglas-fir inhabit the basalt formations, while off the lava the forest consists almost entirely of ponderosa pine.

Much of the area that surrounds the Paxton Springs Crater was heavily logged and grazed during the late 19th and early 20th centuries (Rother 2010). The ponderosa harvest from the Zuni Mountains was one of the most prolific in the West (Mangum 1990). Today, the proximity of the PAX site to public roads allows easy access for tree-ring sampling, but also provides persons gathering firewood an ideal location for collecting juniper and other tree species. The mixed-conifer woodlands at the PAX site appear to have suffered less from recent anthropogenic activity than the ponderosa pine forest that surrounds them, but cut stumps, severed branches, and small amounts of human refuse indicate that the PAX site is not pristine.

5.3 Methods

5.3.1 The PAX Chronology

Few dendrochronological studies have incorporated tree-ring data from Rocky Mountain juniper (Sieg *et al.* 1996; Grissino-Mayer *et al.* 1997). Dendrochronologists favor co-dominant species (*e.g.*, ponderosa pine, Douglas-fir, and piñon pine) that produce more-clearly defined growth rings and have fewer locally absent growth rings.

Research teams from the University of Tennessee Laboratory of Tree-Ring Science recovered increment cores from Rocky Mountain juniper at PAX during July 2008. The master chronology for PAX consists of 24 tree-ring series (3,577 total annual rings) collected from 24 Rocky Mountain juniper trees at the Paxton Springs Malpais. The chronology spanned between 1692 and 2007 (316 years). Although many of the cores we collected at the PAX site could not be included in our chronology due to rot, fractures, or compressed growth, intact cores with the clear growth patterns dated very well against the El Malpais Long Chronology (Grissino-Mayer 1995). Confident dating was aided by several marker rings (very narrow or locally absent rings) identified by Grissino-Mayer (1995) and Stahle *et al*. (2009) including: 1761, 1782, 1819, 1847, 1876, 1900, 1925, 1951, 1971, 1996, and 2002. We also found the 2006 growth ring to be consistently narrow or locally absent. Missing rings complicated dating, but in every case the existence of a locally absent ring was found by intra-site crossdating and the persistent relationship to previously identified marker rings. Locally absent rings represented 2.8% of the total rings in the chronology. Density fluctuations within radial growth rings, commonly called "false rings," were distinguishable from actual annual ring boundaries by the careful identification of terminal latewood cells (Hoadley 1990).

5.3.2 Dendroclimatic Analyses

We performed correlation analysis between the PAX Rocky Mountain juniper tree-ring chronology and a composite index (1300–1979 reconstructed, 1980–2006 instrumental) of DJF SSTs in the El Niño 3.4 region of the central Pacific Ocean (Cook *et al.* 2008). Higher composite index values signify warmer SSTs, while lower index values

signify cooler SSTs. We then performed correlation analysis to investigate relationships between instrumental annual mean SSTs for the El Niño 3.4 region of the central Pacific Ocean (NOAA 2011) and the annual radial growth of Rocky Mountain junipers at the PAX site. The period of analysis began in 1950 and continued until the most recent year of the chronology (2007). Next, we conducted correlation analysis to test the strength of association between instrumental monthly mean SSTs (beginning in 1950) for the El Niño 3.4 region of the central Pacific Ocean and the PAX chronology. We then performed correlation analysis between the PAX chronology and a monthly index of PDO (1948–2007 instrumental) (NOAA 2011). Finally, we performed correlation analysis between the PAX chronology and a monthly index of PNA (1950–2007 instrumental) (NOAA 2011).

Monthly analyses were conducted using DENDROCLIM2002 because the program calculates correlation coefficients with bootstrapped confidence intervals. Bootstrapping is a re-sampling technique that increases confidence in results produced from small sample sizes (Biondi 1997). Data analyzed in DENDROCLIM2002 are assumed to be normal, which allows the program to generate Pearson product-moment correlation coefficients between monthly climate data and tree-ring chronologies (Cook 1985). To verify significance, correlation coefficients were reported with $P < 0.05$. Following the correlation analysis, we used DENDROCLIM2002 to conduct forward evolutionary interval analysis to test the temporal stability of significant relationships identified among monthly mean SSTs for the El Niño 3.4 region, the monthly PDO index, the monthly PNA index, and Rocky Mountain juniper growth (Biondi 1997; Biondi and Waikul 2004). Forward evolutionary interval analysis began with the earliest

year in common to all variables. Evolutionary intervals were progressively enlarged by adding one year to a base interval after each iteration (Biondi and Waikul 2004).

We also conducted correlation analysis using DENDROCLIM2002 (Biondi 1997; Biondi and Waikul 2004) to investigate relationships between local climate variables and the annual radial growth of Rocky Mountain junipers at the PAX site. Our objective was to elucidate relationships between local climate variables and tree growth that may be related to significant correlations identified between radial tree growth and Pacific teleconnections. Divisional climate data are available for much of New Mexico beginning in 1895 (NOAA 2011). We selected monthly mean temperature and monthly total precipitation data for New Mexico Climate Division 1 for our analyses. Instrumental temperature and precipitation values were obtained from the National Climatic Data Center (NOAA 2011).

5.4 Results

A positive correlation was found between composite DJF SST indices for the El Niño 3.4 region of the central Pacific Ocean ($r = 0.38$, $n = 315$, $P < 0.0001$)(Figure 5.2). When the period of analysis was restricted to the instrumental record (beginning in 1950) (Figure 5.3), the relationship was not statistically significant at the 95% confidence level. Significant positive relationships ($P < 0.05$) were identified between instrumental monthly mean SSTs (beginning in 1950) for the El Niño 3.4 region of the central Pacific Ocean and the PAX chronology for the previous September through current April (Figure 5.4). The temporal stability of significant SST-tree growth relationships was tested using forward evolutionary interval analysis. At the PAX site, statistically significant

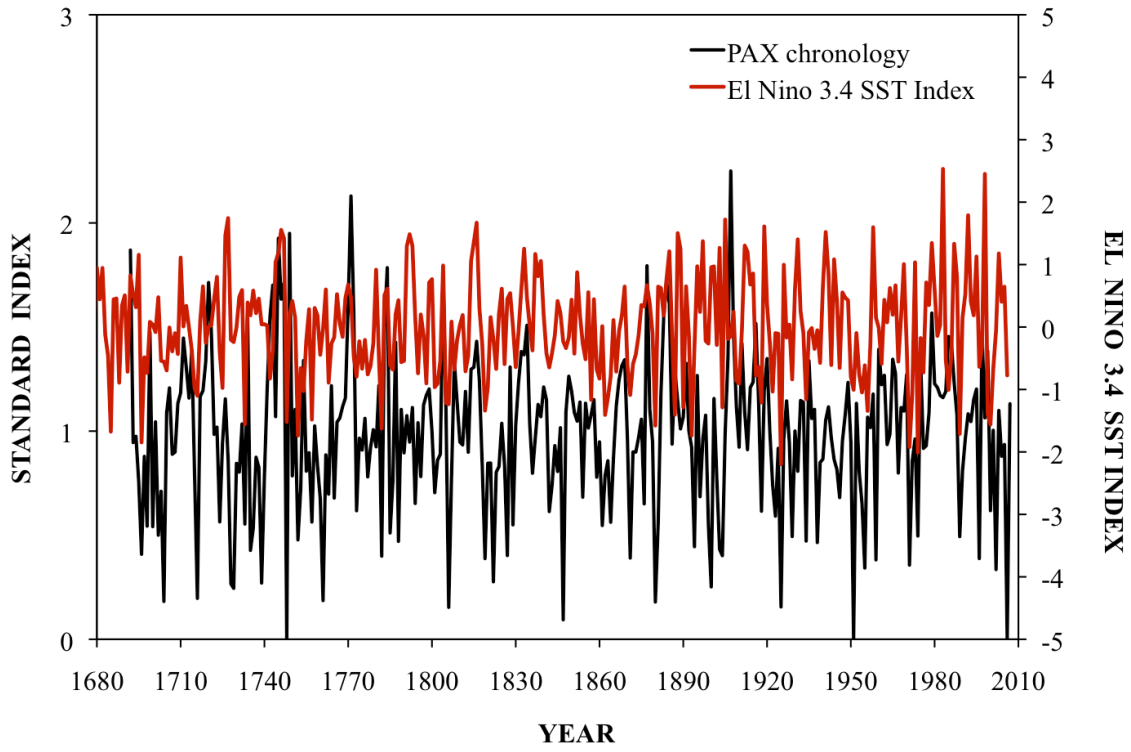


Figure 5.2 Plotted relationships between the standard index of annual radial growth for Rocky Mountain junipers at the PAX site and composite boreal DJF SSTs (1692–2006) for the El Niño 3.4 region of the central Pacific Ocean (r = 0.38) ($P < 0.0001$).

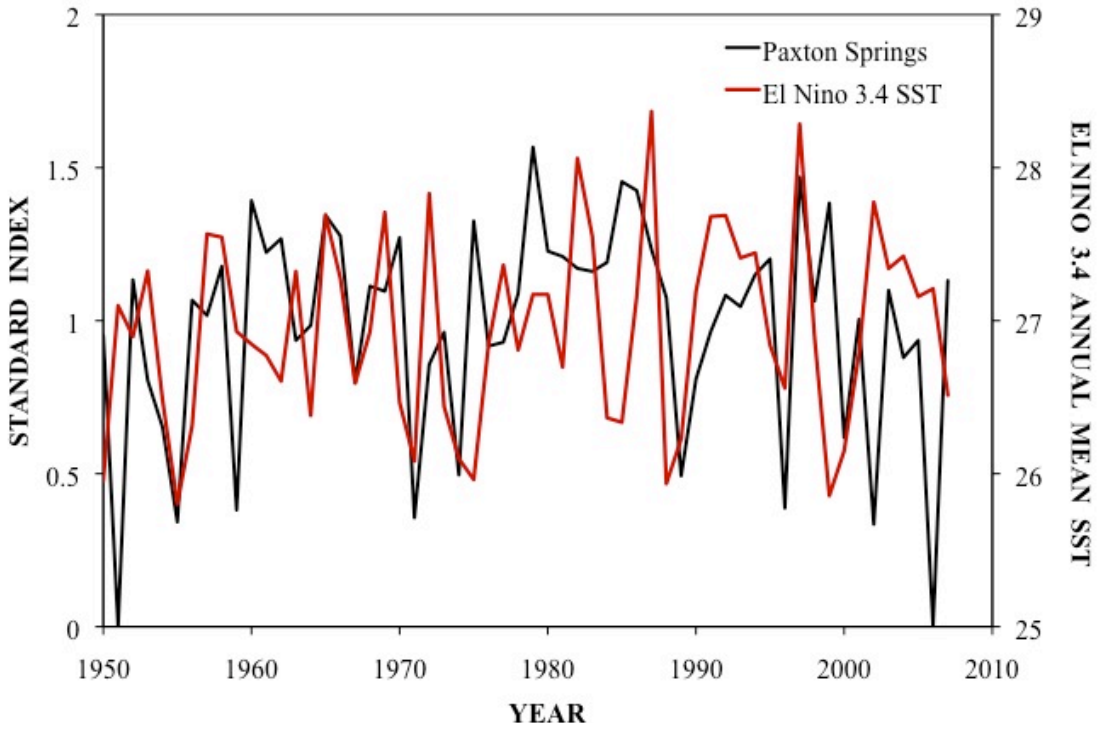


Figure 5.3 Plotted relationships between the standard index of annual radial growth for Rocky Mountain junipers at the PAX site and instrumental annual mean SSTs (ºC) for the El Niño 3.4 region of the central Pacific Ocean (r = 0.17) (1950–2007). The relationship was not significant ($P > 0.05$).

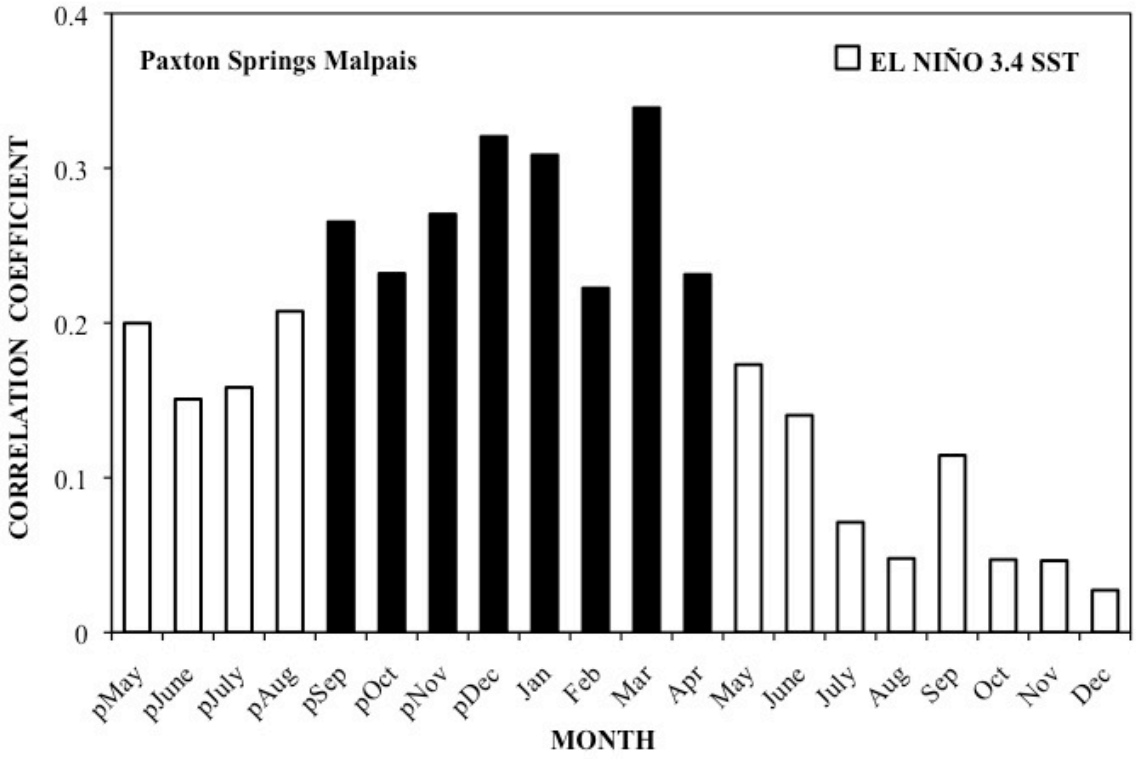


Figure 5.4 Significant positive relationships ($P < 0.05$) were identified between annual radial growth at the PAX site and instrumental monthly mean SSTs for the El Niño 3.4 region of the central Pacific Ocean (1950–2007) during the previous September–current April. Shaded bars show significant relationships ($P < 0.05$). Insignificant relationships ($P > 0.05$) are shown as unshaded bars.

correlations between monthly SST data and annual radial tree growth (1950–2007) were persistent for all months that showed a significant relationship except the current February and current April (Figure 5.5).

Significant positive relationships ($P < 0.05$) were identified between annual radial growth and the PDO index for the previous October–November, current February–April, and current August (Figure 5.6). Statistically significant correlations between monthly PDO index values and annual radial tree growth at the PAX site (1948–2007) were most persistent during current March and April (Figure 5.7). We also identified significant positive relationships ($P < 0.05$) between annual radial growth and the PNA index for current January, current March, and current June (Figure 5.8). Statistically significant correlations between monthly PNA index values and annual radial tree growth at the PAX site (1950–2007) were persistent for current January and March, while the relationship between current June PNA and tree growth was less stable (Figure 5.9).

Additional correlation analyses revealed multiple seasonal relationships between radial growth and both monthly mean temperature and monthly total precipitation. Significant positive relationships ($P < 0.05$) were identified between monthly total precipitation (New Mexico Climate Division 1) and annual radial tree growth from previous October through current May (Figure 5.10). Significant negative relationships ($P < 0.05$) were found between Rocky Mountain juniper growth and monthly mean temperatures (New Mexico Climate Division 1) for the previous August, previous October and November, and current April through July.

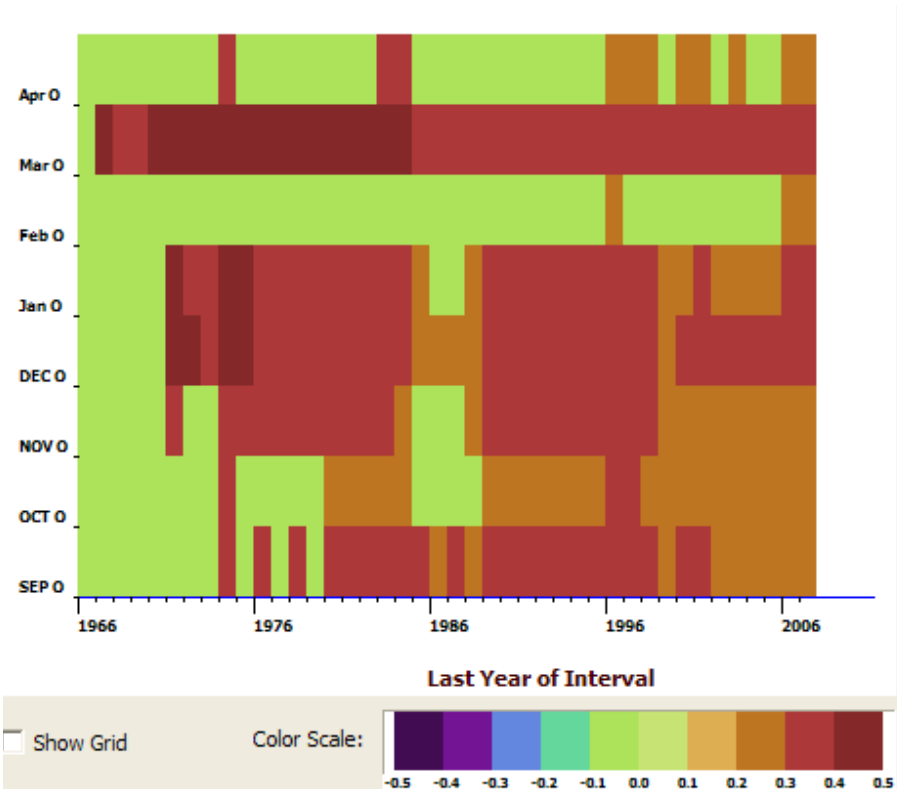


Figure 5.5 Results of forward evolutionary interval analysis (1950–2007) between instrumental monthly mean SSTs for the El Niño 3.4 region of the central Pacific Ocean and the PAX chronology, using a base 16-year interval. Monthly variables are shown on the y-axis, beginning with the previous September in the lower left corner and ending with current April in the upper left corner. The last years of forward intervals are listed on the x-axis. Periods during which a variable is significant are colored according to the strength of the correlation coefficient. Green shading shows periods that are not significantly correlated to tree growth.

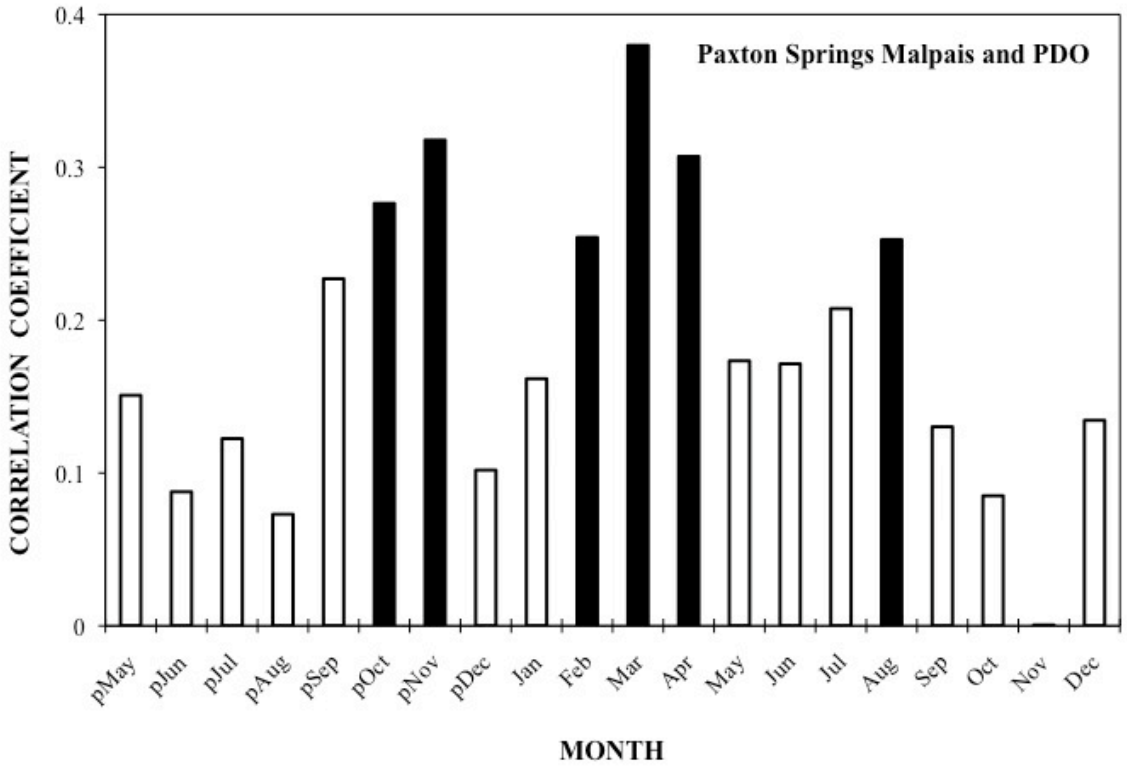


Figure 5.6 Significant positive relationships ($P < 0.05$) were identified between annual radial growth at the PAX site and a monthly index of the PDO (1948–2007) during the previous October–November, current February–April, and current August. Shaded bars show significant relationships ($P < 0.05$). Insignificant relationships ($P > 0.05$) are shown as unshaded bars.

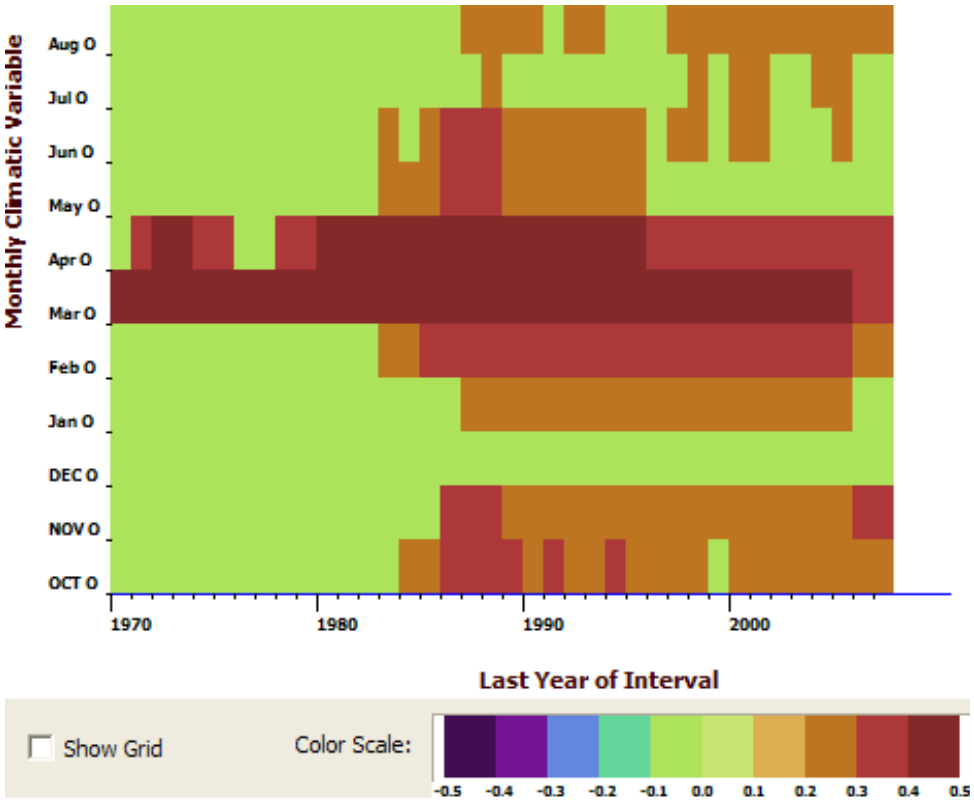


Figure 5.7 Results of forward evolutionary interval analysis (1948–2007) between a monthly index of the PDO and the PAX chronology, using a base 22-year interval. Monthly variables are shown on the y-axis, beginning with the current January in the lower left corner and ending with current December in the upper left corner. The last years of forward intervals are listed on the x-axis. Periods during which a variable is significant are colored according to the strength of the correlation coefficient. Green shading shows periods that are not significantly correlated to tree growth.

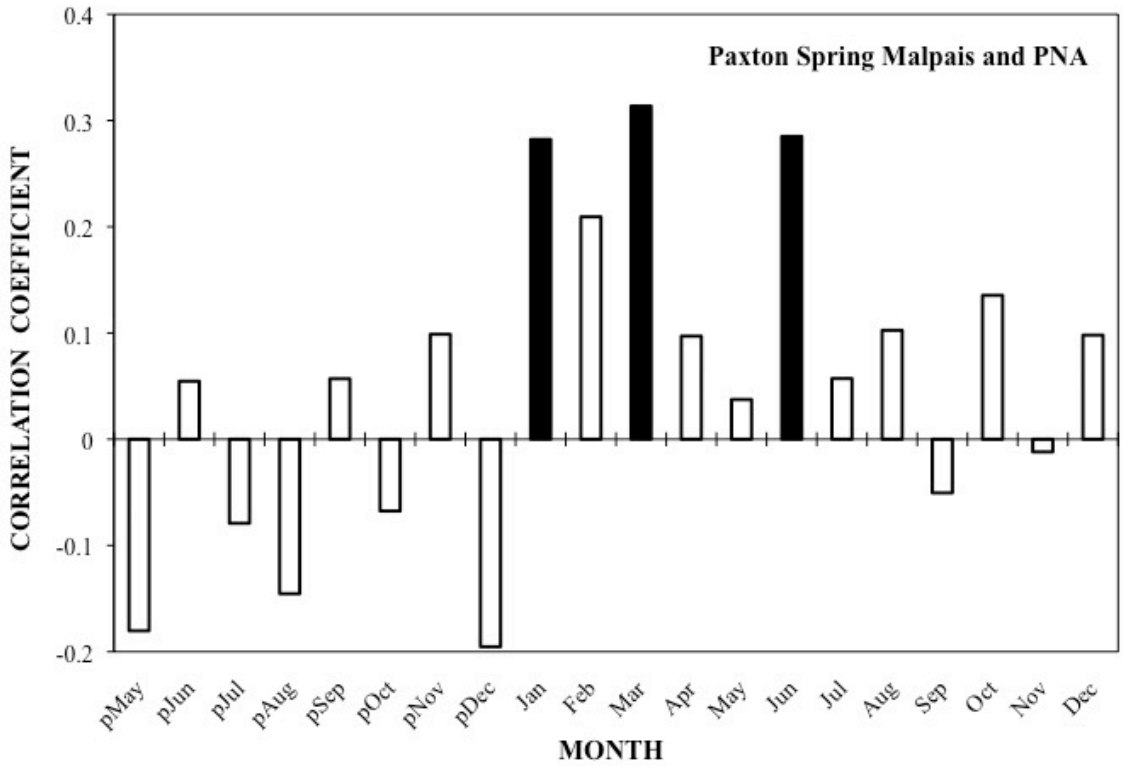


Figure 5.8 Significant positive relationships ($P < 0.05$) were identified between annual radial growth at the PAX site and a monthly index of the PNA (1950–2007) during current January, current March, and current June. Shaded bars show significant relationships ($P < 0.05$). Insignificant relationships ($P > 0.05$) are shown as unshaded bars.

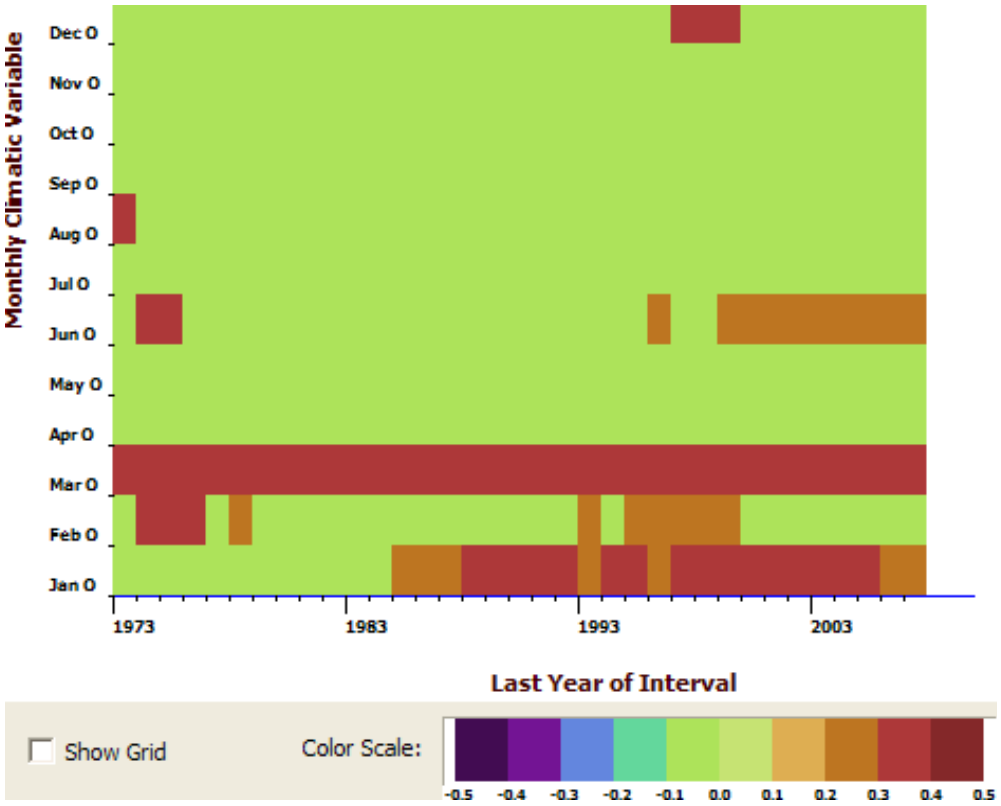


Figure 5.9 Results of forward evolutionary interval analysis (1950–2007) between a monthly index of the PNA and the PAX chronology, using a base 24-year interval. Monthly variables are shown on the y-axis, beginning with the current January in the lower left corner and ending with current December in the upper left corner. The last years of forward intervals are listed on the x-axis. Periods during which a variable is significant are colored according to the strength of the correlation coefficient. Green shading shows periods that are not significantly correlated to tree growth.

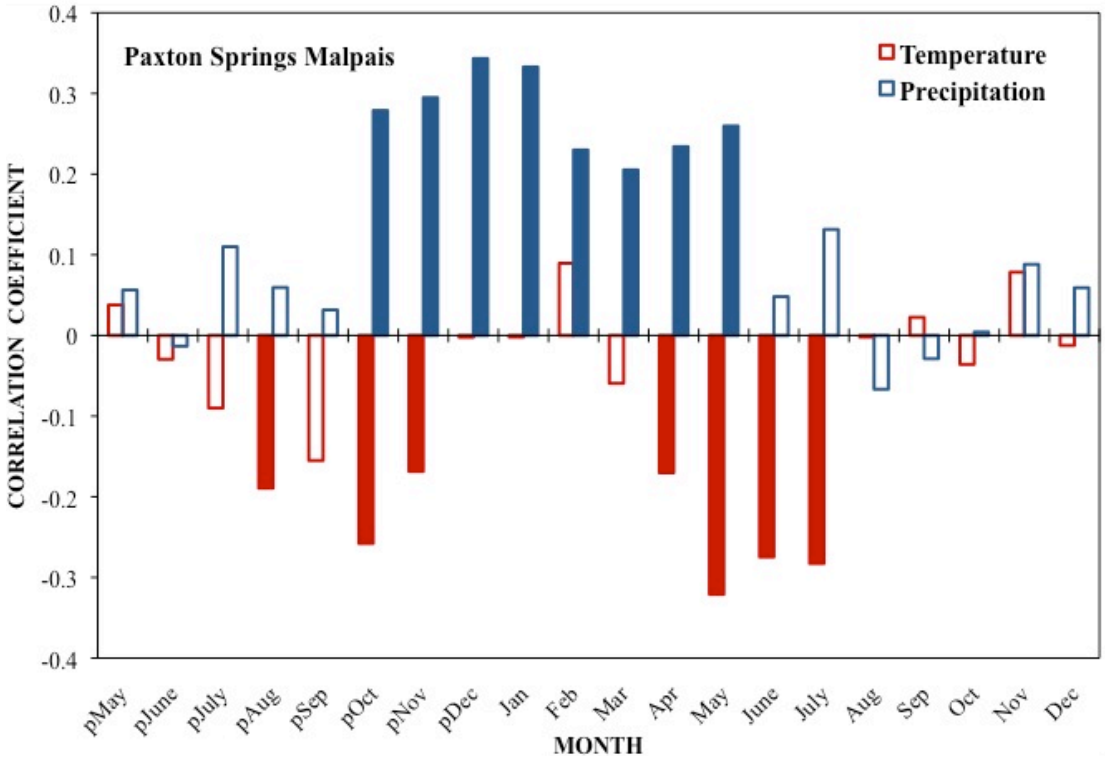


Figure 5.10 Pearson product-moment correlation coefficients (y-axis) showing the relationships between the PAX chronology and monthly mean temperature and monthly total precipitation from the previous May (pMay) to the current December (Dec) (1895–2007). Shaded bars show significant relationships ($P < 0.05$). Insignificant relationships ($P > 0.05$) are shown as unshaded bars.

5.5 Discussion

5.5.1 Climate-Tree Growth Relationships

Our first objective was to test for relationships between SST in the El Niño 3.4 region of the central Pacific Ocean and growth in Rocky Mountain juniper at the PAX site. A positive correlation was found between annual radial growth and both the composite index of SSTs and the instrumental monthly mean SST data for the El Niño 3.4 region of the central Pacific Ocean. Significant relationships between instrumental monthly mean SSTs and annual radial growth (previous September–current April) at the PAX site initiate and terminate one month before the beginning and end of a period of persistent positive relationships (previous October–current May) between monthly total precipitation and annual radial tree growth. Cool-season precipitation is vital for tree growth in the Southwest (Fritts 1976; Swetnam and Betancourt 1990). Perhaps a one-month lag exists between cool-season SST observations in the El Niño 3.4 region of the central Pacific Ocean and associated climatic effects in the Southwest.

The El Niño phase of ENSO typically increases cool-season precipitation in the American Southwest, while the La Niña phase results in reduced cool-season precipitation (Ropelewski and Halpert 1986; Swetnam and Betancourt 1990; Gutzler and Preston 1997). The effects can be explained by the teleconnective properties of ENSO (Swetnam and Betancourt 1990). During El Niño conditions (low SOI values), warm waters in the eastern Pacific Ocean supply the energy necessary for the development of low-pressure cells along the west coasts of northern South America and southern North America (Swetnam and Betancourt 1990). The troughs disrupt the easterly trade winds, promoting increased atmospheric interaction between tropical and temperate zones

(Swetnam and Betancourt 1990; Trenberth 1997; Brown and Comrie 2004). The tropical-subtropical teleconnection, combined with lower-latitude winter-storm tracks, allows moist air masses to reach the southwestern United States increasing cool season precipitation (Swetnam and Betancourt 1990; Gutzler and Preston 1997). In contrast, La Niña conditions typically produce persistent high pressure over much of the contiguous United States, including the Southwest, which often leads to reduced cloud cover, increased warm-season temperatures, and reduced moisture availability for trees (Fritts 1976; Swetnam and Betancourt 1990).

Our correlation analysis identified significant relationships between the PDO and annual radial growth in Rocky Mountain juniper at the PAX site. Significant positive relationships between monthly PDO index values (previous October–November, current February–April, and current August) and annual radial growth were concentrated during the cool months prior to the current growing season. Concurrent relationships among tree growth, ENSO, mean temperature, and total precipitation suggest that Rocky Mountain juniper growth at the PAX site is associated with SSTs in the Pacific Ocean and their influence on atmospheric conditions in the Southwest (Sheppard *et al.* 2002; Kitzberger *et al.* 2007; Stahle *et al.* 2009). Although PDO data for previous December–current January were not significantly correlated with the PAX chronology, the established relationships indicate a seasonal effect. PDO-tree growth relationships at the PAX site are likely related to an intensification of the phenomenon during the boreal cool season (Mantua *et al.* 1997; Newman *et al.* 2003). The association between higher cool-season SSTs in the eastern North Pacific Ocean and moisture advection into western New Mexico may explain the seasonal relationship between the PDO and tree growth.

Increased atmospheric moisture during the cooler months produces cloud cover and increased precipitation, which aid tree growth during the subsequent growing season (Fritts 1976; Swetnam and Betancourt 1990). The positive relationship between the PAX chronology and the monthly PDO index for current August may stem from PDO modulation of the North American Monsoon and associated moisture advection from the Pacific Ocean (Sheppard *et al*. 2002; Stahle *et al.* 2009).

We established significant relationships between the PNA and annual radial growth in Rocky Mountain juniper at the PAX site. However, the relationships were positive, not negative as we expected. Significant positive relationships between monthly PNA index values (current January, current March, and current June) and tree growth at the PAX site contradicted our hypothesis that Rocky Mountain juniper growth is negatively correlated with the PNA index. Previous studies suggested that the positive phase of the PNA is associated with decreased precipitation and warmer temperatures during the boreal cool season across much of western North America (Wallace and Gutzler 1981; Trouet and Taylor 2009). Warmer, drier cool-season conditions are not conducive to tree growth at the PAX site, leading us to hypothesize that PNA is negatively correlated with Rocky Mountain juniper growth at the PAX site. The positive relationships we identified between the PNA and annual radial growth at the PAX site do not suggest a clear seasonal signal. In particular, no winter pattern is apparent. Relationships between the annual radial growth at the PAX site and PNA do not appear synchronized with relationships among precipitation, temperature, and the PAX chronology. Perhaps, the positive correlations are an effect of the large distances between

the PAX site and the centers of PNA activity over the Pacific Northwest and southeastern United States (Franzke *et al.* 2011).

5.5.2 Stability of Climate-Tree Growth Relationships

Results for the PAX chronology appear consistent with our current knowledge on the effects of ENSO teleconnections on the southwestern United States (Ropelewski and Halpert 1986; Green *et al.* 1997). We identified a significant positive relationship between the annual growth index (1692–2006) for Rocky Mountain juniper at the PAX site and the composite index of DJF SSTs in the El Niño 3.4 region of the central Pacific Ocean. The PAX chronology also produced a significant relationship between cool season instrumental monthly mean SSTs (1950–2006) for the El Niño 3.4 region of the central Pacific Ocean. However, additional correlation analysis between instrumental annual mean SST data (1950–2006) did not produce a significant relationship. Our results conflicted with previous research by Mo (2010) that concluded positive relationships between SST conditions in the central equatorial Pacific Ocean and winter precipitation in the Southwest became more significant during 1962–2006. The inconsistency of our results suggests that the relationship may not be stable through our initial period of analysis (1692–2006).

Instability between SST-growth relationships could be related to periodic shifts in the Intertropical Convergence Zone (Haug *et al.* 2001; Sachs *et al.* 2009) that potentially reduce ENSO variability and subsequent climate teleconnections (Haug *et al.* 2001), allowing other abiotic and biotic factors to become more associated with tree growth (Fritts 1976). Lower-frequency, broad-scale phenomena such as the North Pacific Gyre

Oscillation and the PDO might influence relationships between SSTs in the El Niño 3.4 region of the Pacific Ocean and annual radial growth in Rocky Mountain juniper at the PAX site (Di Lorenzo *et al.* 2010). The skill of composite SST data, biological biases, and emergent global changes (*i.e.*, global warming) may also contribute to inconsistent relationships between ENSO and Rocky Mountain juniper growth (McGregor *et al.* 2010).

Forward evolutionary interval analysis showed that significant relationships were generally stable between instrumental monthly mean SSTs for the El Niño 3.4 region of the central Pacific Ocean and tree growth at the PAX site (1950–2006). Previous research indicated that the general trend of SSTs in the equatorial Pacific Ocean has been a shift toward more "El Niño-like" conditions during recent decades (Federov and Philander 2000). Warming in the central Pacific Ocean (*i.e.*, El Niño Modoki) occurred with greater frequency during this period, likely resulting in increased cool season precipitation in the Southwest (Mo 2010). The general trend of more warm SST episodes across the tropical Pacific Ocean possibly reinforced teleconnective relationships that provide Rocky Mountain junipers at the PAX site with vital cool-season precipitation (Swetnam and Betancourt 1990; Gutzler and Preston 1997).

Stable PDO-growth relationships during the cool months prior to current growing season suggest a persistent link between SSTs in the North Pacific Ocean and trees at the PAX site. The start of significant positive correlations for the previous October, previous November, and current February during 1983 and 1984 may be related to the transition from the cool to the warm phase of the PDO during 1977 (Mantua *et al.* 1997). Increased cool-season moisture advection associated with the warm phase of the PDO possibly

intensified tree dependence on precipitation during that period. PDO variability may also affect the temporal stability of relationships between annual radial growth at the PAX site and the PNA (1950–2007). The relationship between Rocky Mountain juniper growth and current March PNA was persistent throughout the period of analysis. However, the significant positive association between annual growth and the PNA index for the current January initiated during 1985 following the transition to the warm phase of the PDO. The unstable relationship between tree growth at the PAX site and the PNA index for current June may be associated with the persistence of higher SSTs during the late spring following cool-season intensification of the PDO (Mantua *et al.* 1997; Mantua and Hare 2002).

5.6 Conclusions

We conclude that SST data for the El Niño 3.4 region of the central Pacific Ocean is associated with annual radial growth at the PAX site. The relationships we identified appear to agree with established ENSO teleconnections that influence monthly mean temperatures and monthly total precipitation values that are significantly linked to annual radial tree growth. In addition, persistent positive relationships between annual growth and the PDO index during the cool months prior to the current growing season indicate an association between SSTs in the Pacific Ocean and Rocky Mountain junipers at the PAX site. Positive relationships between monthly PNA index values and annual radial growth may result from the large distances between the PAX site and PNA centers of activity over the Pacific Northwest and southeastern United States. Unstable relationships

between annual radial growth and monthly PNA data suggest the influence of ENSO, the PDO, or other oceanic-atmospheric teleconnections.

Rocky Mountain juniper chronologies archived in the ITRDB (ITRDB 2011) should be updated to identify potential dendroclimatic relationships that have emerged during recent decades. Additional Rocky Mountain juniper tree-ring chronologies are also needed to conduct tests for spatial and temporal patterns in the response of Rocky Mountain juniper growth to oceanic-atmospheric teleconnections between the Pacific Ocean and western North America. Our results suggest a high degree of dendroclimatic potential for Rocky Mountain junipers at the PAX site and other locations on the volcanic badlands of western New Mexico. In particular, future dendroclimatic research should address the old-growth Rocky Mountain junipers growing on the lava flows at EMNM. Preliminary analysis of cores and cross-sections collected at EMNM suggests that some of the Rocky Mountain junipers are > 1,500 years old (Grissino-Mayer 1995). The ancient Rocky Mountain junipers at EMNM could potentially produce a tree-ring chronology suitable for additional research pertaining to relationships between Pacific teleconnections and annual radial tree growth. Identifying significant relationships between Pacific teleconnections and the radial growth of Rocky Mountain junipers at EMNM would further substantiate the climatic link between the American Southwest and the Pacific Ocean.

Chapter Six

CONCLUSIONS AND RECOMMENDED FUTURE RESEARCH

"It is said that character in a man stems from struggles against adversity. It certainly does in the case of trees." – Alton A. Lindsey, *Naturalist On Watch*, 1983

The use of "we" in this chapter refers to Mark Spond, Dr. Henri Grissino-Mayer, Dr. Saskia van de Gevel, and Grant Harley, all of whom will be coauthors on manuscripts, taken from this dissertation, to be submitted for peer-reviewed publication.

6.1 Introduction

The primary objectives of this study were to: (1) assess woodland structure and composition dynamics at El Malpais National Monument (EMNM) between 1948–2010 using repeat photography; (2) improve our understanding of potential drivers of vegetation dynamics at EMNM; (3) produce a unique tree-ring data set from Rocky Mountain junipers growing on the malpais; (4) elucidate relationships between Pacific teleconnections and annual radial growth in Rocky Mountain junipers on the malpais; and (5) increase our understanding of the dynamic nature of climate in the Southwest. To address the objectives, we: (1) rephotographed sites in and around EMNM that were visited during the 20th century by the ecologist and photographer, Alton A. Lindsey; (2) created a multi-century tree-ring chronology from Rocky Mountain juniper on the volcanic malpais of western New Mexico for use in dendroclimatological analyses; and (3) investigated relationships between Pacific teleconnections and Rocky Mountain juniper growth on the malpais. This chapter summarizes the conclusions from Chapters 3, 4, and 5, and provides recommendations for future research.

6.2 Vegetation Dynamics on the Bandera Lava Flow 1948–2010

(1) Our findings suggest that the old-growth woodlands on the interior of the Bandera Lava Flow experienced few changes between 1948 and 2010, while noticeable vegetation changes occurred at the edge of the lava flow.

We hypothesized that vegetation changes would be apparent at the lava-substrate interface, while minimal changes would be detected at our sample site on the lava interior. Stand inventory data collected from the mixed-conifer woodland on the basalt interior and visual assessments of vegetation change from a nearby location at the lava edge supported our hypothesis. The mixed-methods approach provided us concurrent vegetation-dynamics data from two ecologically different locations on the EMNM lava flows. Tree-ring data suggested that the woodland structure of the interior Bandera Lava Flow changed little during the period of analysis. Meanwhile, repeat photographs revealed that trees at the boundary of the Bandera Lava Flow and the surrounding substrate might have succumbed to 20–21st century droughts or anthropogenic influences. The persistence of trees on the lava interior is likely linked to the inaccessible nature of the badlands and the ability of the porous basalt to store water during dry periods.

(2) The repeat-photography sequences produced by this study provide a record of fine-scale vegetation dynamics at one location on the Bandera Lava Flow and may suggest conditions at other sites along the edge of the Bandera Lava Flow.

Alton Lindsey's photographs provide a visual record of past conditions that can be used to complement forest-inventory analysis, dendrochronology, Geographic Information Systems, and other methods of ecological monitoring. Although the

photographs used in this study were subjectively chosen and do not represent all locations on the Bandera Lava Flow, our results agreed with previous studies that suggested the interior of the malpais insulates against drought and anthropogenic activities that alter stand structure and composition (Grissino-Mayer 1995; Grissino-Mayer and Swetnam 1997; Lewis 2003).

6.3 Crossdating and Dendroclimatic Potential of Rocky Mountain Juniper

(1) Tree-ring crossdating revealed that Rocky Mountain junipers growing on the Paxton Springs Malpais (PAX) produce distinct annual growth rings.

The PAX chronology is the first Rocky Mountain juniper chronology produced on the Colorado Plateau and only the fourth verified tree-ring chronology for the species (ITRDB 2011). A high average mean sensitivity value (0.53) indicates that the PAX chronology exhibits enough annual variability to detect fluctuations in environmental conditions. The PAX average interseries correlation (0.74) is statistically significant for confident crossdating. This value suggests a strong association among individual tree growth rates within the stand. Sufficient sampling and core inspection are needed to produce precisely dated tree-ring chronologies from Rocky Mountain juniper growing on the malpais of western New Mexico. Contorted growth forms and severely compressed growth rings complicated crossdating on most samples. However, 24 of the trees we sampled on the PAX of western New Mexico produced cores that were suitable for crossdating and chronology development. Dating was complicated by locally absent rings, which were typically contemporaneous with the narrowest rings on ponderosa pine (*Pinus ponderosa* Douglas ex P. Lawson and C. Lawson) and Douglas-fir (*Pseudotsuga*

menziesii (Mirb.) Franco) samples used in the Malpais Long Chronology (Grissino-Mayer 1995).

(2) Rocky Mountain juniper samples collected on the Paxton Springs Malpais have potential for use in dendroclimatic analyses.

Although most monthly response function coefficients were not significant, statistically significant correlations between the PAX chronology and monthly climate data for New Mexico Climate Division 1 support our hypothesis that Rocky Mountain junipers growing on the malpais of western New Mexico are suitable for dendroclimatic analyses. The strength of our crossdating ensures the necessary confidence to report climate-growth relationships. Correlation analyses did not reveal results identical to those identified in ponderosa pine and Douglas-fir at EMNM (Grissino-Mayer 1995) and ponderosa pine atop the Paxton Springs Crater (Rother 2010), but they did show similar seasonal trends.

(3) Rocky Mountain junipers at the PAX site are highly sensitive to climate factors that influence moisture availability during dry periods of the growing season.

Positive correlations between the PAX chronology and total precipitation for the local water year (previous 1 July–current 30 June) were statistically significant. Significant positive correlations were identified between monthly Palmer Drought Severity Index (PDSI) values (previous August–current December) and Rocky Mountain juniper radial growth at the PAX site. We also identified a positive relationship between the PAX chronology and monthly total precipitation for the previous October–current May. An inverse relationship was identified between radial growth and monthly mean

temperature during periods of the preceding year and current growing year. The inverse relationship between monthly mean temperature and annual radial growth is unique for the American Southwest.

(4) A strong positive correlation was identified between annual radial growth at the PAX site and total water year precipitation.

Grissino-Mayer (1995) found a very strong, positive relationship ($r = 0.75$; $P < 0.0001$) between local water year precipitation and the annual radial growth of ponderosa pine and Douglas-fir at EMNM. He interpreted the relationship to suggest that the trees were responding more to hydrological constraints than climatic factors due to the tendency of the porous basalt to retain water throughout the year, including during annual precipitation minima. Our PAX chronology was also positively correlated ($r = 0.53$; $P < 0.001$) with total water year precipitation for the malpais region. The relationship between water year precipitation and Rocky Mountain juniper growth at the PAX site further suggests the ability of trees growing on the basalt malpais to record environmental data that would be unavailable from Southwestern conifers growing on less-porous surfaces (Grissino-Mayer 1995).

(5) Positive correlations between monthly PDSI values and radial growth at the PAX site appeared to persist throughout the period of analysis, but temporal variability was detected in relationships between radial growth and both monthly total precipitation and monthly mean temperature.

We tested the persistence of relationships between Rocky Mountain juniper at the PAX site and climate variables selected from New Mexico Climate Division 1 using

moving interval correlation analysis and forward evolutionary interval analysis. The two methods did not produce identical results, nor did they indicate that all variables identified as significant in the initial correlation analyses persisted throughout the observation period. Despite noticeable discrepancies, the two tests of temporal stability did produce some agreement. Both methods indicated that monthly PDSI for the previous November to the current September was significantly correlated with radial growth throughout the period of observation. In contrast, relationships between monthly mean temperature and monthly total precipitation appeared less stable over time.

(6) Several possible explanations exist for the temporal instability of climate-growth relationships at the PAX site.

First, climate data from New Mexico Climate Division 1 is less spatially comprehensive during the early part of the instrumental record. Second, biological competition from other plants that inhabit the site (*e.g.,* shorter-lived quaking aspen) potentially disrupted the climate signal of sampled Rocky Mountain juniper during portions of the period of analysis. Third, fluctuations in broad-scale atmospheric-oceanic oscillations may influence climate-growth relationships at the site. Fourth, anthropogenic activity (*e.g.*, cutting branches for firewood) may explain some of the temporal variability in the relationships between Rocky Mountain juniper growth and local climate.

6.4 Pacific Teleconnections and Rocky Mountain Juniper Growth

(1) Sea-Surface Temperature (SST) data for the El Niño 3.4 region of the central Pacific Ocean were associated with annual radial growth in Rocky Mountain junipers at the PAX site.

We identified a significant ($P < 0.0001$) positive relationship between the annual growth index (1692–2006) for Rocky Mountain juniper at the PAX site and the composite index (Cook *et al.* 2008) of boreal winter (DJF) SSTs in the El Niño 3.4 region of the central Pacific Ocean. We also found a relationship between the PAX chronology and instrumental monthly mean SSTs for the El Niño 3.4 region of the central Pacific Ocean (1950–2007). The relationships we identified generally agreed with established ENSO teleconnections that influence monthly mean temperatures and monthly total precipitation values for western New Mexico that are significantly linked to annual radial tree growth. However, additional correlation analysis between instrumental annual mean SST data (1950–2006) did not produce a significant relationship at the PAX site. The results conflicted with previous research by Mo (2010) who concluded that positive relationships between SST conditions in the central equatorial Pacific Ocean and winter precipitation in the Southwest became more significant between 1962 and 2006.

(*2) The inconsistency of our results at the PAX site suggests that relationships between SSTs in the El Niño 3.4 region of the central Pacific Ocean and annual radial growth in sampled Rocky Mountain junipers are unstable.*

Instability in the SST and tree growth relationship could be related to periodic shifts in the Intertropical Convergence Zone (Haug *et al.* 2001; Sachs *et al.* 2009) that potentially reduce ENSO variability and subsequent climate teleconnections (Haug *et al.* 2001), allowing other abiotic and biotic factors to influence tree growth (Fritts 1976). Lower-frequency, broad-scale phenomena such as the Pacific Decadal Oscillation (PDO) and North Pacific Gyre Oscillation might influence relationships between SSTs in the El

Niño 3.4 region of the Pacific Ocean and annual radial growth in Rocky Mountain juniper (Mantua *et al.* 1997; Di Lorenzo *et al.* 2010). The accuracy of composite SST data, biological biases, and emergent global change effects (*i.e.*, global warming) may also contribute to inconsistent relationships between ENSO and Rocky Mountain juniper growth (McGregor *et al.* 2010).

(3) Persistent positive relationships between tree growth and the PDO index during the cool months prior to the current growing season suggest an association between SSTs in the northern Pacific Ocean and Rocky Mountain junipers at the PAX site.

Strengthening of the PDO-tree growth relationship at the PAX site is likely related to an intensification of the PDO phenomenon during the boreal cool season (Mantua *et al.* 1997; Newman *et al.* 2003). The association between higher cool-season SSTs in the eastern North Pacific Ocean and moisture advection into western New Mexico may explain the seasonal relationship between the PDO and tree growth. Increased atmospheric moisture during the cooler months produces cloud cover and increased precipitation, which aid tree growth during the subsequent growing season (Fritts 1976; Swetnam and Betancourt 1990). Stable relationships between PDO index values (1948–2007) during the cool months prior to the current growing season likely indicate a persistent link between SSTs in the North Pacific Ocean and annual radial growth in Rocky Mountain junipers at the PAX site. The start of significant positive correlations for the previous October, previous November, and current February during 1983 and 1984 may be related to the transition from the cool to the warm phase of the PDO during 1977 (Mantua *et al.* 1997).

(4) Positive relationships between monthly PNA index values and annual radial growth may result from the large distances between the PAX site and PNA centers of activity over the Pacific Northwest and southeastern United States.

Significant positive relationships between monthly PNA index values (current January, current March, and current June) and tree growth at the PAX site contradicted our hypothesis that Rocky Mountain juniper growth is negatively correlated with the PNA index. Previous studies suggested that the positive phase of the PNA is associated with decreased precipitation and warmer temperatures during the boreal cool season across much of western North America (Wallace and Gutzler 1981; Trouet and Taylor 2009). Warmer, drier cool-season conditions are not conducive to tree growth at the PAX site, leading us it hypothesize that PNA is negatively correlated with Rocky Mountain juniper growth at the PAX site. The positive relationships we identified between the PNA and annual radial growth at the PAX site do not suggest a clear seasonal signal. In particular, no winter pattern is apparent. Relationships between the annual radial growth at the PAX site and PNA do not appear synchronized with relationships among precipitation, temperature, and the PAX chronology. Unstable relationships between annual radial growth and monthly PNA data suggest the influence of ENSO, the PDO, or other oceanic-atmospheric teleconnections.

6.5 Recommended Future Research

(1) The continued use of repeat photography, complemented by additional vegetation inventories and dendroclimatological analysis, could clarify contemporary relationships

among drought, human activity, and vegetation dynamics on the malpais of western New Mexico and throughout the greater Southwest.

The current drought and projections of regional "drying" through the remainder of the 21st century (Seager *et al.* 2007; Hughes and Diaz 2008) raise questions concerning the future effects of climate change in Southwestern ecosystems (Baron *et al.* 2009). Existing studies suggest that the ongoing drought has already increased mortality rates in some Southwestern conifer species (Breshears *et al.* 2005; Allen *et al.* 2010). However, additional information is needed regarding vegetation dynamics in old-growth woodlands that are highly resistant to moisture stress (Shields and Crispin 1956; Fritts 1976; McDowell *et al.* 2008). Alton Lindsey's photographs of the mixed-conifer woodlands at EMNM are important sources for investigating vegetation changes across the spatial and ecological gradients of the volcanic badlands. The resilience of interior trees following periods of reduced precipitation suggests that the mixed-conifer woodlands of EMNM may persist on the porous lava flows despite a potential increase in regional aridity during future decades. Similarly, the remoteness and inaccessibility of the interior malpais will likely continue to minimize anthropogenic-induced tree mortality.

(2) Future dendroclimatic research on the malpais of western New Mexico should incorporate the old-growth Rocky Mountain junipers growing on the lava flows at EMNM and other locations across western North America.

Preliminary analysis of cores and cross-sections collected at EMNM suggests that many of the Rocky Mountain junipers are > 1,500 years old (Grissino-Mayer 1995). It is very likely that Rocky Mountain junipers growing on the lava flows of EMNM are also

sensitive to climate. Relationships between climate and the radial growth of Rocky Mountain junipers at EMNM could further substantiate our findings at the PAX site and encourage future research at other locations within the expansive distribution of the species. Capitalizing on the dendroclimatic potential of Rocky Mountain juniper would advance our understanding of climate-growth relationships in multiple ecosystems and strengthen the spatial and temporal resolution of the tree-ring record throughout much of western North America.

(3) Additional tree-ring chronologies are needed to conduct tests for spatial and temporal patterns in the response of Rocky Mountain juniper to Pacific teleconnections.

Our results indicate a high degree of dendroclimatic potential for Rocky Mountain juniper samples collected at the PAX site and additional locations on the volcanic badlands of western New Mexico. However, advancing the use of Rocky Mountain juniper in dendroclimatic research requires the establishment of tree-ring data sets beyond the malpais of western New Mexico. Existing Rocky Mountain juniper chronologies in Nevada, North Dakota, and South Dakota should be updated and assessed for dendroclimatic research. Identifying additional links between Pacific oceanic-atmospheric oscillations and Rocky Mountain juniper growth would expand the resources available to dendroclimatologists and improve our understanding of teleconnections between the Pacific Ocean and western North America.

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Appendix

Tree-Ring Data For The Paxton Springs Malpais Chronology (PAX)

This appendix contains COFECHA descriptive statistics (Part 7) and the ring-width measurements (precision of measurements = 0.001 mm) for the 24 samples included in the PAX chronology.

COFECHA Results for the PAX Chronology

PART 7: DESCRIPTIVE STATISTICS: 18:39 Thu 2

Seq	Series	Interval	No. Years	No. Segmt	No. Flags	Corr with Master	Unfiltered Mean msmt	Unfiltered Max msmt	Unfiltered Std dev	Unfiltered Auto corr	Filtered Mean sens	Filtered Max value	Filtered Std dev	Filtered Auto corr	AR ()
1	PAX_10	B 1949 2007	59	3	0	.769	.76	1.40	.317	.280	.457	2.58	.551	-.047	1
2	PAX_11	B 1909 2007	99	5	0	.692	.28	.69	.134	.217	.499	2.71	.535	-.032	1
3	PAX_13	A 1883 2007	125	6	0	.806	.62	1.51	.290	.497	.445	2.75	.502	-.041	1
4	PAX_17	B 1877 2007	131	7	0	.857	.68	1.54	.295	.222	.524	2.49	.382	-.016	1
5	PAX_33	A 1857 2007	151	8	0	.808	.47	1.28	.283	.711	.478	2.47	.372	-.038	1
6	PAX_42	B 1823 2007	185	9	0	.698	.56	1.58	.256	.399	.414	2.49	.293	-.034	1
7	PAX_46	B 1831 2007	177	9	0	.712	.47	1.38	.283	.563	.490	2.33	.281	-.028	1
8	PAX_52	A 1940 2007	68	3	1	.564	1.15	2.31	.611	.444	.530	2.32	.469	-.036	1
9	PAX_56	A 1947 2007	61	3	0	.525	.97	2.10	.506	.741	.353	2.66	.552	.018	1
10	PAX_59	B 1940 2007	68	3	0	.590	.62	1.88	.373	.693	.382	2.50	.393	-.026	1
11	PAX_58	C 1944 2007	64	3	1	.518	.43	1.52	.323	.702	.429	2.71	.473	-.032	1
12	PAX_43	A 1815 2007	193	10	0	.871	.36	.99	.146	.271	.450	2.68	.413	-.034	1
13	PAX_27	B 1703 2007	305	15	0	.697	.44	2.42	.310	.504	.595	2.77	.435	.000	1
14	PAX_41	A 1692 2007	316	15	0	.713	.27	.82	.139	.317	.560	2.48	.383	-.045	1
15	PAX_22	C 1832 2007	176	9	0	.885	.44	1.10	.219	.355	.490	2.62	.425	-.051	1
16	PAX_45	B 1777 2007	231	12	2	.716	.44	1.65	.283	.659	.478	2.72	.363	-.007	1
17	PAX_40	A 1890 2007	118	6	0	.753	.33	.80	.169	.262	.598	2.63	.425	.028	1
18	PAX_14	C 1840 2007	168	8	0	.675	.45	1.26	.246	.577	.451	2.62	.364	-.048	1
19	PAX_36	A 1771 2007	237	12	0	.770	3.82	9.55	2.049	.248	.677	2.54	.453	-.032	1
20	PAX_19	E 1900 2007	108	5	0	.748	.45	.96	.214	.531	.407	2.46	.425	-.060	1
21	PAX_49	A 1870 2007	138	7	0	.732	.25	.61	.131	.136	.629	2.44	.395	-.053	1
22	PAX_37	A 1744 2007	264	13	0	.782	.43	1.01	.225	.060	.701	2.56	.434	.006	1
23	PAX_07	A 1941 2007	67	3	0	.751	.38	1.39	.281	.238	.710	2.66	.618	-.055	1
24	PAX_39	A 1940 2007	68	3	0	.703	.65	1.72	.349	.344	.600	2.63	.571	-.026	1
Total or mean:			3577	177	4	.740	.69	9.55	.371	.396	.531	2.77	.416	-.027	

Ring-Width Measurements for the PAX Chronology

PAX_10	B1949	1302									
PAX_10	B1950	666	285	723	706	837	748	734	404	1262	427
PAX_10	B1960	794	741	785	631	562	1071	895	762	885	824
PAX_10	B1970	1310	225	819	962	430	901	794	807	814	1258
PAX_10	B1980	909	1350	921	908	1102	1315	1404	1127	1114	425
PAX_10	B1990	665	812	918	754	733	856	209	622	768	790
PAX_10	B2000	356	712	210	441	461	355	0	328	-9999	
PAX_11	B1909	168									
PAX_11	B1910	168	274	169	316	337	211	295	337	146	439
PAX_11	B1920	314	315	210	189	400	0	338	338	247	112
PAX_11	B1930	148	99	323	232	63	507	232	232	126	273
PAX_11	B1940	189	337	273	210	252	253	148	190	421	377
PAX_11	B1950	333	0	367	97	112	97	219	309	303	110
PAX_11	B1960	535	431	446	344	693	503	402	141	142	323
PAX_11	B1970	346	510	371	394	229	501	212	290	397	668
PAX_11	B1980	398	440	397	376	331	472	472	410	246	172
PAX_11	B1990	193	285	326	265	162	299	89	356	275	436
PAX_11	B2000	135	200	91	198	187	207	375	213	-9999	
PAX_13	A1883	871	807	717	387	611	427	305			
PAX_13	A1890	327	492	268	309	62	639	206	391	354	186
PAX_13	A1900	65	382	328	143	163	474	606	1083	416	334
PAX_13	A1910	397	627	543	250	374	621	881	695	467	732
PAX_13	A1920	893	686	393	269	579	125	481	629	567	315

PAX_13	A1930	667	436	712	626	250	768	502	609	314	458
PAX_13	A1940	498	620	578	517	455	519	483	738	676	950
PAX_13	A1950	722	95	738	567	294	105	675	908	444	190
PAX_13	A1960	823	759	802	550	761	846	843	907	949	797
PAX_13	A1970	1265	633	908	715	629	1280	944	862	945	1072
PAX_13	A1980	1031	1119	1196	791	1282	1515	1099	664	426	633
PAX_13	A1990	756	963	593	998	588	709	408	1155	1083	908
PAX_13	A2000	507	613	380	761	550	930	526	553	-9999	
PAX_17	B1877	1163	519	474							
PAX_17	B1880	68	215	775	791	841	885	546	828	894	519
PAX_17	B1890	788	847	645	730	269	951	384	803	1030	316
PAX_17	B1900	180	811	373	336	210	588	889	1130	880	543
PAX_17	B1910	693	1155	851	391	785	830	1017	567	508	875
PAX_17	B1920	787	528	589	392	569	71	688	863	534	251
PAX_17	B1930	623	688	753	856	332	921	649	777	436	523
PAX_17	B1940	879	863	820	462	615	554	334	540	976	1065
PAX_17	B1950	398	0	801	440	282	89	384	312	646	310
PAX_17	B1960	894	935	1030	524	753	984	1026	551	773	588
PAX_17	B1970	887	190	455	876	383	1537	825	942	734	1182
PAX_17	B1980	1478	1138	933	831	951	1053	914	1085	842	391
PAX_17	B1990	461	773	1042	659	1070	961	213	914	928	667
PAX_17	B2000	320	767	101	677	421	617	767	449	-9999	
PAX_33	A1857	1136	1096	865							
PAX_33	A1860	887	740	888	978	692	719	1098	1284	1197	921
PAX_33	A1870	877	417	732	649	625	844	463	1118	968	736
PAX_33	A1880	231	442	1052	1009	821	842	526	821	845	824
PAX_33	A1890	697	844	654	674	484	839	420	673	602	354
PAX_33	A1900	105	703	393	248	249	436	581	1046	783	554
PAX_33	A1910	489	553	443	591	763	713	836	493	443	507
PAX_33	A1920	675	444	294	210	357	84	336	399	379	230
PAX_33	A1930	418	357	544	623	352	591	387	542	0	354
PAX_33	A1940	396	396	606	523	450	346	308	164	385	325
PAX_33	A1950	524	0	204	420	146	59	346	345	381	85
PAX_33	A1960	396	324	348	292	229	267	257	178	258	316
PAX_33	A1970	334	0	178	189	84	204	278	263	296	358
PAX_33	A1980	278	336	175	282	285	443	377	418	356	75
PAX_33	A1990	212	243	303	202	380	289	67	326	322	346
PAX_33	A2000	131	216	59	262	293	213	0	352	-9999	
PAX_42	B1823	21	1034	1036	1142	549	1226	676			
PAX_42	B1830	1330	1075	1109	961	803	718	738	951	971	652
PAX_42	B1840	612	570	401	634	423	528	612	169	507	740
PAX_42	B1850	570	422	528	613	148	423	401	550	507	275
PAX_42	B1860	507	338	507	529	401	444	613	498	432	465
PAX_42	B1870	423	211	381	465	382	506	381	1035	549	634
PAX_42	B1880	317	634	909	825	1142	1577	782	1353	973	683
PAX_42	B1890	716	885	648	624	489	740	439	608	526	315
PAX_42	B1900	232	695	463	399	484	610	737	1153	851	560
PAX_42	B1910	562	690	353	372	395	450	572	477	246	375
PAX_42	B1920	414	559	247	248	422	184	369	533	470	319
PAX_42	B1930	479	354	437	416	271	539	371	428	0	392
PAX_42	B1940	309	392	598	492	452	412	411	328	486	462
PAX_42	B1950	502	181	544	324	305	221	688	873	611	265
PAX_42	B1960	911	797	710	516	349	900	403	770	728	783
PAX_42	B1970	972	204	608	717	311	727	499	501	608	883
PAX_42	B1980	485	623	721	464	506	653	694	695	436	219
PAX_42	B1990	401	465	592	528	740	634	295	886	526	716
PAX_42	B2000	380	528	190	675	527	611	0	634	-9999	
PAX_46	B1831	464	498	498	622	564	419	377	415	248	
PAX_46	B1840	410	523	552	272	351	311	435	0	580	498
PAX_46	B1850	477	480	398	523	460	442	296	422	506	232
PAX_46	B1860	258	102	465	258	105	291	359	465	486	422
PAX_46	B1870	361	165	485	338	359	401	127	584	366	298
PAX_46	B1880	0	211	441	465	592	507	359	507	486	275

PAX_46	B1890	465	676	359	380	127	464	316	337	464	190
PAX_46	B1900	0	459	259	121	106	238	379	590	421	315
PAX_46	B1910	249	406	296	251	426	338	443	338	296	380
PAX_46	B1920	253	336	274	209	265	0	197	208	156	100
PAX_46	B1930	238	286	215	208	158	269	377	341	253	206
PAX_46	B1940	173	189	273	333	250	270	169	1142	881	1384
PAX_46	B1950	1083	0	567	289	388	0	767	730	624	0
PAX_46	B1960	1149	839	970	760	608	567	841	421	927	1139
PAX_46	B1970	1329	844	1281	691	647	1131	1005	811	729	1043
PAX_46	B1980	897	1085	626	748	624	1008	935	893	817	548
PAX_46	B1990	717	761	694	507	781	718	613	674	506	673
PAX_46	B2000	461	665	273	559	480	444	0	672	-9999	
PAX_52	A1940	1078	1592	1572	1607	1208	188	249	1565	1090	1622
PAX_52	A1950	369	758	1669	1653	1843	1704	1729	1404	1304	911
PAX_52	A1960	1245	1663	1761	2167	1975	2314	2292	0	1356	1330
PAX_52	A1970	1400	863	1720	1840	0	1997	2022	1770	1551	1648
PAX_52	A1980	1518	1359	1194	1647	1462	1140	1156	505	672	0
PAX_52	A1990	871	843	832	754	823	270	114	950	700	720
PAX_52	A2000	369	560	280	951	520	687	126	871	-9999	
PAX_56	A1947	1343	1210	923							
PAX_56	A1950	545	206	2095	1825	2030	1395	1543	1585	1361	1475
PAX_56	A1960	1261	1116	1034	925	1039	1727	1601	1697	1349	1684
PAX_56	A1970	1795	1245	1312	943	971	1034	966	1099	1099	1246
PAX_56	A1980	1035	1350	844	970	844	929	951	591	675	400
PAX_56	A1990	422	549	800	377	813	709	314	628	565	816
PAX_56	A2000	417	395	114	114	393	269	0	327	-9999	
PAX_59	B1940	902	1010	564	937	646	832	1188	1428	1273	1881
PAX_59	B1950	1302	574	1631	941	1320	1361	1128	973	662	739
PAX_59	B1960	795	820	673	442	540	730	586	442	421	401
PAX_59	B1970	401	117	347	295	315	419	272	377	557	714
PAX_59	B1980	380	444	550	338	486	570	591	382	253	147
PAX_59	B1990	338	400	505	463	440	544	125	681	373	701
PAX_59	B2000	227	290	102	454	349	410	513	384	-9999	
PAX_58	C1944	1518	1204	936	1249	1089	1096				
PAX_58	C1950	836	275	639	569	628	564	573	877	806	0
PAX_58	C1960	1013	794	663	450	345	266	507	317	528	338
PAX_58	C1970	381	402	232	168	114	182	242	298	369	275
PAX_58	C1980	275	194	297	311	241	159	252	273	231	185
PAX_58	C1990	200	144	224	473	211	232	97	177	204	437
PAX_58	C2000	204	254	158	388	420	397	26	416	-9999	
PAX_43	A1815	273	316	344	225	147					
PAX_43	A1820	358	253	189	357	314	460	439	230	526	253
PAX_43	A1830	379	506	315	589	526	379	358	358	423	338
PAX_43	A1840	380	464	232	379	422	317	381	85	430	500
PAX_43	A1850	402	296	465	370	116	444	296	422	465	275
PAX_43	A1860	380	190	338	254	211	423	359	486	526	484
PAX_43	A1870	358	189	314	376	442	463	295	633	380	271
PAX_43	A1880	88	275	570	486	591	676	380	506	421	210
PAX_43	A1890	464	568	463	442	190	422	317	359	338	282
PAX_43	A1900	56	402	338	233	190	317	486	994	613	507
PAX_43	A1910	296	528	324	267	359	380	507	465	338	380
PAX_43	A1920	486	317	296	275	380	127	317	289	331	158
PAX_43	A1930	321	211	275	296	169	381	296	345	246	169
PAX_43	A1940	232	260	309	190	211	231	127	295	274	439
PAX_43	A1950	217	0	372	232	146	0	487	422	591	359
PAX_43	A1960	591	634	507	380	465	507	634	423	486	571
PAX_43	A1970	677	190	317	444	211	613	422	379	378	504
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PAX_43	A1990	281	251	481	418	522	505	167	661	323	402
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PAX_27	B1703	620	0	949	945	822	847	1017			
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PAX_27	B1720	971	957	649	589	81	517	624	647	422	164

PAX_27	B1730	546	474	1062	585	1452	498	548	638	1099	423
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PAX_27	B1750	980	934	565	672	968	737	738	486	675	483
PAX_27	B1760	463	126	505	463	800	441	670	670	980	719
PAX_27	B1770	851	1417	909	613	654	490	540	437	576	591
PAX_27	B1780	380	402	242	493	699	270	270	372	227	516
PAX_27	B1790	270	498	521	504	291	588	400	436	498	325
PAX_27	B1800	111	519	291	766	363	98	0	563	0	516
PAX_27	B1810	511	451	493	332	311	398	442	567	399	98
PAX_27	B1820	63	427	91	98	377	354	125	48	474	271
PAX_27	B1830	354	441	589	337	631	316	147	358	316	358
PAX_27	B1840	358	439	146	0	439	0	188	0	314	270
PAX_27	B1850	602	541	646	356	188	521	484	294	336	400
PAX_27	B1860	253	380	105	366	309	357	547	525	586	670
PAX_27	B1870	296	0	264	452	715	592	388	746	524	283
PAX_27	B1880	0	121	296	858	867	620	323	504	262	323
PAX_27	B1890	383	484	305	185	103	311	249	308	498	126
PAX_27	B1900	0	421	231	92	84	372	439	794	438	374
PAX_27	B1910	308	516	436	229	413	310	434	349	103	370
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PAX_27	B1930	348	159	237	223	131	380	380	359	120	283
PAX_27	B1940	290	275	332	253	279	239	150	392	334	631
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PAX_27	B1960	575	420	613	280	248	493	137	232	211	169
PAX_27	B1970	148	106	180	178	84	421	253	359	275	485
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PAX_27	B1990	242	401	358	356	481	397	167	825	338	528
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PAX_41	A1710	253	528	485	507	569	458	91	444	421	526
PAX_41	A1720	693	544	356	398	313	374	457	272	0	83
PAX_41	A1730	292	292	209	105	354	63	104	262	70	0
PAX_41	A1740	208	311	436	332	289	534	699	411	0	516
PAX_41	A1750	207	290	125	188	292	167	125	145	263	214
PAX_41	A1760	182	49	225	227	346	143	205	267	228	270
PAX_41	A1770	498	478	520	168	249	248	289	268	226	247
PAX_41	A1780	247	343	81	326	467	101	183	345	81	204
PAX_41	A1790	248	187	144	267	165	249	187	290	123	287
PAX_41	A1800	328	245	286	286	407	264	122	184	340	272
PAX_41	A1810	203	223	271	215	321	283	400	143	126	81
PAX_41	A1820	174	290	47	228	109	237	159	203	228	66
PAX_41	A1830	215	356	402	359	397	332	98	232	293	237
PAX_41	A1840	306	252	95	196	106	170	135	0	163	270
PAX_41	A1850	411	592	279	371	437	565	345	363	326	280
PAX_41	A1860	210	136	269	230	134	207	252	329	504	484
PAX_41	A1870	289	136	304	278	342	349	194	523	355	305
PAX_41	A1880	71	161	256	516	552	538	280	380	340	420
PAX_41	A1890	336	464	330	247	164	438	161	133	224	225
PAX_41	A1900	77	420	167	83	125	231	462	711	479	354
PAX_41	A1910	335	504	210	105	210	210	505	141	85	301
PAX_41	A1920	352	211	155	106	233	42	232	296	253	84
PAX_41	A1930	211	169	401	232	162	387	253	275	0	275
PAX_41	A1940	275	247	387	296	232	211	211	105	253	238
PAX_41	A1950	372	0	231	224	90	0	317	274	316	0
PAX_41	A1960	337	293	399	315	210	316	275	359	282	204
PAX_41	A1970	335	91	204	259	133	386	168	126	377	500
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PAX_41	A2000	207	281	51	335	250	250	0	304	-9999	
PAX_22	C1832	718	864	802	549	486	760	803	683		
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PAX_22	C1850	486	359	676	613	148	634	528	571	591	359

PAX_22	C1860	548	232	465	423	190	486	507	655	486	550
PAX_22	C1870	359	141	366	268	451	338	253	613	381	381
PAX_22	C1880	85	295	506	548	633	613	401	507	423	423
PAX_22	C1890	233	507	296	261	141	592	275	359	392	106
PAX_22	C1900	42	359	232	127	91	379	378	740	338	430
PAX_22	C1910	289	400	316	210	379	359	395	195	97	375
PAX_22	C1920	312	271	208	210	252	63	337	315	294	189
PAX_22	C1930	336	293	418	418	146	439	376	294	231	231
PAX_22	C1940	252	378	315	252	231	252	168	274	400	401
PAX_22	C1950	148	0	589	190	147	84	315	315	464	126
PAX_22	C1960	549	464	443	400	399	673	692	400	485	485
PAX_22	C1970	630	169	463	568	168	629	399	419	482	820
PAX_22	C1980	649	794	502	666	734	866	1095	866	675	399
PAX_22	C1990	544	648	417	626	429	840	312	822	716	816
PAX_22	C2000	332	843	315	799	505	672	0	802	-9999	
PAX_45	B1777	1158	902	1004							
PAX_45	B1780	938	964	644	1435	1646	654	772	1538	1073	1122
PAX_45	B1790	1129	958	688	716	448	560	608	499	402	527
PAX_45	B1800	724	348	398	650	753	670	302	444	801	758
PAX_45	B1810	642	726	839	593	852	966	1016	699	580	379
PAX_45	B1820	570	507	309	676	497	727	679	300	946	423
PAX_45	B1830	638	978	1021	1012	1010	608	579	555	872	710
PAX_45	B1840	731	656	271	379	275	253	338	0	317	421
PAX_45	B1850	336	316	444	339	84	294	357	359	550	296
PAX_45	B1860	337	211	274	285	232	346	423	486	502	583
PAX_45	B1870	502	230	501	451	410	446	322	689	490	387
PAX_45	B1880	113	174	374	586	701	639	351	434	457	311
PAX_45	B1890	250	390	332	303	82	287	226	309	328	185
PAX_45	B1900	81	411	390	225	143	326	492	1129	581	521
PAX_45	B1910	371	486	482	314	376	439	419	210	63	147
PAX_45	B1920	147	294	189	104	83	230	188	376	125	190
PAX_45	B1930	103	167	168	317	170	125	566	315	294	168
PAX_45	B1940	231	251	315	336	210	169	210	105	211	338
PAX_45	B1950	233	148	381	254	127	0	275	317	401	148
PAX_45	B1960	359	359	317	253	295	549	273	146	419	463
PAX_45	B1970	422	0	232	266	199	445	211	83	380	759
PAX_45	B1980	738	170	504	548	630	634	527	254	465	107
PAX_45	B1990	231	528	211	756	189	380	62	759	424	631
PAX_45	B2000	210	329	84	432	254	234	42	127	-9999	
PAX_40	A1890	145	208	146	165	240	136	126	211	232	84
PAX_40	A1900	147	125	338	78	43	209	314	565	315	378
PAX_40	A1910	252	168	462	695	316	801	567	609	423	465
PAX_40	A1920	655	423	275	254	471	77	339	430	373	211
PAX_40	A1930	548	274	481	587	168	547	294	397	293	326
PAX_40	A1940	464	567	463	270	317	291	228	416	479	399
PAX_40	A1950	146	0	470	96	83	0	272	252	358	93
PAX_40	A1960	455	273	380	127	347	331	505	254	359	254
PAX_40	A1970	186	0	267	325	147	374	232	308	277	757
PAX_40	A1980	359	423	402	613	402	676	523	340	366	155
PAX_40	A1990	357	312	500	396	523	419	147	503	432	554
PAX_40	A2000	213	295	131	423	333	350	0	328	-9999	
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PAX_14	C1850	190	275	380	420	338	169	302	201	258	232
PAX_14	C1860	401	286	163	211	84	126	142	159	263	247
PAX_14	C1870	184	53	168	127	211	211	127	529	232	304
PAX_14	C1880	49	154	141	281	338	528	211	380	295	189
PAX_14	C1890	336	441	296	296	127	253	211	211	380	380
PAX_14	C1900	156	436	401	268	218	444	769	1259	1052	528
PAX_14	C1910	379	610	169	251	504	637	905	688	357	464
PAX_14	C1920	676	613	380	359	169	92	309	571	571	381
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PAX_14	C1940	402	613	592	443	443	549	423	571	676	740
PAX_14	C1950	592	0	550	465	374	49	589	655	550	169

PAX_14	C1960	592	527	610	631	590	697	717	612	592	761
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PAX_14	C1980	951	740	909	845	908	422	824	950	712	441
PAX_14	C1990	484	792	480	727	888	709	396	816	855	945
PAX_14	C2000	442	724	345	723	487	782	57	703	-9999	
PAX_36	A1771	812	461	74	319	333	536	149	323	450	
PAX_36	A1780	294	422	95	750	624	77	0	250	571	386
PAX_36	A1790	184	442	333	445	145	336	168	400	444	445
PAX_36	A1800	358	253	357	297	723	471	56	493	492	497
PAX_36	A1810	0	282	308	254	376	587	714	773	366	168
PAX_36	A1820	337	263	74	296	155	246	83	0	462	0
PAX_36	A1830	359	253	515	478	611	380	253	276	526	662
PAX_36	A1840	640	725	327	691	643	760	714	47	628	955
PAX_36	A1850	623	511	465	457	161	519	441	522	501	312
PAX_36	A1860	647	107	342	369	110	407	605	526	570	908
PAX_36	A1870	545	183	514	608	500	439	376	810	638	531
PAX_36	A1880	69	295	720	716	759	524	442	698	486	613
PAX_36	A1890	592	586	513	474	160	723	355	423	625	281
PAX_36	A1900	685	295	176	162	0	437	452	803	576	432
PAX_36	A1910	338	464	718	507	677	550	655	481	323	613
PAX_36	A1920	513	267	254	169	275	44	633	380	317	148
PAX_36	A1930	422	326	497	464	0	528	422	421	0	253
PAX_36	A1940	348	391	422	357	368	246	246	170	286	348
PAX_36	A1950	423	0	190	232	0	124	297	126	358	0
PAX_36	A1960	401	401	485	232	400	335	420	84	253	274
PAX_36	A1970	317	0	233	232	0	373	296	197	232	486
PAX_36	A1980	274	252	337	379	303	457	465	464	290	111
PAX_36	A1990	275	232	655	338	718	340	85	588	263	470
PAX_36	A2000	137	369	43	430	338	507	0	508	-9999	
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PAX_19	E1910	557	373	296	465	486	528	338	422	0	422
PAX_19	E1920	464	379	252	178	280	88	273	399	357	188
PAX_19	E1930	292	334	376	521	229	376	381	379	338	317
PAX_19	E1940	401	464	444	444	232	254	211	254	444	465
PAX_19	E1950	338	0	591	379	377	188	459	503	567	338
PAX_19	E1960	591	650	670	461	443	549	613	317	613	507
PAX_19	E1970	546	106	489	338	233	548	467	422	738	697
PAX_19	E1980	906	504	714	569	632	775	817	777	861	419
PAX_19	E1990	631	806	607	464	844	945	482	918	960	844
PAX_19	E2000	474	620	372	600	644	623	125	594	-9999	
PAX_49	A1870	308	237	106	126	84	232	106	528	317	148
PAX_49	A1880	0	0	211	423	611	613	463	198	287	380
PAX_49	A1890	254	190	381	191	126	296	100	301	148	127
PAX_49	A1900	107	92	247	85	141	289	351	507	464	337
PAX_49	A1910	253	441	358	231	231	273	357	231	126	230
PAX_49	A1920	334	229	230	230	292	0	292	334	231	105
PAX_49	A1930	270	292	280	286	0	387	204	318	0	133
PAX_49	A1940	223	261	310	268	180	213	287	131	351	319
PAX_49	A1950	474	0	270	347	200	54	216	207	282	84
PAX_49	A1960	370	319	241	231	271	363	381	184	220	227
PAX_49	A1970	90	41	178	225	89	264	122	163	150	385
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PAX_37	A1744	589	846	634	950	0	1015				
PAX_37	A1750	155	507	162	254	972	422	465	162	930	486
PAX_37	A1760	282	0	500	282	588	399	730	585	544	909
PAX_37	A1770	776	645	771	266	429	370	262	200	395	362
PAX_37	A1780	429	736	184	797	817	233	491	655	84	540
PAX_37	A1790	402	422	591	421	338	633	423	587	589	547
PAX_37	A1800	463	250	372	290	935	622	0	146	667	479
PAX_37	A1810	605	293	500	354	542	688	523	481	332	105
PAX_37	A1820	458	167	62	475	374	353	339	0	419	0

PAX_37	A1830	469	237	647	703	700	388	374	314	441	541
PAX_37	A1840	615	430	105	0	424	229	357	0	456	699
PAX_37	A1850	693	443	400	478	527	501	504	632	555	296
PAX_37	A1860	324	0	120	423	430	437	712	683	655	564
PAX_37	A1870	345	84	422	402	465	464	252	866	399	531
PAX_37	A1880	76	224	540	758	601	462	347	441	273	417
PAX_37	A1890	592	551	425	463	163	611	357	405	486	162
PAX_37	A1900	0	524	199	86	154	407	658	1009	640	320
PAX_37	A1910	271	766	417	397	561	542	601	455	100	433
PAX_37	A1920	635	234	274	162	296	0	350	580	306	111
PAX_37	A1930	403	287	459	477	0	164	813	360	0	560
PAX_37	A1940	220	381	322	412	531	397	258	317	138	353
PAX_37	A1950	485	0	615	315	568	206	495	268	537	0
PAX_37	A1960	667	565	586	335	650	583	602	166	747	602
PAX_37	A1970	481	0	336	284	140	993	315	364	561	843
PAX_37	A1980	590	462	589	495	428	735	546	631	296	127
PAX_37	A1990	253	358	760	633	527	546	91	795	554	538
PAX_37	A2000	208	481	0	516	382	228	0	646	-9999	
PAX_07	A1941	575	1244	1395	803	127	169	1181	273	352	
PAX_07	A1950	245	99	505	568	878	0	771	418	784	0
PAX_07	A1960	604	456	354	460	903	572	425	124	393	523
PAX_07	A1970	583	83	208	461	126	394	118	205	295	465
PAX_07	A1980	274	338	274	297	330	393	490	317	486	113
PAX_07	A1990	260	211	359	317	317	311	92	346	264	325
PAX_07	A2000	135	247	99	302	182	227	0	319	-9999	
PAX_39	A1940	570	1058	556	681	373	749	1414	1717	801	1102
PAX_39	A1950	323	82	365	251	337	527	757	972	570	0
PAX_39	A1960	917	468	881	525	672	1240	1509	831	863	520
PAX_39	A1970	858	295	165	776	400	1264	971	910	642	1081
PAX_39	A1980	838	880	642	494	531	788	1058	990	753	258
PAX_39	A1990	345	466	566	547	606	637	211	827	345	786
PAX_39	A2000	313	556	186	416	291	499	0	562	-9999	

Vita

Mark Daniel Spond was born to Daniel and Mary Spond on April 7, 1980 in Little Rock, Arkansas. Mark has one older sister, Katherine (Katie), one older brother, Matthew (Matt), and one younger brother, Michael. Daniel (B.S.E. Vanderbilt 1969, M.S.E. Tennessee 1975) and Mary (B.B.A. St. Edward's 1973) were committed to providing a quality education for their children. Mark and his three siblings attended Catholic elementary and high schools in the Little Rock area where they received outstanding preparation for college. Mark developed much of his passion for the natural world while visiting national parks on family vacations. This interest grew during his time as a Boy Scout. He achieved the rank of Eagle Scout in 1996 and went on to work at Philmont Scout Ranch in Cimarron, New Mexico for four summers and one "off season." Mark also served as a Student Conservation Association volunteer at Arches National Park in southeastern Utah, and as an intern at Little Rock (Arkansas) Central High School National Historic Site. Mark was awarded the Bachelor of Arts degree (History) from the University of Arkansas at Little Rock in 2003 and the Master of Arts degree (Geography) from the University of Arkansas in 2007. Upon completion of the Doctorate of Philosophy degree (Geography) at the University of Tennessee, Mark will join his wife, Dr. Saskia van de Gevel, as a faculty member at Appalachian State University in Boone, North Carolina.