

Stand Dynamics of a Unique Pygmy Forest,
El Malpais National Monument, New Mexico, U.S.A.

A Thesis Presented for the
Master of Science
Degree
The University of Tennessee, Knoxville

Sarah Jones Wayman

May 2015

Copyright © Sarah Jones Wayman

All rights reserved

ACKNOWLEDGMENTS

I would like to express my deep appreciation to my advisor and mentor, Dr. Henri Grissino-Mayer. He has a passion for all students to learn, and he provided me many opportunities to advance my skills in science. I appreciate the time Dr. Grissino-Mayer took to offer advice, brain-storm for this research, edit and make countless revisions, and write letters of recommendation. I would like to thank Henri personally for believing in me and pushing me to pursue a Master of Science degree. I could not have done this without his invaluable guidance and support.

I would also like to thank my committee members, Drs. Sally Horn and Yingkui Li. I appreciate their knowledge and time in helping revise this thesis. Both have been a positive support throughout the development of this research. I would like to thank the members of the Laboratory of Tree-Ring Science—Niki Garland, Grant Harley, Alex Pilote, Dorothy Rosene, Alex Dye, Savannah Collins, and Maegen Rochner—whose friendship and encouragement gave me confidence in my abilities as a dendrochronologist. I especially thank Lauren Stachowiak and Elizabeth Schneider for their motivation and help in revising my thesis. I greatly appreciate all the field assistance from Niki Garland, Clint Wayman, Grant Harley, Pixi Pickthall, Alex Pilote, SallyRose Anderson, Ebony Lemons, James Ensley, Robert Bastic of El Malpais National Monument, and El Malpais volunteer Lara Lehman. I also thank Ebony Lemons and Maria Owens for their assistance in lab work.

I am thankful for financial support provided by the Western National Parks Association, and the Bruce Painter and Eva Woody Seaton Graduate Fellowship from the Graduate School at

the University of Tennessee. I am very grateful to the College of Arts and Sciences and Department of Geography for the financial support I received as a graduate teaching assistant. I will always appreciate the experience to teach students and be a part of the path they take to find a passion.

Finally, I would like to thank my family and friends for their constant support during my time as a graduate student. My husband, Clint Wayman, and my friend, Jessica Elkins, have encouraged me to believe in myself, even when it seemed beyond my capabilities. My siblings, Carin Brown and Wesley Jones, and friends, Alex Blackwelder, Laura Cutler, Bethany Priode, Meredith Wayman, and others have all been there to offer pep talks along the way. My parents, Randy and Trudy Jones, have gone out of their way to support any endeavor I have undertaken, and I would not be where I am today without their gracious help and unwavering love. To them I am forever grateful.

DEDICATION

This thesis is dedicated to my husband, Clint Marshall Wayman. Without his motivating words and positive outlook, I would not have been able to complete this work. Thank you, Clint, for always being there for me.

With Love,

Sarah Jane

ABSTRACT

The pygmy forest is a rare ecosystem found on the 3000-year-old McCarty's basalt flow in El Malpais National Monument, New Mexico. The forest is dominated by contorted, short-statured forms of ponderosa pine (*Pinus ponderosa* Douglas ex C. Lawson) and piñon pine (*Pinus edulis* Engelm.). The purpose of this research was to investigate the history of this unique forest and attempt to isolate reasons why the trees grow in such peculiar forms. We first used tree-ring patterns from 32 ponderosa pines growing on a sandstone kipuka located within the McCarty's flow as a proxy for past precipitation, and used this to identify linkages between climate and tree establishment. We collected 286 cores in seven plots in the pygmy forest to analyze species composition, age distribution, and establishment dates, and also tallied seedlings and saplings to project the future forest composition. Climate response analyses revealed that tree growth responds positively to precipitation during the pre-monsoonal months of January through May. The pines are sensitive to drought years, and we found three major drought episodes since the early 1800s. We found that the oldest trees in the pygmy forest were junipers aged at least 400 years, and that no forest likely existed until approximately A.D. 1600. The forest is regenerating mostly with Gambel oak (*Quercus gambelii* Nutt.) and piñon pine. We found only 10 seedlings of ponderosa pine. Disturbance features observed on the trees, such as lightning scars, dead leaders, and "stagheaded" shapes in the crown, indicated that the peculiar growth forms of the pygmy trees are likely the result of dieback from one or more lightning strikes and new apical dominance from branches of the tree. Lightning storms are known to occur more often over the dark basalt than over the surrounding sandstone areas,

and the McCarty's flow may have properties that enhance convectional uplift and increase storm activity.

TABLE OF CONTENTS

1. INTRODUCTION.....	1
1.1. Background.....	1
1.2. Applications of Dendrochronology	3
1.3. Research Synopsis.....	6
1.4. Research Questions	8
2. LITERATURE REVIEW	9
2.1. Stand History Research in the American Southwest.....	9
2.2. Research at El Malpais National Monument	12
2.3. Lightning Strikes and Tree Growth	16
3. STAND DYNAMICS OF A UNIQUE PYGMY FOREST, EL MALPAIS NATIONAL MONUMENT, NEW MEXICO, U.S.A.	20
3.1. Abstract	20
3.2. Introduction.....	21
3.3. Study Site	25
3.4. Methods	28
3.4.1. Field Techniques at Middle Kipuka	28
3.4.2. Field Techniques at the Pygmy Forest.....	28
3.4.3. Laboratory Methods	30
3.4.4. Climate Reconstruction.....	31
3.4.5. Stand Dynamics	32
3.5. Results	33
3.5.1. Chronology Development	33
3.5.2. Climate Reconstruction.....	33
3.5.3. Stand Dynamics	34
3.6. Discussion.....	41
3.6.1. Middle Kipuka	41
3.6.2. Pygmy Forest.....	42
3.7. Conclusions	46
4. CONCLUSIONS AND FUTURE RESEARCH	49
4.1. Major Conclusions.....	49
4.1.1. <i>What trends in climate are shown by ponderosa pines growing on Middle Kipuka?</i>	49
4.1.2. <i>What can age structure, stand structure, and species composition tell us about the history of the pygmy forest?</i>	50
4.1.3. <i>What evidence exists that lightning strikes affect tree growth and may contribute to the pygmy forest growth form?</i>	51
4.2. Future Research	52
REFERENCES.....	54
APPENDICES	59
VITA.....	76

LIST OF TABLES

Table 3.1 Kolmogorov-Smirnov test of normality	36
Table 3.2 Seedling, sapling, and adult tree count for the pygmy forest	38
Table 3.3 Characteristics of pygmy forest plots	40
Table 3.4 Number of tree by species with visible lightning strikes.....	43

LIST OF FIGURES

Figure 1.1 Mature trees at Middle Kipuka	2
Figure 1.2 Pygmy growth forms	4
Figure 1.3 View of the pygmy forest from Middle Kipuka	5
Figure 2.1 Evidence of lightning in the pygmy forest	18
Figure 3.1 El Malpais National Monument.....	26
Figure 3.2 Seven plots within the pygmy forest.....	29
Figure 3.3 Middle Kipuka tree-ring chronology	35
Figure 3.4 Diameter at breast height and establishment dates at Middle Kipuka	36
Figure 3.5 Establishment dates and diameter at ground level at the pygmy forest.....	39
Figure 3.6 Photograph of cores from the pygmy forest.....	41

CHAPTER ONE

INTRODUCTION

1.1 Background

El Malpais, or the “badlands” as the early Spanish conquistadors referred to the area, is an ecologically intriguing and unique landscape in the American Southwest (Robinson 1994; Eury 1997). El Malpais National Monument is made up of several volcanic basalt flows and is surrounded by stratified sandstone formations (Lipman and Moench 1972). The eastern side of El Malpais was formed by the young McCarty’s basalt flow (approximately 3000 years old) that originated from nearby McCarty’s cinder cone, itself destroyed by bomb testing during the years of World War II (Nichols 1946; Laughlin and WoldeGabriel 1997). Interspersed within the McCarty’s basalt flow are several kipukas, which are isolated islands of sandstone surrounded by flowing lava that later cooled and hardened into basalt. Although seemingly inhospitable for vegetation, many plant species live on the McCarty’s basalt flow, providing clues to the bioclimatic past of this area. This northwestern New Mexico volcanic landscape boasts a thriving ecosystem with ponderosa pine (*Pinus ponderosa* Douglas ex. C. Lawson) and piñon pine (*Pinus edulis* Engelm.) as the dominant taxa among other coniferous trees, various shrubs, and lichen (Figure 1.1).

Mixed stands of ponderosa pine, piñon pine, one-seed juniper (*Juniperus monosperma* (Engelm.) Sarg.), Rocky Mountain juniper (*Juniperus scopulorum* Sarg.), and Gambel oak (*Quercus gambelii* Nutt.) are sparsely spread across the sandstone formations and basalt of the



Figure 1.1: Mature growth seen in the ponderosa pines growing on the sandstone of Middle Kipuka. As a reference for the size of the trees, I am standing next to the ponderosa pine in the bottom left corner of the photo (arrow).

McCarty's flow. While these same plant species grow on both the basaltic lava flow and the sandstone kipuka, considerable differences exist in the physical appearance of the trees.

In the late 1940s, naturalist Alton Lindsey described the forest of stunted trees growing on the McCarty's basalt flow as the "pygmy forest," and the nickname has since remained. Not only stunted in height, the individual trees have unique contorted figures. The trees are twisted, partially dead in places with branches stretching out and towards the sky, and bent at extreme angles, sometimes at 45° or even 90° from the trunk. Even with the unusual pygmy growth, Lindsey (1997) estimated these trees to be old, with ages possibly reaching 300 or more years.

The trees of the kipuka make up a different type of forest with the mature growth forms expected in the New Mexico desert landscape. The pines growing on Middle Kipuka (the largest kipuka on the eastern side of the malpais) are tall and straight (Figure 1.1). They exhibit typical growth for ponderosa pines growing in the American Southwest, and are on average 30 to 40 m in height with trunks that are 60 to 70 cm in diameter. In contrast, most trees growing on the adjacent basalt flow only reach heights of about 3 to 9 m, with trunk diameters of 5 to 20 cm (Figure 1.2). The trees of the Middle Kipuka forest are smooth and straight, in stark contrast to the neighboring trees that grow on the basalt that are gnarled, twisted, and/or warped.

1.2 Applications of Dendrochronology

Ecologists and natural resource managers acknowledge the importance of understanding past environments to inform future management efforts (Kipfmüller and

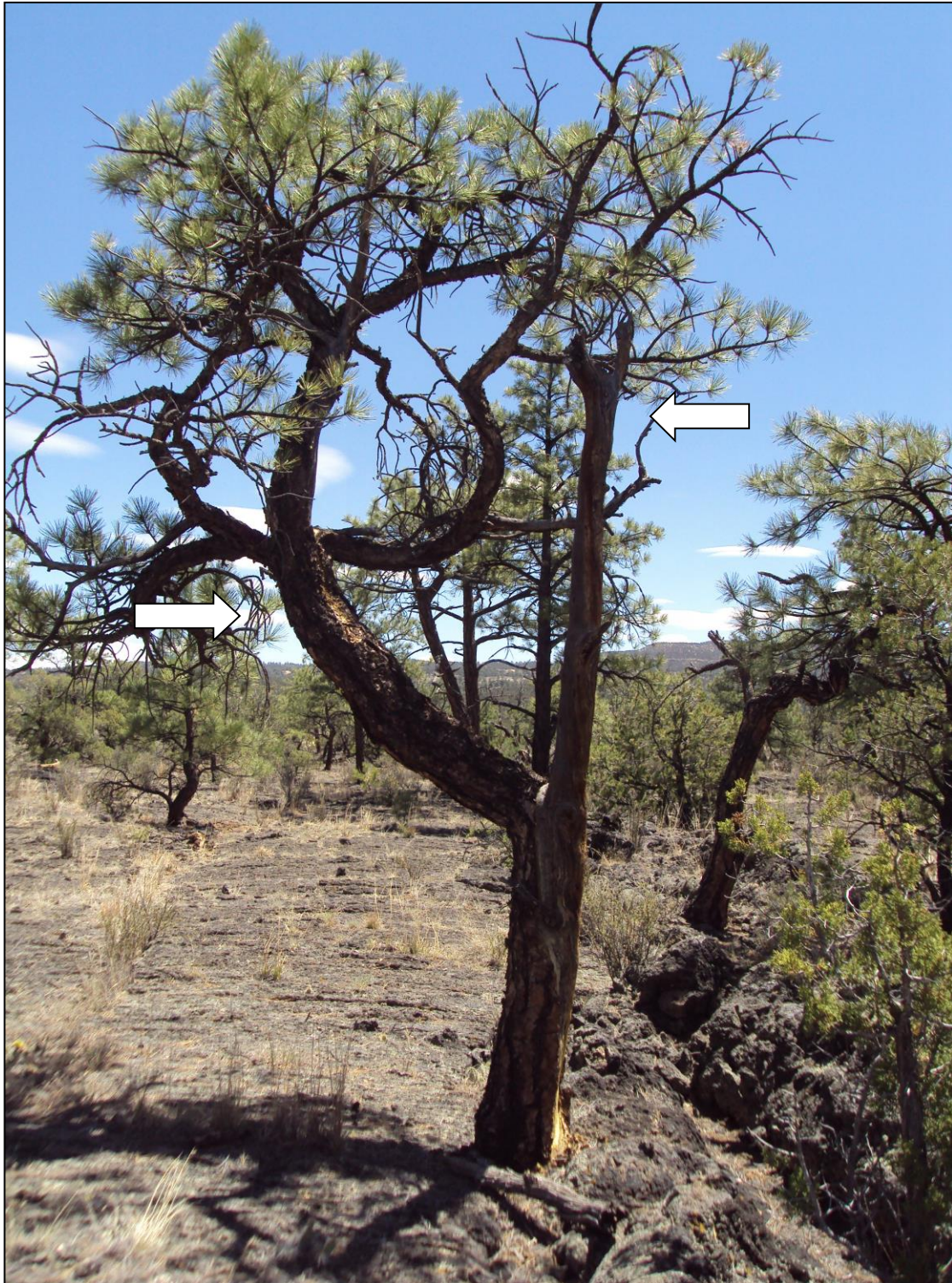


Figure 1.2: Stunted tree growth typical of the plots surrounding Middle Kipuka. This particular ponderosa pine tree reaches just under 6 m in height. Notice the dead leader (right arrow) and the large branch that has taken over apical dominance (left arrow).



Figure 1.3: Northern view of the pygmy forest from the top of Middle Kipuka. The mixed pine forest is spread sparsely over the basalt.

Swetnam 2001). El Malpais National Monument has essentially become a research park whose rare ecosystems are studied to discover the historical relevance of the area and for preservation for future generations as one of the most unique ecosystems in the western United States. The Western National Parks Association has funded this Master's research to share and promote the mysteries of the pygmy forest. As the trees have been growing here years before they were recorded in written history, part of unveiling their mystery is decoding the environmental past.

Dendrochronology is the study of past environmental processes by interpreting tree rings, and is possible because many trees in temperate climates grow annually according to stimulating climate factors, forming one tree ring per year. One of the best ways to understand

past climate is to use tree rings as proxies (Speer 2010). Tree rings serve as a natural archive for climate and environmental variation over time (Fritts 1976; Speer 2010). Tree-ring records provide annual temporal resolution, establishing the precise year in which a disturbance or change within the ecosystem occurred. Once these past ecosystems are reconstructed, ecosystem managers can compare new or emerging characteristics of the particular forest to stand history, and use this information to make informed decisions on future ecosystem conservation (Kipfmueller and Swetnam 2001).

1.3 Research Synopsis

This study investigated potential causes of the pygmy growth forms of the trees growing on the McCarty's basalt flow. Trees that grow on Middle Kipuka were first analyzed to determine dry and wet periods in the past. Due to the close proximity of the two sites, both experienced the same general weather and climate patterns. Even with this geographical closeness, however, microclimatic factors may vary enough to cause the differences in growth form and tree-ring growth patterns seen between the two forest types. I initiated a detailed analysis of the environmental factors that affect this area by collecting a core sample from every adult tree (> 5 cm in diameter at breast height or diameter at ground level) in both study sites. The cores taken from Middle Kipuka were used to create a master chronology and to learn about past climate. I used graphical analysis of pygmy forest plot information to evaluate stand dynamics—age structure, tree density, stand composition, and past disturbances—of the unusual forest (Oliver and Larson 1990).

The pygmy forest growth form is most likely the result of environmental disturbance(s) that can prevent the formation of a common ring pattern over time among the trees. Scouting during the first days of field work revealed that many pygmy trees appear to have suffered from lightning strikes. This is compatible with the high amounts of thunderstorms that El Malpais receives every year (Poore *et al.* 2005). Thunderstorms in this area of the Southwest are common during the monsoon season of July–September and are usually caused by convectonal uplift from warm temperatures radiating from the basalt (Lindsey 1951; Allen 2002). Locals have noticed that it rains more over the volcanic El Malpais than the surrounding area (Robinson 1994).

The basalt of the McCarty's flow is extrusive igneous rock, basalt, composed of magnesium and iron (*mafic*) that formed by the quick cooling of lava (Lipman and Moench 1972). Mafic basalt could be a conductor of electricity. The high incidence of lightning within the pygmy forest could be a result of two sources of charged particles: the mafic basalt and the air molecules directly above the basalt. Small-scale convective thunderstorms occur directly over dark basalt which has a low albedo and absorbs high amounts of insolation (Lindsey 1951; Robinson 1994). The air molecules generate charge from heat energy, the air parcels in the cumulonimbus cloud generate a negative charge, and the metallic basalt may act as a conductor for or conduit through which the lightning can strike. Locations in the surrounding basalt field could possibly generate lightning strikes more often than encountered on Middle Kipuka due to the difference in substrate composition.

1.4 Research Questions

The pygmy forest is ecologically intriguing and this research is intended to help understand the biogeography of this secluded and unique forest. This location has been relatively untouched by humans, and the forest holds a history that has not been fully uncovered. The lack of anthropogenic influences suggests that natural factors likely contributed to the creation of a distinct and peculiar forest of tree species that are otherwise common in the American Southwest and grow in an upright, straight pattern. Consequently, we researched the nature of the forest from the beginning of tree establishment to the present pygmy forest, paying particular attention to the possible effects of lightning disturbance on the character of the forest. The following three research questions were addressed:

- What trends in climate are shown by ponderosa pines growing on Middle Kipuka?
- What can age structure, stand structure, and species composition tell us about the history of the pygmy forest?
- What evidence exists that lightning strikes affect tree growth and may contribute to the pygmy forest growth form?

CHAPTER TWO

LITERATURE REVIEW

2.1 Stand History Research in the American Southwest

The study of forest stand history is an important research area in any environmental management project or biogeographical analysis. Dendrochronologists use tree rings to investigate forest stand history by translating records of tree growth from species that were thriving in past ecosystems. Trees provide a natural record of past climate and information on past disturbance events that include fire events and insect outbreaks. Understanding how forests have developed before anthropogenic influences allows ecologists to project how the forest will change in the future in relation to several possible climate scenarios. In addition, awareness of species distribution, dispersal and establishment timelines, and age structure, among other characteristics, provides biogeographers and ecologists with detailed information needed to project how the forest may change if climate changes.

Fulé *et al.* (1997) determined baseline reference conditions for a ponderosa pine forest at Camp Navajo in Arizona so that forest managers could more readily conceptualize pre-settlement forests. The study revealed that this area experienced fire events as often as one fire every two years prior to Euro-American settlement in 1883. As a result of fire suppression efforts that began after 1883, ponderosa pine forests became extremely dense, filling with less fire-adapted species, such as Gambel oak. Fulé *et al.* (1997) warned that if ecologists attempted to restore fire regimes to what they were prior to Euro-American settlement, widespread severe wildfires could occur in the region.

Biomass accumulation from the past 120 years has created an increased danger of high severity fires. Although advocates for ecosystem conservation, Fulé *et al.* (1997) recognized that a substantial risk exists in changing modern environments to what they once were. However, knowledge of the past enables management personnel to conserve existing forests for the next generation (Fulé *et al.* 1997). Revealing the past environment of El Malpais will reinforce the science-based mission of the monument (Eury 1997). As a National Monument, El Malpais is intended to be conserved for generations to come, and constructing a forest stand history will facilitate management to derive strategies from the dynamic forest.

Brotherson *et al.* (1983) evaluated the age structure of dominant tree species located within Navajo National Monument in northeastern Arizona. These species included quaking aspen (*Populus tremuloides* Michx.), Gambel oak, Douglas-fir (*Pseudotsuga menziesii* (Mirb.) Franco), boxelder (*Acer negundo* L.), chokecherry (*Prunus virginiana* L.), and waterbirch (*Betula occidentalis* Hook.). Pygmy woodland species on the slopes of the canyon included piñon pine and Utah juniper (*Juniperus osteosperma* Torr.). Tree density (stems per hectare) was determined from stem counts for each species, and several species grew in clumps (saltcedar (*Tamarix ramosissima* Ledeb.), quaking aspen, and Gambel Oak). Only Utah juniper and piñon pine showed a clear pattern of dispersal. Ages of some trees were estimated from diameter measurements sufficient to see age trends among species in the relict mountain forest. Population profiles indicated that the oldest trees in the monument were conifers (700–900 years in age), and the deciduous species tended to die at earlier ages. Brotherson *et al.* (1983) hypothesized that different tree species populations growing in the area over time may indicate

small climatic shifts over the past 600 years. As temperature or precipitation shifts, certain trees that favor those climate factors disperse into the area and successfully grow.

Savage (1991) reconstructed the history of a ponderosa pine forest in the Chuska Mountains located across the northern border between Arizona and New Mexico. Aerial photo-mosaics were used to analyze changes in land use since 1930, while tree-ring data provided information on past climates and age structure. Both dendrochronology and aerial photo methods indicated a shift from an open stand of old-growth ponderosa pines to a now dense, thicketed young forest. Historical records from the area show that human presence has been a major factor in land-structure change as logging, sheep herding, and fire suppression were all in practice around the late 1800s. Tree-ring indices suggested a warming trend in the climate during the early 1900s, and the stand today shows an increase in regeneration and density of pines which began in the 20th century. However, this change in regeneration and density over time cannot be attributed solely to human presence. Savage (1991) suggested that further climate research was needed for this site to help separate effects caused by anthropogenic and climatic factors. Past and modern climate trends are equally important to understanding how forests developed over time.

Huffman *et al.* (2008) investigated the fire history of piñon-juniper woodlands in the Tusayan Ranger District of the Kaibab National Forest in Arizona and the Canjilon Ranger District on the Carson National Forest of New Mexico. Although the main focus of their research was to date past fire events by examining piñon pine and Rocky Mountain juniper, these sites were ecotones that bordered areas dominated by ponderosa pines. The sites included

a few individual ponderosa pines, which are well-adapted to low-severity wildfires. Past fires were documented by charred trees at both sites, especially closer to the areas where ponderosa pines were growing. Results showed that no fires in ponderosa pine stands spread to piñon pine and Rocky Mountain juniper stands. Age structure analysis of the piñon-juniper woodlands showed both sites to have trees of various ages. This heterogeneous mixture indicated no evidence of widespread or lethal fires during the last 400 years (Huffman *et al.* 2008).

2.2 Research at El Malpais National Monument

Beginning with the work of Alton Lindsey in 1948, vegetation surveys and tree-ring data have contributed the most to understanding this biologically diverse old-growth site (Lindsey 1951; Grissino-Mayer 1995; Bleakly 1997; Lewis 2003; Spond 2011; Pilote 2012). The semiarid climate at El Malpais National Monument, coupled with the unique volcanic landscape, hinders decomposition of dead and downed woody material and serves to preserve potential tree-ring samples for centuries and even millennia. Erosion occurs slower in this rough and dry terrain, and the inhospitable environment makes it relatively untouched by humans, leaving thousands of old-growth living trees and well-preserved fragments of dead trees throughout the monument (Grissino-Mayer 1995; Spond 2011).

A thorough ecological narrative by Lindsey (1951) became the foundation for later dendroecological research in El Malpais. Lindsey described malpais habitat types of the Grants Lava Bed (later named El Malpais National Monument) and the plant communities found on

them. Lindsey compared plant communities on flow surfaces and described the plant assemblages and their controlling environmental factors. He found three distinct vegetation belts reflected on the flow surfaces based largely on elevation. The upper vegetation belt is dominated by Douglas-fir and ponderosa pine, the intermediate belt consists mostly of ponderosa pine, while the lower belt is dominated by the shrub Apache-plume (*Fallugia paradoxa* (D.Don) Endl. ex Torr.). Lindsey discovered that precipitation is probably greater and more frequent over the lava due to convectional uplift from warming caused by the low albedo of the basalt. He explained that plant communities are influenced by the substrate around the lava flow because of soil development and water availability. Lindsey additionally documented the flora of cinder cones, lava ponds, and ice caves. Lindsey saw unique plant assemblages on different substrates and at different elevations that indicated microclimatic variation over the Grants Lava Bed. The high variety of habitat types and successional patterns of plant species within a small geographic area explains the uniqueness and ecological intrigue of El Malpais National Monument.

Grissino-Mayer (1995, 1996) created a tree-ring chronology for El Malpais National Monument that spans 136 BC to AD 1992, one of the longest for a single site in the American Southwest. The chronology was created with remnant wood from some long-lived Douglas-fir and ponderosa pines that had inner ring dates that extended back prior to AD 150 and many individual living trees older than 400 years. The rough terrain of El Malpais creates a protective environment for these old-growth trees. The Malpais Long Chronology contains important evidence of past climate for northwestern New Mexico, including seven distinct, century-scale

climate episodes of prolonged wet conditions or drought conditions (Grissino-Mayer 1996). Grissino-Mayer compared these episodes to major cultural changes that occurred in the American Southwest, such as the great Puebloan emigration event that occurred during the last half of the 13th century. The long-term climate record can be applied to both climate change and culture change research of the Southwest.

Lewis (2003) explored the forest history of several kipukas within El Malpais National Monument to understand how past fire regimes and current fire suppression efforts have changed these forests during the 20th century. The fire history of the monument had been investigated previously (Grissino-Mayer 1995), but Lewis set out to build on the research by asking whether or not the numerous sandstone kipukas share the same history of fire events, and if the kipuka forests provided additional information on past fire regimes. El Malpais National Monument is only minimally disturbed by anthropogenic forces, and is therefore a key location to reconstruct past fire regimes. Unlike the regions surrounding the basalt flows, fire events on the kipukas did not abruptly terminate ca. AD 1880. In fact, the frequency of fire events stayed much the same throughout the 20th century. Age structure analysis revealed that fire disturbance occurred, but that no high-severity fire event occurred causing widespread mortality. However, Lewis found that human impact on areas adjacent to the national monument had affected the fire regimes in the monument itself.

To investigate the spatial aspects of fire in areas that surround El Malpais National Monument, Rother (2010) reconstructed past fire regimes for the nearby Zuni Mountains to the north. Ponderosa pine cross-sections were collected and 75 samples were dated that contained

over 800 fire scars. Results indicated that up until 1880, fire was driven by interannual climate variability. Superposed epoch analysis and bivariate event analysis revealed that widespread fires were related to the El Nino-Southern Oscillation (ENSO) and Palmer Drought Severity Index. Fires in the dry ponderosa pine forests of the Zuni Mountains were typically high-frequency, low-severity surface fires, and the most significant short-term climate pattern driving these fire events was one or two very wet years followed by a dry year (Rother 2010; Rother and Grissino-Mayer 2014). Beginning in 1880, anthropogenic factors such as commercial logging, livestock grazing, and fire suppression greatly affected fire activity in this area. Forest managers today are allowing many areas of the Zuni Mountains to recover with little human interference, but with a warming global climate, a need exists for further research on climate variations of the Zuni Mountains and for the whole American Southwest region (Rother 2010; Rother and Grissino-Mayer 2014).

Pilote (2012) explored stand dynamics of three different habitat types within the western section of the national monument, including a cinder cone, an ancient basalt flow, and a kipuka. Precipitation records and past fire events were compared to the dates of tree establishment of over 200 trees in each of the three habitat types. Tree growth was positively associated with changes in precipitation over the past 200–300 years. Pilote specifically searched for pulses of recruitment in the age structure patterns of trees on these three habitat types that would indicate a severe fire occurred and likely killed most of the trees that grew prior to that fire event. Results indicated, however, that no such severe wildfires had occurred in any of the three habitats analyzed.

2.3 Lightning Strikes and Tree Growth

Lightning finds the shortest path to the surface of the earth by connecting currents of positive and negative charges. Electrical potential within the cloud exceeds the surrounding air. A negative charge builds up in the lower portion of cumulonimbus clouds and is complemented with a positive charge on the ground. The negatively charged stroke takes the path of least resistance to reach the ground. A positive charge can gather on any source including the ground, buildings, a person, and trees. A positive charge travels up a source toward the cloud to meet the negative charge in the middle. Lightning travels at 30% of the speed of light and has temperatures from 13,000 to 28,000 °C (Fay 2003).

Once lightning strikes the tree, it causes cells in the trunk just inside the bark to explode due to intense heating and rapid expansion of moisture. Sometimes, the lightning strike can instantly set the tree on fire. The impact of the lightning strike will be greater if it occurs during the growing season because at this time the tree will be transporting more moisture from root to crown within the cambium layer (Fay 2003). Lightning mortality in forests alters size and population age structures, and when lightning either disturbs tree growth or kills a tree, it can prove important for stand structure and ecosystem function (Palik and Pederson 1996).

Trees are an excellent conductor of electricity and a path for lightning strikes (DeRosa 1983). Trees growing in relatively open areas are often hit more regularly, and pines are one of the most commonly struck trees on the basalt flows of El Malpais. Lightning destroys wood cells, which makes it possible to date the exact year the lightning strike occurred from tree rings. After the event, callus-like growth cells will soon surround the lightning scar (Schweingruber

2007). Scars range from ca. 2.5 to 10 cm wide (Figure 2.1), and damage is determined by the voltage that the lightning strike carries, in addition to whether or not the tree is translocating moisture (Fay 2003; Brunstein 2006). If the tree is not killed, lightning may leave a spiral scar visible on the outside of the tree that follows the grain of the wood (DeRosa 1983) (Figure 2.1). More evidence for lightning scarred trees includes a “stagheaded” appearance of limbs in the crown or loss of apical growth dominance (both seen in Figure 2.1); however, it is also possible for lightning to leave no visible damage (Fay 2003).

Very few dendrochronological studies have been conducted to explore the effects of lightning strikes on tree growth. In the Rocky Mountains of Colorado, Brunstein (2006) conducted research to understand the growth of bristlecone pines (*Pinus aristata* Engelm.), which live much longer than most tree species. Every noticeable unusual growth form on the pines was documented. Stripped bark and/or stripped cambium layers are evidence of lightning injury, and the presence or absence of vertical cracks within the scars was examined for the study. Brunstein (2006) found that typically some burning occurs after the lightning strike and a main limb will die. Cracks in the trees were caused by damaged cells that were disrupted by lightning-heated water that exists in the phloem, cambium, and xylem. Not all limbs were affected by the lightning strike because the damage occurred primarily at the location of the strike and did not spread significantly (Brunstein 2006).

Palik and Pederson (1996) compared characteristics of mortality and canopy disturbances in longleaf pine (*Pinus palustris* Mill.) in stands across the Georgia Coastal Plain. Lightning strikes were a leading disturbance in this area, and had not been extensively studied



Figure 2.1: A ponderosa pine growing in the pygmy forest that contains evidence of a lightning strike: (top arrow) staghorn appearance of limbs found in the crown; (bottom arrow) a scar spiraling down the tree trunk.

previously. Typically, lightning will strike the taller tree at these drier areas. Out of 70 plots, the more xeric, drier plots witnessed greater mortality from lightning. Lightning struck trees in every diameter class, but was concentrated in the largest diameter class (30 to 45 cm). The high lightning-caused mortality was consistent with the high number of storms with lightning that occur in the Southern United States. When the mortality agent could not be identified, Palik and Pederson (1996) suggested that lightning or fire caused by lightning could have triggered

changes in physiological mechanisms that eventually would kill the tree. They concluded that lightning disturbance has little to no effect on regeneration.

CHAPTER THREE

STAND DYNAMICS OF A UNIQUE PYGMY FOREST, EL MALPAIS NATIONAL MONUMENT, NEW MEXICO, U.S.A.

This chapter is intended for publication in the journal *Southwestern Naturalist*. This research topic was originally developed by me and my advisor, Dr. Henri Grissino-Mayer. The use of “we” throughout the text refers to me and Dr. Grissino-Mayer who assisted with site selection, field work, guidance of project development, and editing. My contributions to this chapter include field work, processing and dating of samples, data analysis, interpretation and graphic displays of results, and writing.

3.1 Abstract

The pygmy forest is a rare ecosystem found on the 3000-year-old McCarty’s basalt flow in El Malpais National Monument, New Mexico. The forest is dominated by contorted, short-statured forms of ponderosa pine (*Pinus ponderosa* Douglas ex C. Lawson) and piñon pine (*Pinus edulis* Engelm.). The purpose of this research was to investigate the history of this unique forest and attempt to isolate reasons why the trees grow in such peculiar forms. We used tree rings from 32 ponderosa pines growing on a sandstone kipuka located within the McCarty’s flow as an indicator of past precipitation patterns and used this to identify linkages between climate and tree establishment. We collected cores from 286 trees in seven plots in the pygmy forest to analyze species composition, age distribution, and establishment dates, and also tallied seedling and sapling counts to project the future forest composition. Climate response analyses revealed that tree growth responds positively to precipitation during the pre-monsoonal months of January through May. The pines are sensitive to drought years, and we found three major drought episodes since the early 1800s. We found that the oldest trees in the pygmy forest were junipers aged at least 400 years, and that no forest likely existed until approximately A.D.

1600. The forest is regenerating mostly with Gambel oak (*Quercus gambelii* Nutt.) and piñon pine. We found only 10 seedlings of ponderosa pine. Disturbance features observed on the trees, such as spiral lightning scars, dead leaders, and “stagheaded” shapes in the crown, indicated that the peculiar growth forms of the pygmy trees are likely the result of dieback from one or more lightning strikes and new apical dominance from branches of the tree. Lightning storms are known to occur more often over the dark basalt than over the surrounding sandstone areas, and the McCarty’s flow may have properties that enhance convectional uplift and increase storm activity.

3.2 Introduction

El Malpais National Monument (ELMA) consists of several volcanic basalt flows and is surrounded by stratified sandstone formations (Lipman and Moench 1972). The eastern side of El Malpais was formed by the McCarty’s basalt flow 3000 years ago (Nichols 1946; Laughlin and WoldeGabriel 1997). ELMA has several forests of old-growth trees, one of which is very unique, a pygmy forest growing on the McCarty’s flow that is characterized by short-statured and contorted trees. Ponderosa pine (*Pinus ponderosa* Douglas ex. C. Lawson) and piñon pine (*Pinus edulis* Engelm.) are the dominant tree species, while one-seed juniper (*Juniperus monosperma* (Engelm.) Sarg.), Rocky Mountain juniper (*Juniperus scopulorum* Sarg.), and Gambel oak (*Quercus gambelii* Nutt.) are secondary taxa.

Several kipukas are found within the McCarty’s flow. Kipukas are outcrops of original substrate that were isolated by coalescing lava that surrounded the outcrop and cooled to form

basalt. Middle Kipuka (MKP) is the largest of the kipukas found at the McCarty's flow. The same plant species grow on both the basaltic lava flow and the sandstone kipuka, but considerable differences exist in the physical appearance of the trees. The pines growing on MKP are tall and straight. They exhibit typical growth for ponderosa pines growing in the American Southwest, averaging 30 to 40 m in height with trunks that are 60 to 70 cm in diameter (Figure 1.1). In contrast, most trees growing on the adjacent basalt flow only reach heights of about 3 to 9 m, with trunk diameters of 5 to 20 cm (Figure 1.2). Trunks of trees growing on the basalt are often gnarled, twisted, partially dead in places, with branches stretching out and towards the sky, bent at extreme angles, sometimes 45° or even 90° from the trunk to give the crown a "stagheaded" appearance. Disturbance is a principal driver of stand dynamics in a forest, and these unique growth forms could be produced by some sort of low-severity disturbance event (Frelich 2002).

The volcanic landscape found in the semiarid climate of the Southwest is ideal for dendrochronological research as the environment hinders wood decomposition. Furthermore, human influences are minimal on the rugged lava flows. Trees here can reach great ages and wood can remain on the lava surface for centuries or even millennia (Lindsey 1951; Grissino-Mayer 1995, 1996; Spond 2011). The naturalist Alton Lindsey first conducted vegetation surveys in 1948, and he first used the name "pygmy forest" (Lindsey 1951). Lindsey estimated the pygmy trees to be old, possibly exceeding ages of 300 years. He described the potential for extreme microclimate events over this low elevation young basalt, and he hypothesized that a

higher frequency of convectional uplift occurred over the lava surface during the summer monsoon months (Lindsey 1951).

Using tree-ring data obtained from snags, logs, remnant wood, and long-lived conifers, Grissino-Mayer (1995, 1996) created the Malpais Long Chronology which spans 136 BC to AD 1992. The chronology was instrumental for understanding cultural changes in the area and serves as a long proxy record for past climate. Grissino-Mayer found prolonged drought events and wet years that he then compared with major cultural changes that occurred in the American Southwest. His research helped explain the great Puebloan emigration event that occurred during the last half of the 13th century, which coincided with a severe extended drought recorded in tree rings (Grissino-Mayer 1996). This is significant because the Ancestral Puebloans had previously experienced a time of population growth and cultural advances that accompanied long-term wetter conditions prior to ca. AD 1260.

In addition to research on past climate, studies have also been performed to better understand the history of past wildfires at ELMA and the relationship between fire activity and past climate. Fire over the monument follows short-term climate fluctuations, yet fire suppression in the present has stopped the historical pattern of fire events (Lewis 2003; Rother 2010; Pilote 2012; Rother and Grissino-Mayer 2014). El Malpais experienced low-severity fire events approximately every five years, and these frequent fires ceased around 100 years ago when land-use practices changed (Lewis 2003; Rother 2010). Lewis (2003) found that fires were primarily high frequency events in the monument. He found no evidence for widespread high-severity fire. Pilote (2012) investigated the stand dynamics of three different habitat types—a

cinder cone, an ancient basalt flow, and a sandstone kipuka—to better understand the mechanisms that facilitate establishment of different tree species. He found that fire-intolerant piñon pine, junipers, and Gambel oak established in the late 1800s with wetter conditions and land-use changes (Pilote 2012).

Understanding climate patterns and how they relate to disturbances of the forests in El Malpais can be challenging in light of climate change and anthropogenic land-use, and further environmental research in the monument aids in management decision-making practices (Rother 2010; Rother and Grissino-Mayer 2014). Subsequently, Rother and Grissino-Mayer (2014) found that interannual climate variation contributes most to fire events. Fires typically occur in a drought year that follows a few consecutive wet years. In the wake of more extreme climate fluctuations along with long-term fire suppression, El Malpais could experience a catastrophic high-severity fire not typical of pre-settlement fire events (Grissino-Mayer and Swetnam 1997).

The national monument is a dynamic area full of unique habitats, and each habitat requires unique management practices (Grissino-Mayer 1996; Lewis 2003; Rother 2010; Pilote 2012). However, previous research missed the ecological history of the pygmy forest, and the National Park Service has been interested in this unique forest since Lindsey first surveyed it. The primary objective of this research is to understand the history and stand dynamics of the pygmy forest. We addressed the following research questions: (1) What trends in climate are shown by ponderosa pines growing on Middle Kipuka? (2) What can age structure, stand structure, and species composition tell us about the history of the pygmy forest? (3) What

evidence exists that lightning strikes affect tree growth and may contribute to the pygmy forest growth form?

3.3 Study Site

El Malpais consists of a volcanic landscape (Figure 3.1) composed of broken and permeable basalt with crevasses that support tree growth because they collect eolian and alluvial material and water. Roots penetrate deep into cracks and stabilize the trees. The roots attain nutrients from the little soil and moisture that is stored in the broken lava formation (Nichols 1946; Grissino-Mayer *et al.* 1997). At least 441 plant species are known to exist in the monument (Bleakly 1997). The McCarty's flow in particular is known for its relatively barren surface, yet open woodlands are common along the eastern periphery of the basalt flow that harbors the pygmy forest. Within the mixed-conifer woodland, the dominant tree species are ponderosa pine, one-seed juniper, Rocky Mountain juniper, Gambel oak, and piñon pine. Shrubs and grasses include Apache plume (*Fallugia paradoxa* (D.Don) Endl. ex Torr.), New Mexico olive (*Forestiera pubescens* Nutt.), and blue grama grass (*Bouteloua gracilis* (Willd. ex Kunth.) Lag. ex Griffiths) (Bleakly 1997).

Middle Kipuka is located within the McCarty's flow on the eastern side of El Malpais National Monument (Figure 3.1). The kipuka was formed when two basalt "tongues" coalesced during the McCarty's cinder cone volcanic event (Nichols 1946; Robinson 1994). Once the basalt hardened, the sandstone outcrop was isolated. On the kipuka, ponderosa pines, piñon pines, and Rocky Mountain juniper make up a relatively denser forest compared to the pygmy forest.

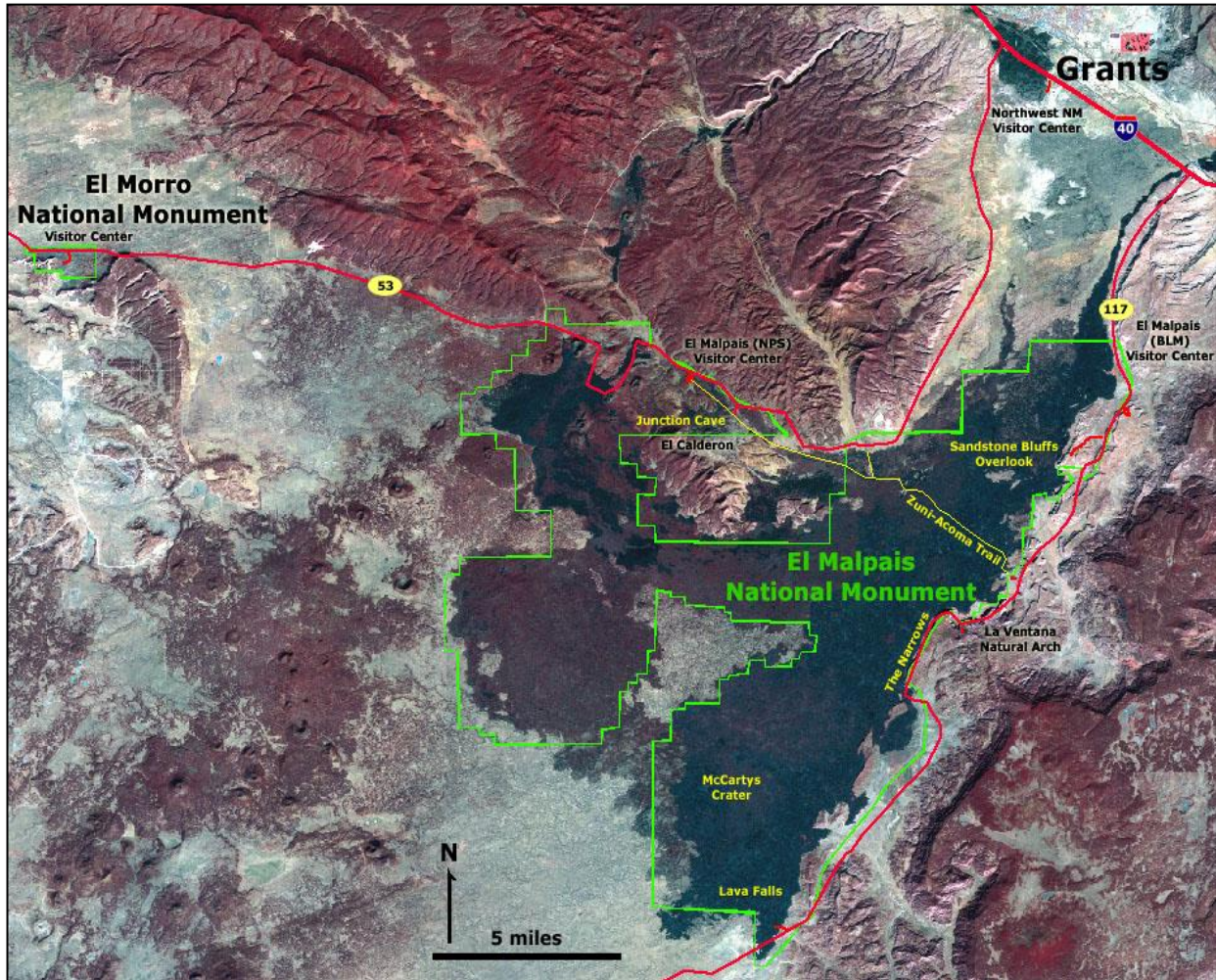


Figure 3.1: The dark color of the basalt flows that make up El Malpais National Monument stands out in a landscape of sandstone. Photo from the USGS (<http://3dparks.wr.usgs.gov/elma/>).

Remains of a small pueblo suggest Native Americans lived on top of the kipuka, possibly using it as a scouting location for hunting over the surrounding lower-lying basalt. Ponderosa pine trees found here grow straight and tall (Figure 1.1) with little evidence of nutrient-stressed or disturbance-stressed growth.

The pygmy forest is found on the McCarty's basalt flow that surrounds Middle Kipuka. Originally thought to be only 1000 years old, the basalt of the McCarty's flow was dated by radiocarbon analysis of organic material retrieved from beneath the flow and found to be about 3000 years old (Laughlin and WoldeGabriel 1997). The McCarty's basalt appears relatively unweathered, has a very dark color, consists of jagged aa lava made of coarse particles, and is very porous, all of which indicate a younger age than that of surrounding or nearby lava flows (Lipman and Moench 1972; Robinson 1994). The trees here are concentrated on the eastern periphery of the basalt, while the center of the flow has little to no vegetation (Nichols 1946). This spatial pattern of the forest is likely the result of eolian seed dispersal over time. Tree roots can grow deep into cracks where moisture collects (Bleakly 1997). Soil does not exist on this young basalt flow, so the flora found on the eastern periphery of the McCarty's flow is a mosaic of sparse shrubs, lichen, and stunted trees. Based on a 1 m diameter ponderosa pine tree mold found in the basalt, Nichols (1946) hypothesized that the climate when the McCarty's cinder cone erupted was similar to what it is now. He further suggested that the ponderosa and piñon pines growing on the McCarty's flow were about 300 years old. These woodlands consist of old-growth forests that have not been altered or damaged by humans since their inception.

Scouting during the first days of field work revealed that many pygmy trees appear to have been struck by lightning. This would be expected given the high amounts of thunderstorms that El Malpais receives every year (Poore *et al.* 2005). Thunderstorms in this area of the Southwest are common during the monsoon season of July–September, and are

usually caused by convectional uplift from warm temperatures radiating from the basalt (Allen 2002; Sheppard *et al.* 2002). Locals have noticed that it rains more over the volcanic El Malpais than the surrounding area (Robinson 1994).

3.4 Methods

3.4.1 Field Techniques at Middle Kipuka

In 2010, we cored 32 of the largest ponderosa pines along the perimeter of Middle Kipuka. We selectively cored trees that were free of injury-related scars to build a disturbance-free reference chronology for the area. We took photographs of the forest as well as of the individual trees. We took field notes that described physical characteristics of individual trees, such as the weightiness of branches, crown condition, trunk lean, and trunk shape. We took coordinates of tree locations with a Garmin GPS unit. Diameter at breast height was measured with a field tape measure. We took two cores from each tree using a standard Haglof increment borer, placed the core samples into labeled paper straws, and placed them in a map tube to be transported to the laboratory.

3.4.2 Field Techniques at the Pygmy Forest

Seven 50 x 20 m (1000 m² or 0.1 ha) rectangular plots were located pseudo-randomly within the eastern area of the McCarty's basalt flow where the pygmy forest is located (Figure 3.2). We walked a random number of paces in a randomly chosen direction indicated by the second hand of a watch. Once the plot corner was located, we laid out four measuring tapes to



Figure 3.2: Oblique view looking north showing Middle Kipuka (center) along with locations of the seven study plots.

create a 50 x 20 m rectangle for each plot. Latitude and longitude coordinates (datum: WGS84) and elevation for each corner were recorded with a Garmin GPS unit. General physical characteristics of the plot were noted in a field journal, including: types of plants present (such as cacti, wildflowers, and shrubs), slope and aspect (if any), whether any dead and downed woody material was present, presence of signs indicating fire or other disturbances, classification of the lava formations (aa or pahoehoe), and amount and type of plant litter (needle cast, branches, dead bunchgrass). We recorded characteristics of individual trees such as the trunk shape, lean degree and direction, crown condition, branching pattern, and presence

of disturbance (e.g. scarring). Photographs were taken at every corner of the plot as well as several from within the plot.

We measured the diameter of every tree within the plot at ground level (= dgl). Because the trees were contorted in shape, ground level would be the most likely location along the trunk in which the tree rings would not so be compressed and difficult to date. The measurements were recorded in a field journal and on biodegradable flagging tape attached to the tree, which also documented the tree species and identification number. We then cored all trees > 5 cm dgl and > 1 m height with a standard Haglof increment borer as close to ground level as possible to maximize the number of rings obtained (Speer 2010). We collected cores from 286 trees from the seven plots. If a tree had a visible lightning scar, we avoided coring through the scar to ensure we obtained a clear record of all tree rings. Cores were placed in paper straws, labeled, and placed into map tubes to be transported back to the laboratory. Once all trees were cored, we tallied all seedlings (diameter < 5 cm, height < 1 m) and saplings (diameter < 5 cm, height > 1 m) by having all field team members line up at one end of the plot and walk slowly to the other end, carefully examining the landscape and calling out to a note taker which tree species were encountered.

3.4.3 Laboratory Methods

Cores were glued on wooden core mounts with the tracheids aligned vertically to ensure a transverse view of the wood (Stokes and Smiley 1996; Speer 2010). The mounts were labeled with corresponding information from the field notes. The cores were sanded with progressively

finer sandpaper, beginning with ANSI 180-grit (63–88 μm) and finishing with 400-grit (20.6–23.1 μm), which reveals the cell structure of the wood under 10x magnification (Stokes and Smiley 1996; Orvis and Grissino-Mayer 2002). We graphically crossdated the tree rings of the MKP cores, then measured all rings to the nearest 0.001 mm. We used the computer program COFECHA to statistically confirm the crossdating (Holmes 1983; Grissino-Mayer 2001). COFECHA tested overlapping 50-year segments of a measured series with the master chronology created from all other measured series. We then used the software program ARSTAN to standardize the measurements into an index chronology.

All notes taken in the field for each tree from the pygmy forest were archived in an Excel spreadsheet. We attempted to crossdate these samples, but irregular growth and lack of a consistent ring pattern prevented successful crossdating across the full length of the core. When possible, we crossdated the rings from these cores by comparison with the MKP master chronology using the list method (Yamaguchi 1991; Stokes and Smiley 1996; Speer 2010), but then simply counted the rings beyond which crossdating was not possible. For core samples that did not reach the pith but did show ring curvature indicating close proximity to the pith, age was approximated using pith estimators (Duncan 1989).

3.4.4 Climate-Tree growth Relationships

Based on previous research at ELMA, we chose to analyze precipitation variables only. We used NOAA climate division 4 monthly precipitation data from 1895 to 2010 to compare with tree-ring data obtained from the ponderosa pines growing on Middle Kipuka. We first

conducted a test of normality to evaluate if the monthly precipitation variables followed a normal distribution (Burt *et al.* 2009). The significance level was set at 0.05. We then used correlation analyses to evaluate the strength of the linear relationships between monthly precipitation and tree growth. We used Spearman's Rank correlation analysis if the variables were not normally distributed and the Pearson's correlation coefficient when the variables were normally distributed. If we found a statistically significant relationship, we then used the tree-ring chronology as a proxy for that climate variable.

3.4.5 *Stand Dynamics*

Plot information was entered into an Excel spreadsheet for graphical analysis of tree establishment, species composition, and stand structure. Tree establishment dates can be used to evaluate successional patterns via the age structure for the forest. In turn, age structure can provide information on disturbance events that could have occurred throughout the history of the forest by identifying pulses of tree establishment that might be linked to major disturbances. We also compared the MKP climate reconstruction with establishment dates of pygmy forest trees to determine if the establishment of trees species coincided with significant climate episodes, especially distinct wet events that could lead to pulses of establishment. Each plot was analyzed for the presence of even-aged stands, yet we expected no stand-initiating mortality event, such as high-severity wildfires. Species composition was combined with adult, seedling, and sapling tallies from each plot to determine the likely future species composition of the pygmy forest.

3.5 Results

3.5.1 Chronology Development

The chronology created from Middle Kipuka spans AD 1656 to 2009 (Figure 3.3). COFECHA determined that the samples all correlated significantly with an average interseries correlation of 0.79. The mean sensitivity of 0.54 suggested these ponderosa pines were highly sensitive to year-to-year changes in climate. Narrow rings were found in the years 1668, 1708, 1724, 1729, 1739, 1756, 1782, 1806, 1819, 1823, 1827, 1880, 1894, 1904, 1925, 1951, 1959, 1971, 2002, and 2006, all of which served as marker rings during the crossdating process. Establishment dates of the pines cored range from AD 1656 to 1891 (Figure 3.4).

3.5.2 Climate-Tree Growth Relationships

Precipitation data for the months of April, May, and November were not normally distributed (Table 3.1), so we used the Spearman's Rank correlation test to evaluate relationships between tree growth and precipitation. Precipitation during April ($r_s = 0.25$, $p < 0.01$) and May ($r_s = 0.34$, $p < 0.0001$) were both found to be statistically significant with tree growth. The Pearson's Correlation Coefficient was applied to all other months and we found statistically significant correlations between tree growth and precipitation in January ($r = 0.27$, $p < 0.01$), February ($r = 0.24$, $p < 0.01$), March ($r = 0.24$, $p < 0.05$), and July ($r = 0.23$, $p < 0.05$). Because precipitation in the consecutive months of January through May had significant correlations with tree growth, these months were combined to create a single seasonal precipitation variable to test against tree growth. The K-S test was used to test the normality

and we found this new variable (winter/spring rainfall) to be normally distributed. Pearson's correlation analysis revealed a highly significant correlation between tree growth and seasonal precipitation ($r = 0.44$, $p < 0.0001$).

Based on these results, we used the MKP tree-ring chronology as a proxy for winter/spring rainfall (Figure 3.3). In addition to the very narrow rings that assisted in the crossdating process, we also noticed multidecadal periods of above-average and below-average rainfall. For example, periods of considerably reduced precipitation occurred from ca. 1725 to 1750, ca. 1775 to 1790, 1820 to 1835, and 1885 to 1905. The lowest precipitation occurred in an extended period that began ca. 1945 and lasted until 1975. Another major drought occurred from 2000 to 2009. Above average rainfall occurred from ca. 1745 to 1770, ca. 1836 to 1860, and 1906 to 1944. The longest period of above-average rainfall occurred during the 20th century from 1975 to 1999.

3.5.3. Stand Dynamics

We sampled 461 total trees in the seven plots, including adult trees, saplings, and seedlings (Table 3.2). The majority of establishment dates (91%) lie between 1770 and 2010 (Figure 3.5H) but two junipers established as early as 1591 (not shown), and 21 out of 231 trees established between the years 1590 and 1769 (Figure 3.5). The most common tree species based on total number of individuals is Gambel oak (38% of the forest), while the next most common species were piñon pine (28%) and ponderosa pine (21%). Plot 4 had the highest tree density with 86 adult trees, while the other six plots ranged from 21 to 44 adult trees. Piñon pine and

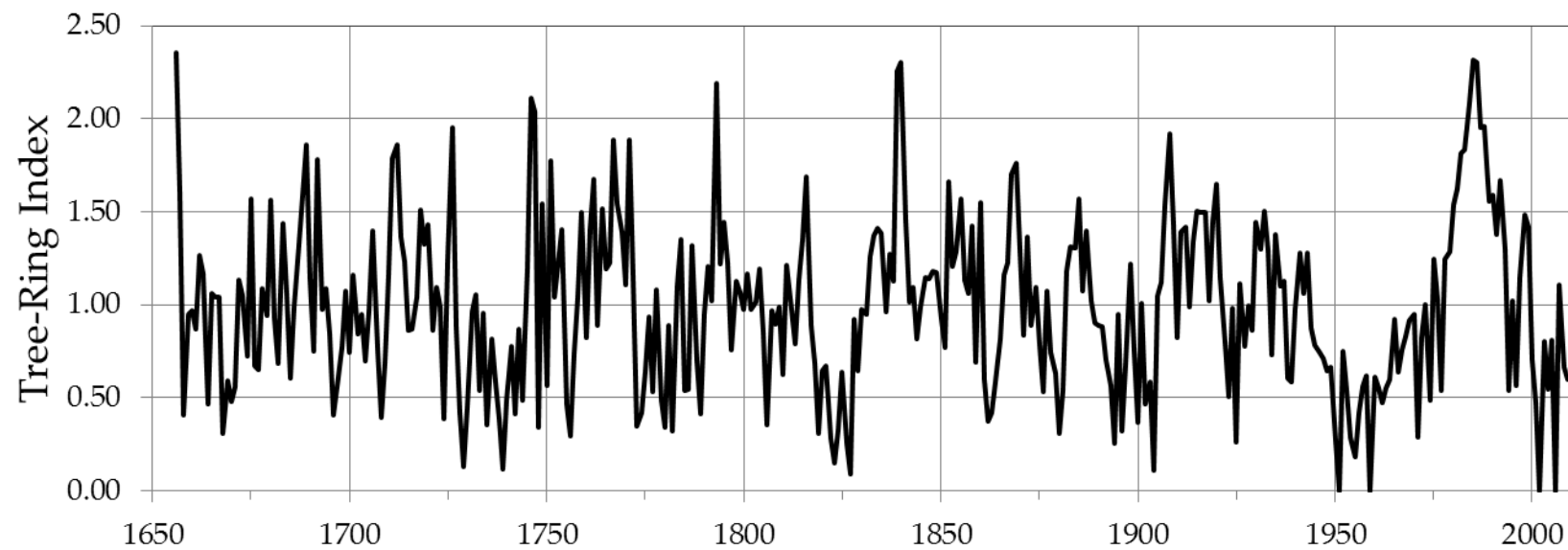


Figure 3.3: The tree-ring chronology developed from 32 ponderosa pine trees growing on Middle Kipuka.

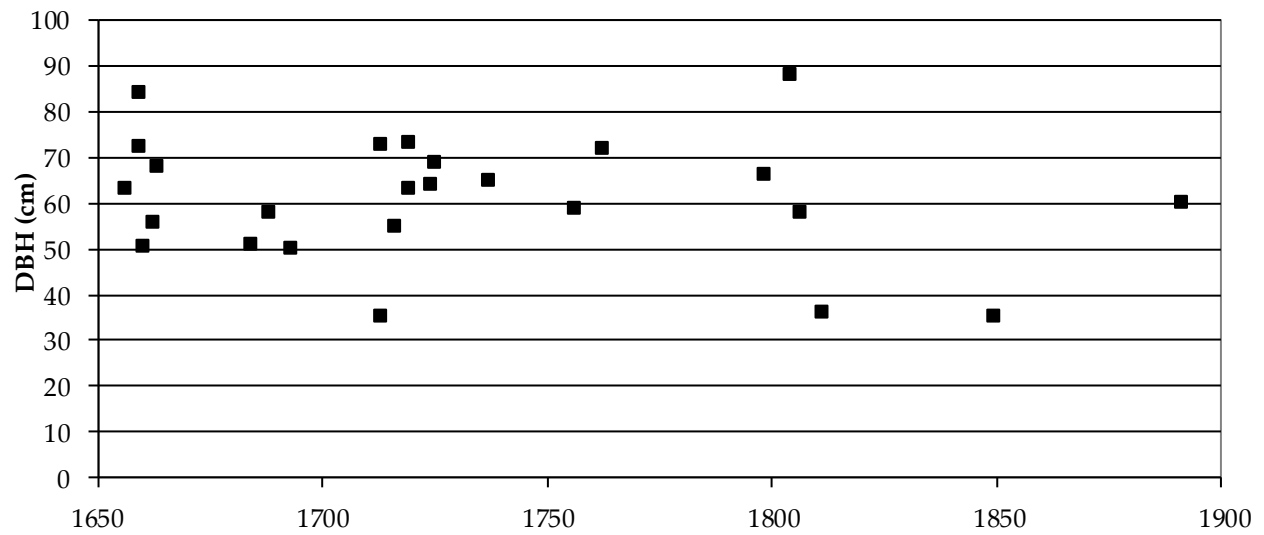


Figure 3.4: Diameter at breast height (DBH) and establishment dates of ponderosa pines growing at the base of Middle Kipuka.

Table 3.1 Kolmogorov-Smirnov Tests of Normality

Month	Mean	Std. Dev.	K-S	Asymp. Sig. (2-tailed)
Jan.	0.703	0.506	0.963	0.311
Feb.	0.622	0.468	1.110	0.170
Mar.	0.624	0.411	1.297	0.069
April	0.484	0.498	1.777	0.004
May	0.502	0.530	1.843	0.002
June	0.706	0.532	1.194	0.115
July	2.684	0.960	0.649	0.794
Aug.	2.684	0.919	1.046	0.223
Sept.	1.648	0.928	0.712	0.691
Oct.	1.104	0.938	1.282	0.075
Nov.	0.577	0.539	1.523	0.019
Dec.	0.7737	0.627	1.234	0.095

Gambel oak showed some regeneration with relatively high numbers of seedlings and saplings compared to other species (Table 3.2). However, plot 4 is the only plot that had a high number of Gambel oak trees which skews the results and is not characteristic of the other six plots. The other tree species – ponderosa pine, Rocky Mountain juniper, and one-seed juniper – have very few seedlings and saplings, suggesting that these three tree species are not regenerating as effectively if at all. Curiously, some trees over 200 years old had very small diameters (Figure 3.5). This could be explained by suppression of tree growth after individual disturbance, or slow growth rates due to other limiting factors such as poor soil development.

We observed that all tree species were struck by lightning (Table 3.3). Both ponderosa pine and piñon pine had the highest percentages of trees struck by lightning in plots 1–3 and 5–7, but Gambel oak had the most evidence for lightning strikes in plot 4. Of five tree species in the pygmy forest, Gambel oak had the least amount of lightning strike evidence (19% of trees struck). Buried scars (damage to the tree trunk that was subsequently grown over in later years) found within tree rings from several cores (Figure 3.6) provided evidence that these trees were struck by lightning. When sampling in the field, increment borers were not inserted directly through visible lightning scars. Instead, we cored away from the damage. Therefore, lightning scars found within core samples were enclosed within the tree as time went on. Including scars found within the cores, many trees had multiple lightning scars, indicating more than one lightning disturbance event during the life of an individual tree.

Table 3.2: Seedling, sapling, and adult count for each plot.

Plot		PIED	PIPO	QUGA	JUSC	JUMO	Total
PYG 1	Seedlings	8	2	0	0	0	10
	Saplings	3	1	0	0	0	4
	Adult	17	8	0	8	0	33
PYG 2	Seedlings	9	2	6	0	0	17
	Saplings	2	0	1	0	0	3
	Adult	13	14	8	3	0	38
PYG 3	Seedlings	4	0	0	0	0	4
	Saplings	0	0	8	1	0	9
	Adult	10	9	1	1	0	21
PYG 4	Seedlings	4	0	30	1	0	35
	Saplings	2	0	59	1	0	62
	Adult	11	13	51	9	0	84
PYG 5	Seedlings	4	5	0	0	0	9
	Saplings	3	1	3	0	0	7
	Adult	12	16	8	0	5	41
PYG 6	Seedlings	9	0	0	0	0	9
	Saplings	1	0	0	0	0	1
	Adult	18	18	0	1	7	44
PYG 7	Seedlings	3	1	0	0	3	7
	Saplings	2	0	0	0	0	2
	Adult	0	9	0	0	13	22
Pygmy Forest	Seedlings	41	10	36	1	3	91
	Saplings	13	2	71	2	0	88
	Adult	81	87	68	22	25	283

PIED, *Pinus edulis*; PIPO, *Pinus ponderosa*; QUGA, *Quercus gambelii*; JUSC, *Juniperus scopulorum*; JUMO, *Juniperus monosperma*

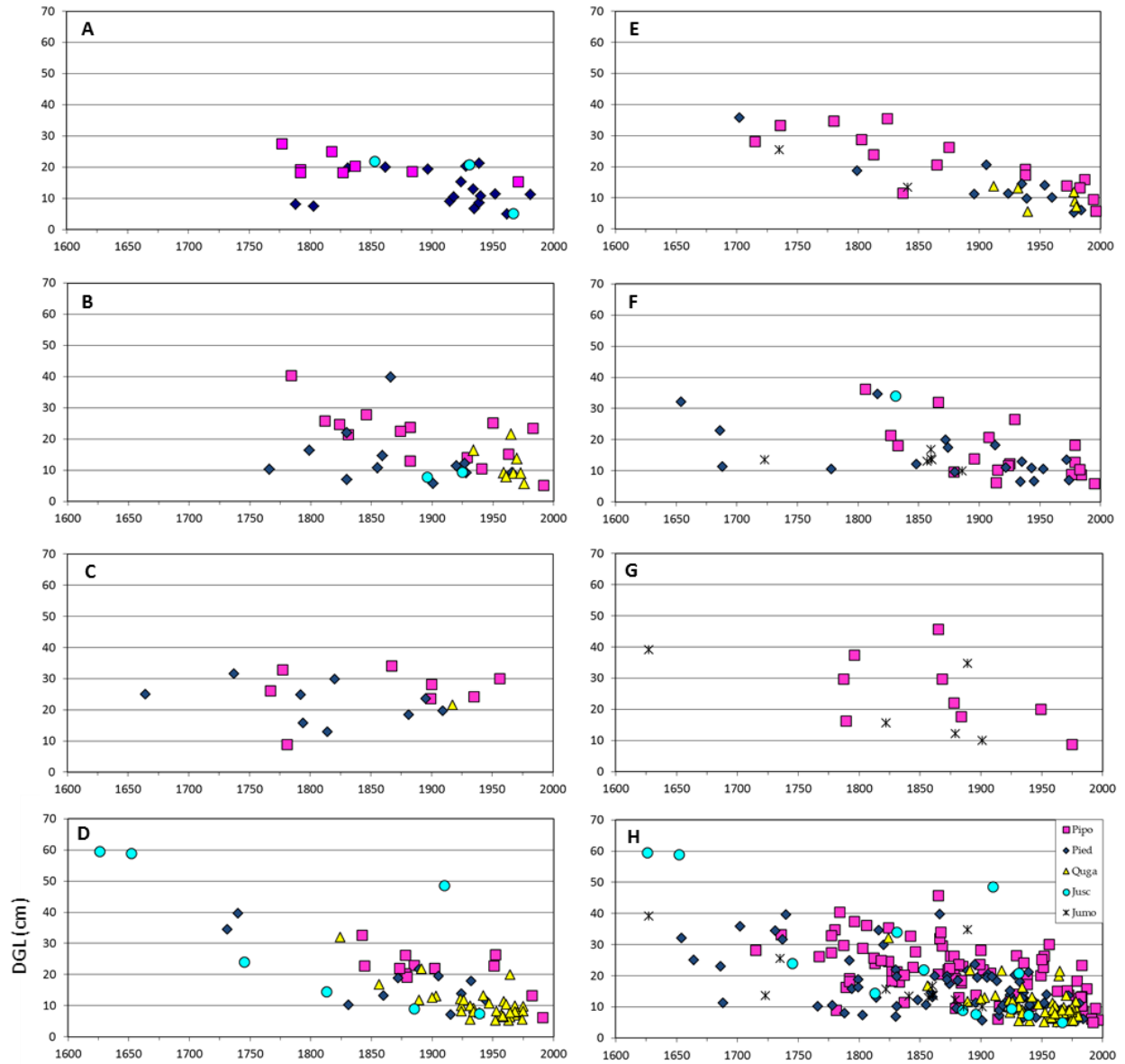


Figure 3.5: Tree establishment plotted by diameter at ground level for adult trees from 1600 to 2000 in the pygmy forest. A–G are plots PYG 1–PYG 7 respectively, and H is all plots of the pygmy forest combined. Species abbreviations are: PIED: *Pinus edulis* (navy diamonds); PIPO: *Pinus ponderosa* (pink squares); QUGA: *Quercus gambelii* (yellow triangles); JUSC: *Juniperus scopulorum* (blue circles); JUMO: *Juniperus monosperma* (black x's).

Table 3.3: Characteristics of seven plots in the pygmy forest.

Plot	Location	Elevation (m)	# Trees Sampled	Percentage of Trees with Visible Lightning Scar(s)
Plot 1	34.83685°N 107.91484°W	2166	33	48%
Plot 2	34.83650°N 107.91639°W	2159	39	58%
Plot 3	34.83453°N 107.92329°W	2182	21	62%
Plot 4	34.83765°N 107.91972°W	2159	86	30%
Plot 5	34.83464°N 107.91588°W	2161	41	61%
Plot 6	34.83238°N 107.91534°W	2169	44	66%
Plot 7	34.82996°N 107.91493°W	2173	22	82%



Figure 3.6: Cores from pygmy forest trees that show evidence of disturbance, most likely lightning strikes, within the tree rings (shown by arrows).

3.6 Discussion

3.6.1 Middle Kipuka

We found a significant seasonal winter/spring precipitation signal which accounted for about 19% ($r^2 = 0.19$) of overall tree growth for ponderosa pines growing on Middle Kipuka.

This signal is important because it occurs when the trees are breaking dormancy and before the monsoonal late summer when trees get most of their annual precipitation. Further, winter precipitation at this location usually occurs as snowfall, suggesting that snowmelt in the early

growing season contributes to enhanced tree growth. The winter/spring precipitation signal accounts for a large amount of tree growth, but it is not the only factor that can explain tree growth. Future research is needed to examine other climate variables, such as temperature and several multidecadal oscillations, which could provide a more complete view of climate factors that influence ponderosa pine growth.

3.6.2 Pygmy Forest

Few trees grow to a height above approximately 6 m, and the pygmy forest showed few adult individuals in an upward, non-contorted stance typical of growth off the lava flows. We infer that disturbance has always been a factor that contributes to the unusual tree growth of this forest stand. Even without a visible scar on the tree trunk, the odd forms of the trees most likely indicate that lightning has affected the tree. As the basalt substrate contributes to the convectional uplift of warm air and increasing the chances of thunderstorm and lightning activity, the trees act as a conduit for the electricity to pass, and all trees in the forest provide that path.

Of the seven pygmy forest plots, most displayed the same forest characteristics. With the exception of plot 4, all plots had trees that were widely distributed, which provide little shade throughout the stand and no competition from one tree to another. These plots also had similar numbers of seedlings and saplings and a similar sparse distribution of other vegetation, which included blue gramma, New Mexico olive, and Apache plume. All plots except plot 4 had a

Table 3.4: Number of trees by species with visible lightning damage out of the total number in each plot.

	PIPO	PIED	QUGA	JUSC	JUMO
Plot 1	6/8	6/11	n/a	4/8	n/a
Plot 2	8/14	11/13	1/8	2/3	n/a
Plot 3	3/9	9/10	0/1	1/1	n/a
Plot 4	4/13	6/11	11/51	5/11	n/a
Plot 5	12/16	8/12	1/8	n/a	4/5
Plot 6	12/18	12/18	n/a	1/1	4/7
Plot 7	8/10	n/a	n/a	n/a	10/13
All plots	53/85	52/75	13/68	13/24	18/25

relatively level landscape with exposed pahoehoe and aa basalt and many crevasses. Plot 4 was characterized by much denser vegetation, and was located within a depression feature of the basalt. The abundant vegetation in plot 4 suggests a moister environment. This is likely caused by precipitation (especially snowfall) that collects within crevasses, and the valley feature may offer shade that inhibits high amounts of evaporation and/or snowmelt. Plot 4 had the most trees (86), yet the lowest percentage of visible lightning scars (30%) (Table 3.4). In contrast, plot 7 was most sparsely populated plot (only 22 trees) but 82% of the adult trees displayed evidence of lightning strikes. Spatially, all plots lay relatively close to one another and close to the edge of the lava, so plot 4 is only different in vegetation density and its topographic depression. As a storm develops and passes over the McCarty's lava flow, all areas of the pygmy forest have the same chance of being affected by lightning.

The oldest tree species in the pygmy forest are Rocky Mountain juniper and one-seed juniper, with the oldest individual being 423 years in age. Ponderosa and piñon pines are the

next oldest species, dominating the forest beginning around 1800. Gambel oak is the last tree species that established in the forest, and the future forest generation could consist of considerable numbers of Gambel oak and piñon pine. Through the history of the pygmy forest, no clear pulses of establishment occurred for any tree species. For every individual plot, most trees established after AD 1800. When compared to the Middle Kipuka tree-ring chronology, establishment dates do not line up with longer wet periods and we could not discern any noticeable relationship between establishment and climate patterns. The majority of trees, however, are less than 200 years old, suggesting that nearly all trees established during the most recent wet climate episode that began ca. AD 1800 as reconstructed by Grissino-Mayer (1995). Overall, forest composition is not stable and continues to change.

For the pygmy forest as a whole, the seedling and sapling count is nearly even (91 and 89 respectively). However, if plot 4 was excluded, then the count for Gambel oak becomes much lower at 18 seedlings and saplings combined from the other six plots. If this were the case, the dominant young tree in the stand would be the piñon pine with 13 seedlings and 41 saplings. For all plots, Rocky Mountain juniper and one-seed juniper have very few seedlings and saplings. Although junipers may have been the first to establish on the McCarty's basalt flow, they are currently not regenerating in the forest. With only 10 seedlings and 2 saplings, ponderosa pine also is not regenerating even though this species was a dominant tree species. Further, it is possible that the number of Gambel oak seedlings and saplings may change the future species composition of the forest if these trees further disperse across the McCarty's basalt flow.

Our field investigations found no evidence of fire-scarred trees and very few dead trees lying on the lava surface, with very few upright standing snags. Lightning may strike an individual tree and may cause a tree to burst into fire, but the fire will not be able to spread far because the finer fuels (grasses) and coarser fuels (large branches and tree trunks) are relatively sparse. The lightning strike locally destroys the cambium cell layer as it moves down the tree, and as the tree continues growth, it calluses over the dead material, eventually covering up the scar (Schweingruber 2007; Stoffel *et al.* 2010). Lightning destroys wood cells, which makes it possible to date the exact year the lightning strike occurred from tree rings. However, injury to a tree can lead to locally absent rings (missing rings) within areas of the trunk (Stoffel *et al.* 2010). After the event, callus-like growth cells will soon surround the lightning scar. If the tree is not killed, lightning may leave a spiral scar visible on the outside of the trees that follows the grain of the wood (DeRosa 1983) (Figure 2.1). More evidence for lightning-scarred trees includes a “stagheaded” appearance of limbs in the crown or loss of apical growth dominance (both seen in Figure 2.1); however, it is also possible for lightning to leave no visible damage (Fay 2003).

Lightning in the pygmy forest seems to be the only locally severe and intense disturbance type, but this disturbance also does not cause widespread mortality. Most of the time, the majority of the cambium layer survives and only the apical leader is killed as it receives the full voltage of the strike. The tree is then left to begin another (secondary) route of dominant growth by using a lower branch. On the McCarty’s flow, the trees could have been struck by lightning more than once, restarting the process of new apical growth from yet another branch. With dominant growth changing throughout the course of the life of a tree, the

tree never reaches its full potential of straight, strong, upward growth. Every tree experiences a slightly different injury, and as a result, every individual of the forest has a distinctive form as the branches take on apical dominance.

3.7 Conclusions

The ponderosa pines growing at the base of Middle Kipuka crossdated and their tree-ring indices were tested against New Mexico climate data. We discovered that winter/spring seasonal precipitation is the primary climate variable to which these trees respond. This is unlike the water year response found in ponderosa pine and Douglas-fir trees that grow directly on the basaltic lava on the western side of El Malpais (Grissino-Mayer 1995) and likely suggests that differing substrates (basaltic lava versus sandstone) cause trees to respond to different climate variables. This information is particularly useful because the winter-spring rainfall information available from the Middle Kipuka trees can be accounted for (or “subtracted”) from the water year response to develop yet another reconstruction of climate: summer/fall rainfall amounts, which would more closely approximate the amount of rainfall that occurs during the monsoon season in the Southwestern U.S. Future research should pay particular attention to ponderosa pine trees growing in sandstone substrate and attempt to locate remnant pine wood that is usually more resistant to decay and erosion than Douglas-fir wood. This could potentially push the current Middle Kipuka tree-ring chronology back in time.

The pygmy forest is made up exclusively of ponderosa pine, piñon pine, Gambel oak, Rocky Mountain juniper, and one-seed juniper. It is unique because the trees take a short-statured pygmy growth form, likely caused by growth-inhibiting disturbances, especially lightning strikes. The pine species make up the majority of the forest, but a large amount of young Gambel oak can be found in the wetter microenvironments. Juniper trees were the first to establish in the forest. The oldest trees in the forest are over 400 years old, but most of the forest is around 200 years old. Tree diameters are relatively narrow even for the oldest trees, which indicates suppressed growth, likely caused by the lack of nutrients found in the lava substrate and the poor moisture retention properties of the basalt surface. Because trees (especially pines) respond positively to precipitation, we expected to find strong pulses of establishment that corresponded to wet periods as indicated in the Middle Kipuka winter/spring rainfall reconstruction. We found, however, no obvious relationship between establishment and wetter climate conditions.

New growth will continue to change the age structure and the species composition as Gambel oak and piñon pine are regenerating in the forest better than the other species. We found, however, only a few seedlings and saplings of ponderosa pine, Rocky Mountain juniper, and one-seed juniper, and conclude these species are not regenerating as successfully. The pygmy forest has a history of lightning disturbance and we found this to be a main driver responsible for the pygmy growth form of these trees. Trees are struck, lightning kills the leader of the tree, and a branch takes on apical growth. As this occurs often, trees take on a gnarled, stunted shape.

While it is presently a pine-dominated forest, the pygmy forest continues to be a fire-resistant community that might be trending to an apache-plume habitat type that is more typical at lower elevations of the malpais. Nichols (1946) and Lindsey (1951) were correct in assuming these trees to be 300 years old, but we suspect that no extensive forest existed during the time the Ancestral Puebloans historically occupied the area (prior to ca. 1400). While winter/spring precipitation is a driving force for tree growth, lightning disturbance also affects tree growth. The McCarty's basalt flow is susceptible to greater convectional energy during the monsoons and therefore a greater chance of lightning activity. We conclude that the unique shapes and sizes of the various tree species found in the pygmy forest are a result of repeatedly being struck by lightning in an environment where convection and materials in the basalt enhance lightning activity.

CHAPTER FOUR

CONCLUSIONS AND FUTURE RESERACH

4.1 Research Questions

4.1.1 What trends in climate are shown by ponderosa pines growing on Middle Kipuka?

Despite being in close proximity to each other, the trees growing on Middle Kipuka and the trees growing on McCarty's basalt flow form two distinct forests. The forest of Middle Kipuka has tall, majestic, old-growth trees that date back to AD 1656. The trees are highly sensitive to climate, so the pattern recorded in the rings is distinct. Several environmental factors can drive tree growth, but statistical analyses revealed that precipitation during the winter to early spring season accounts for almost 20% of the growth for the pines on Middle Kipuka. Narrow marker rings in the Middle Kipuka chronology indicate severe drought years occurred in 1696, 1729, 1806, 1880–1881, 1901–1904, 1951, 1971, 1974, and 2002. Except for the year 2002, these are the same marker rings noted in the Malpais Long Chronology and Paxton Springs cinder cone tree-ring data (Grissino-Mayer 1995; Rother 2010). Extended periods of considerably reduced precipitation occurred from ca. 1725 to 1750, ca. 1775 to 1790, 1820 to 1835, and 1885 to 1905, with the lowest precipitation occurring in an extended period beginning ca. 1945 and lasting until 1975. Another major drought then occurred from 2000 to 2009. Above average rainfall occurred from ca. 1745 to 1770, ca. 1836 to 1860, and 1906 to 1944. The longest period of above-average rainfall occurred during the 20th century from 1975 to 1999.

4.1.2 What can age structure, stand structure, and species composition tell us about the history of the pygmy forest?

Based on estimated pith dates, the oldest trees on the McCarty's basalt flow established between the 1590s and 1610s, with the oldest individual tree being 423 years old. We did observe a few snags and dead trees within the pygmy forest that could have been living four hundred years ago, too, but we concentrated on aging only living trees. Piñon and ponderosa pines dominate the current species composition, but Gambel oak has the greatest number of total seedlings, saplings, and young mature trees present. Gambel oak dominates in only one of the seven plots, however, and may be confined to the areas of the basalt flow where depressions and valleys dominate because acorns are not easily dispersed in this rugged terrain. Piñon pine and Gambel oak showed greater regeneration when compared to the other tree species. Ponderosa pine, Rocky Mountain juniper, and one-seed juniper have very few seedlings and saplings, suggesting that these three tree species are not regenerating as effectively, if at all.

These 300 to 400 year old trees are considered old-growth trees, yet they were not around when Ancestral Puebloans lived or hunted on Middle Kipuka or when the earliest conquistadors journeyed through the region and named the area "el malpais." We were surprised to find few downed logs that would indicate equilibrium between establishment and mortality, and we are certain that fire or other disturbance processes do not remove these larger logs. We propose that this pygmy forest likely did not exist 500 years ago in its present state although a few individuals could have been found as they slowly encroached on the rugged lava landscape from the sandstone cliffs to the east. Between the years of 1650–1800, a few trees

sparsely populated the area, but the majority of the forest established between 1800 and 1980.

Rocky Mountain juniper, one-seed juniper, and piñon pine were the first to populate the basalt flow and create the pygmy forest, while the ponderosa pine became more prevalent after 1800.

Gambel oak is the youngest tree species in the forest.

4.1.3 What evidence exists that lightning strikes affect tree growth and may contribute to the pygmy forest growth form?

Lightning disturbance has become part of the character of the pygmy forest. We found an overwhelming number of scars in the pygmy forest that led us to conclude that lightning repeatedly strikes the trees that grow on the McCarty's lava flow. We found no charred dead trees or logs that could have been caused by lightning strikes, only charcoal left in the spiral scars found on living trees. The microclimate of this location is likely responsible for the high amount of lightning specifically on this relatively small amount of darker basalt. The McCarty's flow is prone to lightning activity because of the high amounts of convective storms that pass through during the monsoon precipitation that northwestern New Mexico receives in the early summer months. Lightning contributes to the pygmy growth by the damage that is left on individual trees. Distinctive signs are seen on trees, such as a stag-headed appearance, dead leaders, non-vertical growth in height, spiral scars on the bark, and other unusual shapes. The trees survive the lightning strikes, and the forest survives because the low amounts of forest litter and fuels across the landscape do not carry fire.

Lightning did not penetrate the trees further than the cambium layer immediately underneath the bark. Because the scars were small relative to the undamaged area on the trees, they were covered by new growth within a few years after the event. Many more scars could be present that were not found within these samples. The trees of the pygmy forest have rings that do not correspond to a pattern of precipitation like those found in pine trees on Middle Kipuka. Because the cores likely have many locally absent rings, we found it difficult if not impossible to crossdate the rings in trees from the pygmy forest due to the lack of a common pattern in the rings. We speculate that lightning has always been a part of this environment and contributes to the difficult tree-ring patterns we found.

4.2 Future Research

The mystery of the pygmy forest may not ever be fully understood, but a history of forest dynamics adds to the story. As a unit of the National Park Service, El Malpais National Monument will always be protected from most types of anthropogenic disturbance, and as such, the location is optimal for future environmental research. Not only are the contorted trees unique, but the location where they grow is also unique. Future research could include radiocarbon dating of charcoal found in the crevasses of the basalt to determine if evidence can be found of a previous forest where the pygmy forest presently exists. The McCarty's basalt flow attracts high amounts of lightning activity. Future research on both the specific characteristics of the McCarty's basalt flow and the convectional storm patterns during northwestern New Mexico's monsoon season is needed to conceptualize why lightning is prone

to disturb this particular forest. Lightning is our strongest hypothesis for the pygmy growth form, but it would be equally important to determine if it is the only factor causing the contorted patterns. Future studies could concentrate on a more systematic sampling of trees on the pygmy forest in all age classes to have a better chance at developing a tree-ring chronology from these trees. This would provide better data for evaluating whether or not a relationship exists between climate patterns and tree establishment. Other studies could concentrate on the root systems of these trees and how they interact with the lava substrate to facilitate water absorption and nutrient uptake. Further sampling of the piñon-juniper trees growing on top of Middle Kipuka could yield older ages for this forest and an extended climate record. Likewise, further sampling on the McCarty's basalt flow of living trees and the few snags could provide information on age structure of the earlier pygmy forest. Mapping the ages of individual trees and their locations over the basalt could determine patterns of tree dispersal across the lava flow from the surrounding sandstone cliffs. Finally, it would be interesting to compare stand dynamics of the pygmy forest with other forests in the American Southwest.

REFERENCES

- Allen, C.D. 2002. Lots of lightning and plenty of people: an ecological history of fire in the upland Southwest. Pages 143–193 in T. Vale (ed.), *Fire, Native Peoples, and the Natural Landscape*. Washington, D.C.: Island Press.
- Bleakly, D.L. 1997. Plant life on the lava—The vegetation and flora of El Malpais. Pages 113–138 in K. Mabery (ed.), *The Natural History of El Malpais National Monument*. New Mexico Bureau of Mines and Mineral Resources *Bulletin* 156.
- Brotherson, J.D., S.R. Rushforth, W.E. Evenson, J.R. Johansen, and C. Morden. 1983. Population dynamics and age relationships of 8 tree species in Navajo National Monument, Arizona. *Journal of Range Management* 36(2): 250–256.
- Brunstein, F.C. 2006. Growth-form characteristics of ancient Rocky Mountain bristlecone pines (*Pinus aristata*), Colorado. U.S. Geological Survey *Scientific Investigations Report* 2006–5219. 90 pp.
- Burt, J.E., G.M. Barber, and D.L. Rigby. 2009. *Elementary Statistics for Geographers*. New York: The Guilford Press.
- DeRosa, E.W. 1983. Lightning and trees. *Journal of Arboriculture* 9(2): 51–53.
- Duncan, R.P. 1989. An evaluation of errors in tree age estimates based on increment cores in Kahikatea (*Dacrycarpus dacrydoides*). *New Zealand Natural Scientist* 16: 31–37.
- Eury, D.E. 1997. Forward. Page 186 in K. Mabery (ed.), *Natural History of El Malpais National Monument*, New Mexico Bureau of Mines and Mineral Resources *Bulletin* 156.
- Fay, N. 2003. Lightning strikes and trees: the possible role of lightning in the tree evolution and biodiversity. *Treework Environmental Practice*. Retrieved September 2011.
www.treeworks.co.uk
- Frelich, L.E. 2002. *Forest Dynamics and Disturbance Regimes: Studies from Temperate Evergreen – Deciduous Forests*. Cambridge, U.K.: Cambridge University Press. 266 pp.
- Fritts, H.C. 1976. *Tree Rings and Climate*. Caldwell, N.J.: The Blackburn Press. 567 pp.
- Fulé, P.Z., W.W. Covington, and M. M. Moore. 1997. Determining reference conditions for ecosystem management of southwestern ponderosa pine forests. *Ecological Applications* 7(3): 895–908.

- Grissino-Mayer, H.D. 1995. *Tree-Ring Reconstructions of Climate and Fire History at El Malpais National Monument, New Mexico*. Ph. D. Dissertation, The University of Arizona, Tucson. 407 pp.
- Grissino-Mayer, H.D. 1996. A 2129-year reconstruction of precipitation for northwestern New Mexico, USA. Pages 191–204 in J.S. Dean, D.M. Meko, and T.W. Swetnam, (eds.), *Tree Rings, Environment, and Humanity*. Department of Geosciences, The University of Arizona, Tucson.
- Grissino-Mayer, H.D. 2001. Evaluating cross-dating accuracy: a manual and tutorial for the computer program COFECHA. *Tree-Ring Research* 57(2): 205–221.
- Grissino-Mayer, H.D., T.W. Swetnam, and R.K. Adams. 1997. The rare, old-aged conifers of El Malpais: Their role in understanding climatic change in the American Southwest. Pages 155–161 in K. Mabery, (ed.), *The Natural History of El Malpais National Monument*. New Mexico Bureau of Mines and Mineral Resources *Bulletin* 156.
- Grissino-Mayer, H.D., and T.W. Swetnam. 1997. Multi-century history of wildfire in the ponderosa pine forests of El Malpais National Monument. Pages 163–171 in K. Mabery, (ed.), *The Natural History of El Malpais National Monument*. New Mexico Bureau of Mines and Mineral Resources *Bulletin* 156.
- Holmes, R.L. 1983. Computer-assisted quality control in tree-ring dating and measurement. *Tree-Ring Bulletin* 43: 69–78.
- Huffman, D.W., P.Z. Fulé, K.M. Pearson, and J.E. Crouse. 2008. Fire history of pinyon-juniper woodlands at upper ecotones with ponderosa pine forests in Arizona and New Mexico. *Canadian Journal of Forest Research* 38: 2097–2108.
- Kipfmüller, K.F., and T.W. Swetnam. 2001. Using dendrochronology to reconstruct the history of forest and woodland ecosystems. Pages 199–228 in D. Egan and E.A. Howell (eds.), *The Historical Ecology Handbook: A Restorationist's Guide to Reference Ecosystems*. Washington, D.C.: Island Press.
- Laughlin, A.W., and G. WoldeGabriel. 1997. Dating the Zuni-Bandera volcanic field. Pages 25–29 in K. Mabery, (ed.), *The Natural History of El Malpais National Monument*. New Mexico Bureau of Mines and Mineral Resources *Bulletin* 156.
- Lewis, D.B. 2003. *Fire Regimes of Kipuka Forests in El Malpais National Monument, New Mexico*. Master's Thesis, The University of Tennessee, Knoxville. 145 pp.

- Lindsey, A.A. 1951. Vegetation and habitats in a southwestern volcanic area. *Ecological Monographs* 21(3): 227–253.
- Lindsey, A.A. 1997. Introduction. Pages 7–11 in K. Mabery, (ed.), *The Natural History of El Malpais National Monument*. New Mexico Bureau of Mines and Mineral Resources *Bulletin* 156.
- Lipman, P.W. and R.H. Moench. 1972. Basalts of the Mount Taylor volcanic field, New Mexico. *Geological Society of America Bulletin* 83(5): 1335–1344.
- Nichols, R.L. 1946. McCarty's basalt flow, Valencia County, New Mexico. *Bulletin of the Geological Society of America* 57: 1049–1086.
- Oliver, C.D., and B.C. Larson. 1990. *Forest Stand Dynamics*. New York City: McGraw-Hill, Inc. 467 pp.
- Orvis, K.H., and H.D. Grissino-Mayer. 2002. Standardizing the reporting of abrasive papers used to surface tree-ring samples. *Tree-Ring Research* 58(1/2): 47–50.
- Palik, B.J., and Pederson, N. 1996. Overstory mortality and canopy disturbances in longleaf pine ecosystems. *Canadian Journal of Forest Research* 26(1): 2035–2047.
- Pilote, A.J. 2012. *Interacting Effects of Fire Activity, Climate, and Habitat Diversity on Forest Dynamics, El Malpais National Monument, New Mexico, USA*. Master's Thesis, The University of Tennessee, Knoxville. 100 pp.
- Poore, R.Z., M.J. Pavich, and H.D. Grissino-Mayer. 2005. Record of the North American southwest monsoon from Gulf of Mexico sediment cores. *Geology* 33(3): 209–212.
- Robinson, S. 1994. *El Malpais, Mt. Taylor, and the Zuni Mountains: A Hiking Guide and History*. Albuquerque: University of New Mexico Press. 294 pp.
- Rother, M.T. 2010. *Influences of Climate and Anthropogenic Disturbances on Wildfire Regimes of the Zuni Mountains, New Mexico, U.S.A.* Master's thesis, The University of Tennessee, Knoxville. 153 pp.
- Rother, M.T., and H.D. Grissino-Mayer. 2014. Climatic influences on fire regimes in ponderosa pine forests of the Zuni Mountains, NM, USA. *Forest Ecology and Management* 322: 69–77.
- Savage, M. 1991. Structural dynamics of a southwestern pine forest under chronic human influence. *Annals of the Association of American Geographers* 81(2): 271–289.

- Schweingruber, F.H. 2007. *Wood Structure and the Environment*. Berlin: Springer Verlag. 279 pp.
- Sheppard, P.R., A.C. Comrie, G.D. Packin, K. Angersbach, and M.K. Hughes. 2002. The climate of the US Southwest. *Climate Research* 21: 219–238.
- Smiley, T.L., and M.A. Stokes. 1996. *An Introduction to Tree-Ring Dating*. Tucson: The University of Arizona Press. 73 pp.
- Speer, J.H. 2010. *Fundamentals of Tree-Ring Research*. Tucson: The University of Arizona Press. 333 pp.
- Spond, M.D. 2011. *Dendroclimatology and Woodland Dynamics on the Volcanic Badlands of Western New Mexico, U.S.A.* Ph.D. Dissertation, The University of Tennessee, Knoxville. 177 pp.
- Stahle, D.W., M.K. Cleaveland, H.D. Grissino-Mayer, and R.D. Griffin. 2009. Cool- and warm-season precipitation reconstructions over western New Mexico. *Journal of Climate* 22: 3729–3750.
- Stoffel, M., M. Bollschweiler, D.R. Butler, and B.H. Luckman. 2010. Tree rings and natural hazards: An introduction. Pages 3–23 in M. Stoffel et al. (eds.) *Tree Rings and Natural Hazards: A State-of-the-Art*. New York: Springer.
- Yamaguchi, D.K. 1991. A simple method for cross-dating increment cores from living trees. *Canadian Journal of Forest Research* 21: 414–416.

APPENDICES

APPENDIX 1

Pygmy Forest Plot Data

Tree identification number, species*, diameter at ground level (DGL), lightning evidence (L), pith date**, and age of trees sampled at all plots within the Pygmy Forest of El Malpais National Monument.

*Species abbreviations are as follows: *Pinus ponderosa*: PIPO; *Pinus edulis*: PIED; *Quercus gambelii*: QUGA; *Juniperus scopulorum*: JUSC; *Juniperus monosperma*: JUMO.

**Pith dates from a few cores could not be determined due to missing pieces of the core or excessive rot.

PLOT 1					
Tree ID	Species	DGL (cm)	Lightning Scar	Pith	Age
1	PIED	21.2		1939	75
2	PIED	11.2		1981	33
3	JUSC	20.8	L	1931	83
4	PIPO	15.3		1971	43
5	PIED	19.7		1831	183
6	PIPO	20.3	L	1837	177
7	PIPO	27.5	L	1777	237
8	PIPO	18.5	L	1884	130
9	PIED	20.3	L	1928	86
10	PIPO	19.2	L	1792	222
11	PIPO	18.2	L	1792	222
12	JUSC	21.7	L		
13	JUSC	21.6	L		
14	PIED	11.3		1952	62
15	PIED	8.5		1939	75
16	PIPO	18.3	L	1827	187
17	JUSC	9.3			
18	PIED	8.1	L	1788	226
19	PIED	19.4	L	1897	117
20	JUSC	6.9			
21	JUSC	6.8			
22	JUSC	5.1		1967	47
23	PIED	10.7	L	1940	74
24	PIED	19.9		1862	152
25	PIED	6.7	L	1935	79
26	PIPO	25		1818	196
27	PIED	9		1915	99
28	PIED	15.3		1924	90
29	PIED	12.9	L	1934	80
30	PIED	5		1962	52
31	PIED	10.5		1918	96
32	PIED	7.4		1803	211
33	JUSC	21.9	L	1853	161

PLOT 2					
Tree ID	Species	DGL (cm)	Lightning Scar	Pith	Age
1	PIED	22	L	1830	184
2	PIED	16.3	L	1799	215
3	PIED	31.5	L		
4	PIPO	14.1		1929	85
5	N/A	SEE #38			
6	PIED	10.2	L	1766	248
7	PIPO	25.7		1812	202
8	PIPO	21.4	L	1831	183
9	PIED	12.1	L	1927	87
10	PIPO	27.8	L	1846	168
11	PIPO	5.1		1992	22
12	JUSC	9.4		1925	89
13	PIPO	24.6	L	1824	190
14	PIED	5.7	L	1901	113
15	PIPO	13	L	1882	132
16	JUSC	6.6	L		
17	JUSC	7.7	L	1896	118
18	PIED	10.7	L	1855	159
19	PIPO	23.4		1983	31
20	PIED	14.6	L	1859	155
21	PIPO	15.1	L	1963	51
22	PIED	11.4	L	1920	94
23	PIPO	25.2	L	1950	64
24	PIPO	23.7	L	1882	132
25	PIED	9.2		1966	48
26	PIED	7	L	1830	184
27	PIED	9.2	L	1928	86
28	PIED	39.8		1866	148
29	PIPO	10.4		1941	73
30	QUGA	9		1967	47
31	QUGA	9.2	L	1959	55
32	QUGA	5.7		1976	38

33	QUGA	21.5		1965	49
34	PIPO	22.5	L	1874	140
35	QUGA	13.7		1970	44
36	QUGA	16.3		1934	80
37	QUGA	9		1973	41
38	PIPO	40.4		1784	230
39	QUGA	7.9		1961	53

PLOT 3					
Tree ID	Species	DGL (cm)	Lightning Scar	Pith	Age
1	PIPO	30.1		1956	58
2	PIPO	22.2			
3	PIPO	8.9	L	1781	233
4	PIPO	34.1	L	1867	147
5	PIPO	24.2		1935	79
6	PIED	18.5	L	1881	133
7	PIED	19.8		1909	105
8	PIPO	28.2		1900	114
9	PIED	31.6	L	1737	277
10	PIED	23.7	L	1895	119
11	PIED	25.1	L	1664	350
12	PIED	24.9	L	1792	22
13	PIED	29.9	L	1820	194
14	PIED	13	L	1814	200
15	PIED	15.8	L	1794	220
16	QUGA	21.6		1917	97
17	PIPO	26.2		1767	247
18	JUSC	13.3	L		
19	PIPO	23.7		1899	115
20	PIPO	32.9	L	1777	237
21	PIED	17.2	L		

PLOT 4					
Tree ID	Species	DGL (cm)	Lightning Scar	Pith	Age
1	PIED	7.2		1915	99
2	PIED	39.7	L	1740	274
3	QUGA	6.9		1968	46
4	QUGA	21.8		1891	123
5	JUSC	24.2	L		
6	PIED	11.7		1944	70
7	PIED	21.7		1889	125
8	PIED	13.8		1924	90
9	JUSC				
10	JUSC				
11	PIPO	23	L	1885	129
12	QUGA	17.1			
13	JUSC	59.6	L	1626	388
14	QUGA	9.9		1968	46
15	QUGA	36.6			
16	JUSC	9.5			
17	JUSC	14.5		1813	201
18	PIPO	22.8		1844	170
19	QUGA	29.7	L		
20	JUSC	9		1885	129
21	PIPO	7.3		1967	47
22	PIPO	20.3	L	1878	136
23	QUGA	17			
24	QUGA	15			
25	QUGA	7.9		1970	44
26	QUGA	17.4			
27	PIED	34.5	L	1731	283
28	QUGA	13.1		1903	111
29	QUGA	8.3			
30	QUGA	10.9			
31	QUGA	13.3	L		
32	PIPO	6.2		1991	23

33	PIPO	32.7		1842	172
34	JUSC	24	L	1745	269
35	QUGA	9.8		1975	39
36	QUGA	7.1		1957	57
37	QUGA	12.6		1900	114
38	PIED	18.8	L	1872	142
39	QUGA	11.4		1959	55
40	PIED	18	L	1932	82
41	QUGA	8.3		1975	39
42	QUGA	13.2		1942	72
43	QUGA	10.8		1947	67
44	QUGA	6.4		1964	50
45	QUGA	9.2	L	1934	80
46	QUGA	10	L	1931	83
47	QUGA	7.9			
48	QUGA	7.8		1939	75
49	QUGA	8.1		1968	46
50	QUGA	8.3		1953	61
51	QUGA	5.2		1963	51
52	JUSC	48.6	L	1910	104
53	QUGA	10.4		1961	53
54	QUGA	5.6		1974	40
55	PIPO	26.4	L	1952	62
56	QUGA	6.3	L	1959	55
57	QUGA	32.1	L	1824	190
58	QUGA	19.9	L	1964	50
59	PIPO	26.3		1878	136
60	QUGA	12.2			
61	QUGA	9.9		1924	90
62	QUGA	5.6		1931	83
63	PIPO	22.8		1951	63
64	QUGA	18.1			
65	QUGA	8.1		1934	80
66	QUGA	5.2		1952	62
67	PIED	19.5	L	1905	109
68	QUGA	14.9			
69	QUGA	16.8	L	1856	158

70	PIPO	22	L	1902	112
71	QUGA	8.2		1924	90
72	QUGA	11.8	L	1889	125
73	PIPO	19.2		1879	135
74	JUSC	58.9	L	1652	362
75	QUGA	16.7			
76	QUGA	12.1	L	1923	91
77	PIPO	22		1873	141
78	QUGA	11.9			
79	PIED	13.2	L	1860	154
80	QUGA	14.8	L		
81	PIED	10.2		1831	183
82	PIPO	13.2		1982	32
83	QUGA	6.7		1958	56
84	JUSC	7.4		1939	75
85	QUGA	11.8		1926	88
86	QUGA	7.7		1964	50

PLOT 5					
Tree ID	Species	DGL (cm)	Lightning Scar	Pith	Age
1	PIPO	15.9		1987	27
2	PIED	5.3		1978	36
3	QUGA	12.4	L		
4	PIPO	33.3	L	1736	278
5	PIPO	28.8	L	1803	211
6	PIPO	26.3	L	1875	139
7	PIPO	5.8	L	1996	18
8	PIED	14.6		1935	79
9	JUMO	13.5		1841	173
10	PIED	11.4	L	1924	90
11	PIED	10.2		1960	54
12	PIPO	19.2	L	1938	76
13	PIED	6.1		1984	30
14	PIED	14	L	1954	60
15	JUMO	36.8	L		
16	PIPO	24	L	1813	201
17	PIPO	20.6	L	1865	149
18	PIPO	34.8	L	1780	234
19	PIPO	9.6		1994	20
20	PIED	11.3	L	1896	118
21	PIED	19.1	L		
22	PIPO	13.3		1983	31
23	PIED	9.8	L	1939	75
24	JUMO	25.5	L	1735	279
25	PIED	20.6	L	1906	108
26	QUGA	8.9		1979	35
27	QUGA	7.1		1980	34
28	PIED	18.8	L	1799	215
29	QUGA	7.3			
30	QUGA	11.8		1978	36
31	PIPO	17.3	L	1938	76
32	PIPO	13.9	L	1972	42

33	PIPO	28.2	L	1715	299
34	PIPO	11.5	L	1837	177
35	PIED	35.9	L	1702	312
36	JUMO	12.6	L		
37	JUMO	15.6	L		
38	PIPO	35.5		1824	190
39	QUGA	13.1		1932	82
40	QUGA	5.6		1940	74
41	QUGA	13.7		1912	102

PLOT 6					
Tree ID	Species	DGL (cm)	Lightning Scar	Pith	Age
1	PIED	6.5	L	1934	80
2	PIPO	8.7		1984	30
3	PIPO	12.3	L	1925	89
4	PIED	10.9		1943	71
5	JUMO	13.9	L	1860	154
6	PIPO	26.5	L	1929	85
7	PIED	10.6		1953	61
8	JUMO	13.6	L	1723	291
9	PIED	12.9		1935	79
10	PIED	32.2	L	1654	360
11	PIPO	11.7	L	1924	90
12	PIPO	13.8	L	1896	118
13	PIPO	5.9		1995	19
14	PIPO	8.9	L	1976	38
15	PIED	9.6		1880	134
16	PIPO	32	L	1866	148
17	JUSC	34	L	1831	183
18	PIED	6.7	L	1945	69
19	PIPO	6.2	L	1914	100
20	JUMO	24.9	L		
21	PIED	34.7	L	1816	198
22	PIPO	18.3		1979	35
23	PIPO	12.8		1979	35
24	PIED	10.6	L	1778	236
25	PIED	12.2	L	1848	116
26	PIED	19.9	L	1872	142
27	PIPO	10.4		1983	31
28	PIED	18.3	L	1913	101
29	PIED	17.4	L	1874	140
30	PIED	6.9		1974	40
31	PIED	11.3	L	1688	326
32	PIED	11.1	L	1922	92

33	PIPO	18.1	L	1833	181
34	PIED	23	L	1686	328
35	PIPO	36.2		1806	208
36	PIPO	20.8	L	1908	106
37	PIED	13.6		1972	42
38	PIPO	21.4	L	1827	187
39	JUMO	13.6		1861	153
40	JUMO	16.8	L	1860	154
41	JUMO	13.1		1857	157
42	JUMO	10		1886	128
43	PIPO	10.2	L	1915	99
44	PIPO	9.6	L	1879	135

PLOT 7					
Tree ID	Species	DGL (cm)	Lightning Scar	Pith	Age
1	PIPO	45.8	L	1865	149
1	PIPO	29.7	L	1868	146
2	PIPO	16.3	L	1789	225
3	JUMO	44.5	L		
4	PIPO	29.8	L	1787	227
5	PIPO	26.8	L		
6	PIPO	17.7	L	1884	130
7	PIPO	37.5	L	1796	218
8	PIPO	8.7		1975	39
9	PIPO	22.1	L	1878	136
10	JUMO	7.7	L		
11	JUMO	6.2	L		
12	JUMO	44.2	L	1838	176
13	JUMO	9.2		1898	116
14	JUMO	39.7	L	1591	423
15	JUMO	39.2	L		
16	JUMO	19.1	L		
17	JUMO	34.8	L	1889	125
18	JUMO	10		1901	113
19	JUMO	12.2		1879	135
20	JUMO	15.7	L	1822	192
21	PIPO	20.1		1949	65
22	JUMO	39.2	L	1627	387

APPENDIX 2

Middle Kipuka Data

Core identification number, species*, diameter at breast height (DBH), pith date**, age, correlation with the master chronology, and mean sensitivity (relative change in ring width from year to year) of trees sampled at Middle Kipuka of El Malpais National Monument.

*Species abbreviations are as follows: *Pinus ponderosa*: PIPO.

**Pith dates from a few cores could not be determined due to missing pieces of the core or excessive rot.

Core ID	Species	DBH	Pith	Age	Correlation with Master	Mean Sensitivity
1A	PIPO	72.8	1703	307	0.80	0.55
1B	PIPO		1659	351	0.80	0.54
2A	PIPO	73.2	1722	288	0.87	0.43
2B	PIPO		1713	297	0.85	0.55
3A	PIPO	63.6	1719	291	0.83	0.37
3B	PIPO		1701	309	0.82	0.47
4	PIPO	45.9				
5	PIPO	47.4				
6A	PIPO	58.2	1813	197	0.81	0.42
6B	PIPO		1806	204	0.79	0.39
7A	PIPO	72.3	1762	248	0.85	0.74
8A	PIPO	69.2	1725	285	0.85	0.51
9B	PIPO	55	1716	294	0.77	0.63
10	PIPO	36.5				
11	PIPO	26.8				
12A	PIPO	60.2	1891	119	0.78	0.40
13B	PIPO	73.5	1719	291	0.82	0.51
14	PIPO	39.1				
15A	PIPO	50.8	1660	350	0.82	0.44
15B	PIPO		1681	329	0.85	0.67
16B	PIPO	51	1684	326	0.86	0.68
17B	PIPO	63.4	1656	354	0.86	0.84
18B	PIPO	58.2	1688	322	0.81	0.68
19A	PIPO	35.3	1713	297	0.80	0.79
19B	PIPO	25.5	1713	297	0.82	0.73
21B	PIPO	64.5	1724	286	0.76	0.60
22A	PIPO	66.7	1798	212	0.84	0.39
22B	PIPO		1867	143	0.84	0.39
23A	PIPO	59.2	1756	254	0.87	0.64
24	PIPO	67.5				
25A	PIPO	68.2	1663	347	0.74	0.39
25B	PIPO		1694	316	0.72	0.35
26A	PIPO	65	1737	273	0.82	0.49

26B	PIPO		1730	280	0.78	0.57
27A	PIPO	55.9	1662	348	0.81	0.76
28A	PIPO	88.4	1804	206	0.63	0.24
28B	PIPO		1810	200	0.65	0.24
29B	PIPO	50.5	1693	317	0.72	0.52
30B	PIPO	84.5	1659	351	0.76	0.45
31A	PIPO	35.2	1849	161	0.65	0.38
32A	PIPO	36.2	1811	199	0.72	0.45
Total:				9643	0.80	0.54

VITA

Sarah Jones Wayman grew up in Powell, Tennessee, and has many happy memories of a childhood spent exploring the Great Smoky Mountains National Park. She is the daughter of Randy (Norfolk Southern) and Trudy (homemaker) Jones of Powell, and has an older brother, Wesley Jones, and an identical twin sister Carin (Jones) Brown. She graduated in 2007 from Powell High School, after which she attended the University of Tennessee. She met Dr. Grissino-Mayer in her first geography course, and he inspired her to pursue a major in physical geography. As an undergraduate, Sarah met her husband, Clint Wayman, when they were both members of the Pride of the Southland Marching Band. She earned a Bachelor of Arts in Geography in May 2011 and went on to work for a Master of Science in Geography with a concentration in dendrochronology, dendroecology, biogeography, and physical geography with Dr. Grissino-Mayer as her advisor.

At UT, Sarah worked as a Graduate Teaching Assistant in Fall 2011–Spring 2012, and as Head Graduate Teaching Assistant during Fall 2012. During the Spring 2013 semester, she took time off to serve as a Geography Intern for the National Geographic Society in Washington, D.C., and to lead the U.S.A. delegation in a peace building and global friendship camp called Children’s International Summer Villages in the Czech Republic. Sarah wishes to teach others to appreciate their environment for her career. Sarah and Clint married in August 2013, and together they plan to see the world, have children, continue to learn, and serve The Lord.