

**Dynamics of Juniper Invaded Grasslands and Old-Growth
Woodlands at Wupatki National Monument, Northern Arizona,**

USA

By Frank C. Hassler Jr.

**A Thesis Submitted in Partial Fulfillment of the Requirements
for the Degree of Master of Science in Forestry**

Northern Arizona University

May 2006

Approved:

John D. Bailey, Ph.D., Chair

David W. Huffman, Ph.D.

Neil S. Cobb, Ph.D.

Abstract:

**Dynamics of Juniper Invaded Grasslands and Old-Growth Woodlands at
Wupatki National Monument, Northern Arizona, USA**

Frank C. Hassler Jr.

Land managers at Wupatki National Monument in northern Arizona, USA have become increasingly concerned about expansion of *Juniperus monosperma* (Engelm.) Sarg.(one-seed juniper) into the semi-arid grassland ecosystem. I reconstructed recruitment rates and tree densities by means of dendrochronological analysis within the Monument and south of it on the Coconino National Forest. Size attributes (height, drip line, stem diameter) of 216 juniper trees were measured. A root collar cross section of select trees were removed for dendrochronological analysis.

The most consistent correlation between age and size among all trees was a simple linear regression of stem diameter: $y = 0.6890578 + 0.0706339 x$, where x = years of age and y = stem diameter in cm. This regression had an R^2 value of .785. The correlation between age and size of trees in more droughty environments was more difficult to predict than trees in less stressful environments. This strong correlation of stem diameter to age likely reflects the fact that growth patterns of *J. monosperma* in arid woodlands are different than those of other tree species competing for resources in a traditional forest environment. I recommend that land managers use the diameter of the largest stem of *J. monosperma* to evaluate tree age and stand age structure.

Juniper trees became established in the young juniper "savanna" stands within the Monument within the last 200 years. In these past grasslands, trees of all ages were found to be equally susceptible to wildfire-induced mortality, with an average of 55% mortality. Prescribed fire can therefore be an effective management tool for maintaining grassland and open savanna conditions.

Conversely, denser, juniper woodland stands on the adjacent National Forest appear to have been established for 700 years or more. Little evidence of low severity surface fires was found in these areas. Therefore, it seems that the fire regime and overstory structure of these older juniper woodlands has not been significantly altered by fire suppression and grazing in the last 150 years. Subsequently, there is no ecologically-based motivation for thinning, prescribed fire or other high-intensity "restoration" activities and management of these stands.

Acknowledgements

I would like to thank the National Park Service and the NAU School of Forestry Mission Research Program for providing the funding which made my research and this thesis possible.

Special Thanks to: Bryan Zebrowski, Robert Speers, Cindy Parker and my advisor John Bailey for teaching me the ropes and helping me get things done.

Additional Thanks to: Mark Brell, Raul Castro, Jeremy Derekson, Shawn Fiaella, Maria Irwin, Jon Lamb, and Tyler Ward, Paul Whitefield and Brian Zebrowski and anyone in the Silviculture Lab who I failed to mention here. Also, thanks to Brent Burch, Roy St. Laurent and others at the Statistical Consulting Lab. And thanks to my committee members Neil Cobb, Catherine Gehring, Dave Huffman and Paul Whitefield.

And a final thanks to my wife Carol for her emotional, financial, and at the worst of times, physical support over the past 2.5 years. I don't know what I'd do without her.

Table of Contents

ABSTRACT:	2
DYNAMICS OF JUNIPER INVADED GRASSLANDS AND OLD-GROWTH WOODLANDS AT WUPATKI NATIONAL MONUMENT, NORTHERN ARIZONA, USA	2
ACKNOWLEDGEMENTS	4
TABLE OF CONTENTS	5
LIST OF TABLES	8
LIST OF FIGURES	9
PREFACE	12
CHAPTER 1: LITERATURE REVIEW	15
Wupatki National Monument	15
Site Description.....	15
Site History.....	16
History of the Monument	17
Semi-arid grasslands	18
Piñon-juniper and juniper woodlands	20
Encroachment: The expansion into grasslands and infill of woodlands	23
Fire exclusion as the driver of encroachment	24
Other causes of expansion and infilling	25
Stability and natural “succession” in piñon-juniper forests	27
Juniper Allometrics	28
Research Questions	29
LITERATURE CITED	32
CHAPTER 2: ALLOMETRIC RELATIONSHIP FOR <i>JUNIPERUS MONOSPERMA</i> IN AND NEAR WUPATKI NATIONAL MONUMENT, NORTHERN ARIZONA	41
Abstract	41

Introduction.....	42
Methods	44
Site Description.....	44
Stands	48
Stand Description.....	49
Sample Plots.....	51
Tree Measurements.....	52
Tree Cross Section Samples.....	54
Data Analysis	56
Results.....	58
Discussion.....	59
Best Model Forms.....	59
Understanding predictability	61
Comparing growth rates	62
Conclusion.....	64
LITERATURE CITED	66
FIGURES.....	70
CHAPTER 3: ESTABLISHMENT OF <i>JUNIPERUS MONOSPERMA</i> IN INVADED GRASSLANDS AND OLD-GROWTH WOODLANDS IN AND NEAR WUPATKI NATIONAL MONUMENT, NORTHERN ARIZONA	80
Abstract	80
Introduction.....	81
Methods	82
Site Description.....	82
Site History.....	83
Stand Description.....	84
Tree Measurements and Samples	84
Lab Methods	85
Data Analysis	86
Results.....	87
Comparing <i>J. monosperma</i> densities.....	87
Comparing <i>J. monosperma</i> Establishment.....	88
Fire Evidence	88
Discussion	89
The effects of bedrock type on <i>J. monosperma</i> populations.....	89
Densities of woodlands and savannas	90
Establishment of juniper woodlands and savannas at Wupatki.....	91
LITERATURE CITED	95

FIGURES.....	99
 CHAPTER 4: FUTURE TRENDS AND MANAGEMENT CONSIDERATIONS OF <i>JUNIPERUS MONOSPERMA</i> SAVANNAS AND WOODLANDS IN AND NEAR WUPATKI NATIONAL MONUMENT, NORTHERN ARIZONA.....	
Introduction.....	105
Methods	107
Field Work	107
Modeling <i>J. monosperma</i> establishment.....	108
Results and Discussion	110
Modeling Juniper Encroachment	110
Modeling Management Effects.....	111
Juniper Encroachment as Succession	112
Juniper Encroachment as a Biological Invasion	113
 LITERATURE CITED	 115
 FIGURES.....	 118

List of Tables

<i>Table 2.1. Attributes of the six stands included in this study.</i>	<i>70</i>
<i>Table 2.2. Detailed description of percent live crown categories as defined for this study.</i>	<i>70</i>
<i>Table 2.3. Chart of the growth models used in this chapter displaying the formula, variables used and a brief description of the model.</i>	<i>70</i>
<i>Table 2.4. Results of simple linear regression of age (x) predicting stem diameter in cm (y) for each stand and blocks of stands. The gray numbers in the columns "Slope prob>t" and "y intercept prob>t" highlight that those numbers indicate the slope is not different from zero or that the y intercept is not different from zero.</i>	<i>71</i>
<i>Table 2.5. Results of regression of ln of age (x) predicting tree height in meters (y) for each stand and blocks of stands. The gray numbers in the columns "Slope prob>t" and "y intercept prob>t" highlight that those numbers indicate the slope is not different from zero or that the y intercept is not different from zero.</i>	<i>71</i>
<i>Table 2.6. Results using age (x) in the monomolecular growth model to predict tree height in meters (y) for each stand and blocks of stands.</i>	<i>72</i>
<i>Table 3.1. Summary of research questions, data and results of analysis. Density is in units of trees per hectare (tph), establishment is in units of calendar years.</i>	<i>99</i>

List of Figures

Figure 1.1. Location of Wupatki National Monument (in orange), 45 miles NNE of Flagstaff, AZ on the southern Colorado Plateau.	40
Figure 2.1. Wupatki National Monument Test area with stands, sample plots and elevation.	73
Figure 2.2. Vegetation cover types at the Wupatki National Monument study area courtesy of Hansen et al. 2004. Light grey represents grassland areas, dark grey represents woodland areas and the intermediate grey represents other community types. Hansen et al. did not recognize savannas as distinct community types.	74
Figure 2.3. Graph of Model A, the linear fit of stem diameter as predicted by age, for the block of All stands. The regression equation is $y = 0.6890578 + 0.0706339 x$, $R^2 = .785$. Solid line indicates the linear fit of the regression.	75
Figure 2.4. Graph of Model B, the linear regression of height as predicted by the log of age, for the block of all stands. $R^2 = .686$	75
Figure 2.5. Graph of Model C, height as predicted by age using the monomolecular growth model, for the block of all stands. $R^2 = .695$	76
Figure 2.6. Graph of Model A, the linear fit of stem diameter as predicted by age, for the block of savanna stands. The regression equation is $y = 0.815772 + 0.0688178 x$, $R^2 = .367$. Solid line indicates the linear fit of the regression.	76
Figure 2.7. Graph of Model A, the linear fit of stem diameter as predicted by age, for the block of woodland stands. The regression equation is $y = 0.8828239 + 0.0701818 x$, $R^2 = .712$. Solid line indicates the linear fit of the regression.	77
Figure 2.8. Graph of Model B, the regression of height as predicted by the log of age, for the block of savanna stands. $R^2 = .464$	77
Figure 2.9. Graph of Model B, the regression of height as predicted by the log of age, for the block of woodland stands. $R^2 = .601$	78
Figure 2.10. Graph of Model C, the regression of height as predicted by age using the monomolecular model, for the block of savanna stands. $R^2 = .457$. ..	78
Figure 2.11. Graph of Model C, height as predicted by age using the monomolecular model, for the block of woodland stands. $R^2 = .613$	79
Figure 2.12. Graph of Model A, the linear fit of stem diameter as predicted by age, for the block of AF and WFN (solid line). Slope = 0.0961257, $R^2 = .622$.	

Solid line indicates the linear fit of the regression. Dashed line indicates the linear fit when the intercept is forced to zero, with a slope of 0.0903055. 79

Figure 3.1. Distribution of plots by density when blocked by basalt and limestone bedrock types. Note the substantial separation between higher density woodland plots and lower density savanna plots. Histograms are not to scale. 100

Figure 3.2. Distribution of plots by density when blocked by habitat type. Histograms are not to scale. 100

Figure 3.3. Mean density of stands in woodland and savanna environments in trees per hectare (tph). Error bars represent the maximum and minimum densities observed in each habitat type (maximum value for woodland is 256.8 tph). 101

Figure 3.4. Distribution of juniper tree establishment dates when blocked by bedrock type. Histograms are not to scale. 102

Figure 3.5. Distribution of juniper establishment dates when blocked by habitat type. Note that all of the savanna trees have become established within the past 200 years. Histograms are not to scale. 102

Figure 3.6 (a and b). Establishment dates of junipers sampled from savanna stands (3.6a, left, n=90) and woodland stands (3.6 b, right, n=126). The dotted lines indicate the approximate date of initial heavy grazing impacts in the vicinity. 103

Figure 3.7 (a and b). The average juniper establishment per decade based on frequency of establishment and average juniper density in savanna (3.7a, left) and woodland (3.7 b, right) stands. The dotted lines indicate the approximate date of initial heavy grazing impacts in the vicinity. 104

Figure 4.1 (a and b): Two research plots in savanna stands as seen from aerial photographs in 1936 (left) and again in 1997 (right). Encroaching junipers appear in these photos as black dots. Juniper encroachment is more intense in some sites than in others. 118

Figure 4.2 Establishment of woodland trees as projected by allometric relationships (grey bars) in t/km² per decade. The dotted line indicates the approximate date of the initiation of grazing impacts. 119

Figure 4.3. Establishment of savanna trees as projected by allometric relationships (grey bars) in t/km² per decade and a population growth model for juniper woodland stands since 1850 AD to 2000 AD (black line) in units of t/km² and calendar year. The population model is based on an

intrinsic growth rate of .010, a population carrying capacity of 9,000 t/km² and with an initial population of n=275. 119

Figure 4.4: Establishment of savanna trees as projected by allometric relationships (grey bars) in t/km² per decade and a population growth model for juniper woodland beginning in 1850 AD and projected to 2600 AD (black line) in units of t/km² and calendar year. The population model is based on an intrinsic growth rate of .010, a population carrying capacity of 9,000 t/km² and with an initial population of n=275. 120

Figure 4.5: Population growth model for juniper savanna stands beginning in 1850 AD and projected to 2600 AD (black line) with compensation for 45% mortality due to fire with a fire return interval of 30 years. The logistic models for Powerline Mesa and Antelope Prairie South stands are included for comparison. 120

Figure 4.6: Population growth model for juniper savanna stands beginning in 1850 AD and projected to 2600 AD (black line) with compensation for 35% mortality due to fire with a fire return interval of 10 years for the first 40 years and a 20 year fire return interval following that. The dotted line represents the present time. Note the slow but steady increase in population size..121

Figure 4.7. Two models of succession in juniper encroached systems. 121

Preface

Euro-American settlement brought many changes to the arid Southwest United States. Land uses such as grazing, water development and logging had a substantial impact on the biological communities of the region. Riparian degradation, widespread soil erosion and forest compositional and structural changes receive much of the attention of conservationists. The encroachment of woody species into semi-arid grasslands is a critical conservation issue that has received less attention.

The total area of grassland habitat in the southwestern United States has significantly declined during the past 150 years (Kearney and Peebles 1960, Dick-Peddie 1993, Brown 1994a). Historically, semi-arid grasslands were maintained by wildfires with a return frequency of 15-25 years (Cinnamon 1988), and possibly as frequent as every 5-10 years (Wright and Bailey 1980). The reduction of fine fuels due to cattle grazing and subsequent fire suppression, has favored the establishment of juniper woodland in the upper elevation range of grassland habitat (Foster 1917, Leopold 1924, Johnsen 1962, Bogan et al. 1998, Grahame and Sisk 2002).

Repeat photography, packrat midden analysis, historic vegetation maps, and limited vegetation plot data suggest that, during the last 140 years, *Juniperus monosperma* (Engelm.) Sarg.) (one-seed juniper) has expanded both downward in elevation and northward into Antelope Prairie in Wupatki National Monument (WUPA) in Northern Arizona (Merriam 1898, Cinnamon 1988, Ffoliott and Gottfried 2002).

Increased shading by juniper trees and competition for resources, especially water, has led to a dramatic reduction in species richness in these grasslands (Arnold, 1958; Tausch and West, 1994). Land managers at Wupatki are concerned that the loss of

grassland habitat has had a significant negative impact on grassland dependant species, most notably pronghorn antelope (*Antilocapra americana*) (Neff 1986). In this thesis I have examined this case of juniper encroachment by looking at the establishment and stand conditions of these junipers.

First, I examined the relationship between age and size within *J. monosperma* at this site. The relationship of age to various aspects of juniper tree growth is different from trees in more mesic forest environment. *Juniperus* typically live in arid environments, often on sites with poor soil. They are particularly dominant in both highly arid and cold arid environments (Arnold et al. 1964, Lajtha and Getz 1993, Linton et al. 1998). Sunlight is abundant in these environments, however, moisture is lacking. Thus juniper trees do not often compete with each other for ‘canopy’ space, instead they compete for water. By studying the age/size relationships in these trees I gained a better understanding of how they cope with the harsh environmental conditions in which they thrive. By exploring the allometrics of *J. monosperma* I also provide land managers with useful tools which will allow them to quickly assess the age of juniper trees in a stand and thus have a better understanding of the ecology and history of a stand.

Second, I determined the establishment patterns among trees in the juniper savanna within Wupatki National Monument and among the trees in the juniper forest on the adjacent Coconino National Forest. My goal was to evaluate the age structure of these stands and determine if their establishment, or an increase in tree density, follows the regional pattern corresponding to Euro-American settlement. I determined that the establishment of juniper stands within Antelope Prairie is relatively recent and likely correspond to the influences of cattle grazing, but that the juniper woodlands on the

Coconino National Forest were old-growth woodlands with stand ages of up to 700 years. This information will give land managers at Wupatki knowledge that will be useful for developing management practices. This information also adds to the somewhat limited pool of knowledge regarding the stand dynamics of juniper woodlands.

Third, I used population growth modeling to explore how these juniper stands might change over time and how current and future management practices would affect them. This modeling will help land managers better understand what actions will be needed to restore the juniper savanna areas in Antelope Prairie back to semi-arid grasslands. The knowledge derived from this paper will help us understand biological communities that are often ignored. This project is an important step in developing sound management practices to preserve and restore both grasslands and juniper woodlands.

Chapter 1: Literature Review

Wupatki National Monument

Site Description

Wupatki National Monument (WUPA) lies on the southern Colorado Plateau, approximately 45 km (28 miles) northeast of Flagstaff Arizona. The monument encompasses 14,335 hectares (35,422 acres) (Figure 1.1). The elevation within Wupatki ranges from 1,310 m (4,300 ft) along the Little Colorado River at the northeast corner of the monument to 1,740 m (5,710 ft) in the southwest corner of the park along U. S. Highway 89.

The average annual rainfall at WUPA is 20.8 cm (8.2 inches). Over 50% of this precipitation falls between late July and early September during the summer rain or “monsoon” season. The mean annual temperature at Wupatki is 14.4 C (57.9 F) with an average high in July of 35.2 C (95.3 F) and an average low in January of -4.2 C (24.5 F). All climatic data for the monument is recorded at the Wupatki Visitor Center (elevation 1,490 m (4,900 ft) (Western Regional Climate Center 2005). Precipitation and temperature can vary widely in the monument with higher elevation locations being considerably cooler and moister than lower elevation sites (USDA 1971).

The monument encompasses a sizable natural area, which includes desert scrub, semi-arid grassland and juniper woodland vegetation communities. Shale and sandstone of the Moenkopie formation underlay the eastern portion of the monument which lies below the Doney Monocline. The western portion of the park, an area known as Antelope Prairie, is a mix of Kaibab limestone bedrock, overtopped by basalt which

formed from lava flows of the San Francisco Peaks volcanic field (USDA 1971). The majority of Antelope Prairie is grassland or juniper savanna with juniper trees being more dominant on rocky and more broken terrain (Cinnamon 1988). The research area for this study includes the grasslands and savannas of Antelope Prairie as well as the adjacent juniper and juniper-piñon woodlands south and upslope of Antelope Prairie on the Coconino National Forest.

Site History

Beginning around 675 A.D. the Sinagua people began to inhabit and develop agriculture and permanent structures in the area around the San Francisco Peaks, primarily north and east of present day Flagstaff Arizona (Short 1988, Anderson 1993). Between 1064 and 1180 A.D., a series of eruptions of nearby Sunset Crater forced these people to flee their pit homes and move northward to lower elevation sites in the arid Wupatki Basin (Short 1988, Anderson 1993, SUCR 2005). Here the resulting volcanic ash and cinders allowed for dry farming on land that previously would have been too arid for agriculture. The ancestral Hopi culture flourished here for about 150 years before these pueblo sites were abandoned around 1250 A. D. (Short 1988, Anderson 1993). The reasons for the abandonment of these pueblos are unknown, but this region-wide phenomenon may have been the result of drought, climate change, or war (Johnson 1996).

Captain Lorenzo Sitgreaves was the first Euro-American to document the ruins in present day Wupatki National Monument as he traveled through the area in 1851 (Thybonny 1987). The area was only sparsely used by the Hopi and Navajo people until the mid-19th century, at which time grazing was the primary land use in the region

(Cinnamon 1988). Navajo sheep herding was intense in the years leading up to the Navajo War in 1863. However, these herds were diminished considerably as a result of the war (Roberts 1993). In the period following the war, roughly from 1868 to 1892, Navajo herd numbers again rapidly increased in the area (Roberts 1993); their grazing land included land which would become Wupatki National Monument (Short 1988). The Navajo continue to graze sheep and cattle in the region to this day (Grahame and Sisk 2002). In fact, the Navajo Nation currently controls the grazing rights to the portion of the Coconino National Forest that was part of the study area for this project (Hannemann 2004). Considering the proximity of the Navajo Nation to Wupatki National Monument, it is assumed that this long history of grazing had an impact on the ecosystem within the monument.

Euro-American cattle grazing began to have an impact as early as 1886 when William and Charles Babbitt formed the C O Bar ranch. They grazed cattle on the land that would later become Wupatki National Monument as public domain (Trimble 1982). The intensity of cattle ranching increased quickly with between 24,000 and 40,000 head of cattle ranging the vast CO Bar ranch in the years between 1909 and 1917 (Cinnamon 1988).

History of the Monument

Wupatki National Monument was originally established in 1924 to protect ancestral Hopi sites from looting and other damage (Noble 1993). The monument was expanded significantly in 1937, from the original 656 ha (1,620 acres) to 13,610 ha (33,631 acres). At the time of this expansion, the CO Bar Cattle Company was granted grazing rights within the monument in accordance with National Park Service grazing

guidelines, and they used portions of the monument for winter range (Cinnamon 1990). There have been several smaller expansions of the monument since 1937, in order to protect additional archeological resources (WUPA 2002). Almost 2,700 documented archaeological sites can be found within the monument with many more in the surrounding national forest, tribal and private land (NPS 1990). Cattle grazing continued in the monument until 1989 when the grazing permit expired and a fence was constructed along the park's boundary (Cinnamon 1990).

Semi-arid grasslands

According to Brown (1994) the grassland of Antelope Prairie in Wupatki National Monument are of the plains grassland type, though Wupatki is in the region of transition to the Great Basin grassland type. Dick-Peddie (1993) terms this same type as plains-mesa grassland. Both authors agree that the defining attribute of this grassland type is the dominance of short (< 0.5 m), drought tolerant grasses, specifically *Bouteloua gracilis* (Willd. ex Kunth) Lag. ex Griffiths (blue grama). Other common grasses include *Hilaria jamesii* Torr. (galleta grass), *Achnatherum hymenoides* (Roemer and J.A. Schultes) Barkworth (indian ricegrass) and *Hesperostipa comata* (Trin. and Rupr.) Barkworth (needle-and-thread grass) (Dick-Peddie 1993). Other common plants include sub-shrubs such as *Chrysothamnus* spp. Nutt. (rabbitbrush) and *Gutierrezia* spp. Lag. (snakeweed), forbs that are most strongly represented by the sunflower family (Asteraceae), and succulents such as cacti (Cactaceae) (Brown 1994). However, these shrubs and forbs constitute less than 10% of the flora (Heerwagen 1956). In cases of excessive grazing, shrubs, snakeweed in particular, will be more conspicuous, as will rabbitbrush and other less palatable "weedy" forbs (Brown 1994). Plains grasslands typically receive between

30 cm and 46 cm annually. The majority of this precipitation falls during the winter or during the summer monsoon season (Brown 1994). Hansen et al. (2004) specify the grasslands at Wupatki as being composed primarily of Galleta Mixed Grasslands, with several other community types intermixed, including Rabbitbrush Shrubland, Black Grama Coconino Plateau Shrubland, Galleta Mixed Shrublands and Needle-and-Thread Grassland.

Information on the plains grassland type is limited whereas literature pertaining to desert grasslands and Great Basin grasslands is more prevalent. Therefore, for the purposes of this review the grassland at Wupatki will be generalized and referred to as a semi-arid grassland and utilize the greater pool of knowledge pertaining to these semi-arid grasslands. This is justified on the grounds that, Wupatki is in a region of the plains grasslands type which is transitional, and therefore similar to, the Great Basin grassland type. In addition, the study site is in close proximity to desert grasslands in central Arizona, and shares several similarities with these grasslands, such as the exceptionally arid nature of the climate at Wupatki (Western Regional Climate Center 2005) compared to other plains grasslands (Brown 1994).

Semi-arid grasslands in the Southwest are typically found at elevations between 1,000 and 1,800 m (3,300 to 6,000 ft), situated between piñon-juniper woodlands at higher elevations and semi-arid scrub communities at lower elevations (Van Auken 2000, Grahame and Sisk 2002). These grasslands generally inhabit areas with gentle grades that historically allowed frequent lightning-ignited fires to carry across the landscape. These frequent fires maintained the dominance of grasses and forbs over woody plants (Leopold 1924, Humphrey 1958, Wright and Bailey 1980, Van Auken 2000). Trees such as

Juniperus sp. were excluded by fire at the higher elevation ranges of these grasslands (Johnsen 1962), while at lower elevations fire kept shrub species at bay (Van Auken 2000).

Though several studies have touched on the subject (Leopold 1924, Johnsen, 1962, Cinnamon 1988), there is not a rigorously established fire return interval for semi-arid grasslands, except to say that it is 'frequent'. Ascertaining historical fire frequencies in grasslands is difficult because there are no trees to retain fire scars. Written records of such events are often anecdotal (Hasting 1959). Write et al. (1979) suggested that a fire return interval of 20-30 years would be necessary to prevent the invasion of *Juniperus* into grasslands and shrublands. Brown and Smith (2000) cite an approximate fire return interval of 10 years for arid grasslands. One study of fire scars on a grassland/juniper woodland ecotone in Wupatki National Monument reported a fire return interval of 15-25 years (Cinnamon 1988). However, it is possible that the return interval in pure grassland, where fine fuels are more abundant and consistent, is higher. Fires in the shortgrass prairie, a grassland type very similar in structure and floristic composition to semi-arid grasslands, probably occurred every 5-10 years (Wright and Bailey 1980).

Piñon-juniper and juniper woodlands

Piñon-juniper (PJ) woodlands cover about 29 million hectares in the western United States and are a major component of southwestern wildlands (West 1999). Pinyon-Juniper woodlands are typically distributed at elevations of 1,370 to 2,290 m (4,500 to 7,500 ft) (Gottfried *et al.* 1995), though generally limited to rocky outcroppings at lower elevations (Arnold et al. 1964). These are the most xeric forest types in the

United States, typically receiving 25 cm to 40 cm of precipitation annually (Budy and Meeuwig, 1987). The climate of PJ woodlands in the is generally consists of cool wet winters and hot dry early summers, with a wet late summer monsoon. The soils in PJ woodlands vary greatly over the broad geographical and geological range where PJ woodlands are found and are derived from a variety of parent materials (Pieper 1977, Gottfried 2004). However, generally soils in PJ woodlands are coarse, shallow and low in fertility (Pieper 1977).

Four species of juniper and two species of piñon pine typically compose these woodlands on the Colorado Plateau. The junipers include *Juniperus osteosperma* Torr. (Utah juniper), *Juniperus monosperma* Engelm. (one-seed juniper), *Juniperus deppeana* Stend. (alligator juniper) and *Juniperus scopulorum* Sarg. (Rocky Mountain juniper). The most common piñon species is *Pinus edulis* Engelm. (Colorado piñon pine), however, *Pinus monophylla* Torr. and Frem. (single-leaf piñon pine) can also be found throughout the region (Gottfried 2004). These small trees are well adapted to the arid conditions (Budy and Meeuwig, 1987).

Juniperus are more drought tolerant than piñon pines. Linton et al. (1998) reported that *Juniperus* are tolerant of conditions drier than those that are found in their typical habitat. Therefore, stands of pure juniper woodland or savanna will exist where conditions are too dry or cold for piñon species (Arnold et al. 1964, Lajtha and Getz 1993). As a result of the dominance of juniper species in most communities, West (1999) suggests referring to these woodlands as “juniper-piñon” vegetation type. Pure juniper stands are a significant component woodlands classified as Pinyon-Juniper. In Arizona, PJ woodlands cover 3.1 million hectares, 40 percent of the forested land in the state. An

additional 1.3 million hectares, or 16% of the forested land in Arizona, are classified as pure juniper. For comparison, ponderosa pine forests cover only 1.2 million ha in Arizona (O'Brien 2002).

Despite the limited number of dominant tree species, PJ woodlands include a variety of understory associations and habitat types (Evans 1998). The forest service distinguishes 32 plant community types dominated by piñon pines and 23 dominated by juniper species (Bogen et al. 1998). Moir and Carleton (1987) recognize at least 70 plant associations within the PJ woodland type. West et al. (1998) classified PJ woodlands into 45 Series, 183 Associations and 326 Sub-Associations. The composition of the understory is often similar to that of nearby grasslands, shrublands and chaparral, though typically more sparse, and includes a variety of drought tolerant grasses, shrubs, forbs and succulents. Understory vegetation is more abundant in more open woodland and savanna stands. Conversely, in more dense forest stands there may be little to no understory vegetation (West 1999).

Historical fire regimes in PJ woodlands are poorly understood (Baker and Shinneman 2004). For example, one study in northeast California found that regular, low intensity surface fires produced fire scars and maintained an open *J. occidentalis* woodland (Young and Evans 1981). Another study in southwest Colorado found that PJ forests in Mesa Verde National Park showed little sign of low intensity fires; instead evidence pointed to a high intensity stand replacing fire regime with a return interval of 400-480 years (Floyd et al. 2000). The confusion likely stems from the great variety of PJ communities that, in turn, have various fire regimes.

Romme et al. (2003) suggest three general piñon-juniper community types. Piñon-Juniper Grass Savanna historically had the highest fire frequency. These low-intensity surface fires thinned encroaching trees and maintained an open woodland structure. In Piñon-Juniper Shrub Woodlands there were moderately frequency, high-severity crown fires carried by the shrub understory. In these communities trees would become established and live for short periods between fires, however fire suppression has altered this process. Piñon-Juniper Forests are found on soils and topographic conditions that prevent frequent fires from occurring. These 'old growth' PJ forests experience rare, intense, stand replacing fires.

Encroachment: The expansion into grasslands and infill of woodlands

Piñon-juniper woodlands and semi-arid grasslands have been greatly impacted by Euro-American settlement and the intensive land use associated with this culture. As early as 1924, Aldo Leopold suggested that cattle grazed the once abundant grasses and forbs to the point that there was insufficient surface fuel to carry regular wildfires. Due to the lack of these regular low intensity surface fires, decreased competition from the ground layer, and possibly increased atmospheric CO₂ levels, woody species, including piñons and junipers, have greatly expanded their populations in the northwest United States (Burkhardt and Tisdale, 1976; Young and Evans, 1981; Evans, 1988, Miller and Rose 1995, Soulé et al. 2004) and in the Southwest U. S. (Johnsen 1962, Arnold et al. 1964, Dick-Peddie 1993, Van Auken 2000). There is however evidence that this trend is not universal (Yorks et al. 1994). The result is infill of piñon pine and juniper species to create dense woodlands where there were once more open woodland environments, and the expansion of these woody species into areas that were once grassland (Cottam and

Stewart 1940, Tausch et al. 1981, Van Auken 2000). These processes together are typically termed as encroachment.

Fire exclusion as the driver of encroachment

Euro-American settlement and associated livestock grazing had a substantial impact on the natural fire regime in semi-arid grasslands and piñon-juniper woodlands. Many scholars have suggested that the overstocking of both cattle and sheep eliminated the grass fuels required to carry low intensity wildfires (Leopold 1924, Johnsen 1962, West 1984). As a result, the primary barrier to juniper tree establishment in grasslands was eliminated. Leopold (1924) observed both piñon and juniper trees and shrubs such as manzanita (*Arctostaphylos uva-ursi* (L.) Spreng. Kinnikinnick sp.), snakeweed (*Gutierrezia* sp. Lag.) and sagebrush (*Artemisia* sp. L.) invading areas which were once grassland. He also noted that there was often increased soil erosion associated with this change in cover type, as have later researchers (Price 1993, Wilcox and Davenport 1995, Davenport et al. 1996).

The period of greatest grazing impacts was around the turn of the century, (Leopold 1924, Johnsen 1962, Barney and Frischknecht 1974, Bedell 1987, Van Auken 2000). Later research found that this woody encroachment was a continuing process in some cases, (Burkhardt and Tisdale 1976, Knapp and Soule 1998) however at other sites it was found that encroachment had ceased by the middle of the 20th century (Johnsen, 1962, Ffolliott and Gottfried 2002).

A century of intense grazing has severely reduced the productivity of grasses and other forage plants (van Langevelde et al. 2003). Additionally, juniper trees and woody shrubs can out-compete grasses for soil moisture (Johnsen 1962, Jeppesen 1978, West

1984, Teidman and Eddleman 1987). As a result of these factors tree density increases and herbage cover decreases (Arnold 1964, Pieper 1990). This loss of herbaceous species effectively eliminate fine fuels and thus surface fires from the system (Archer 1994) preventing reestablishment of grassland or savanna conditions by means of natural or prescribed fire (Tausch et al. 1981, West 1984). With fire unable to impact the system and maintain grass dominance, these ecosystems cross an ecological threshold, becoming increasingly dominated by woody species and eventually the grassland or savanna is replaced with scrubland or forest (Laycock 1991, Fuhlendorf et al. 1996).

Interestingly, direct fire suppression efforts are of little consequence to the fire exclusion process in these communities. In the Southwest, organized fire suppression efforts did not begin until the early 20th century. (Friederici 2003). By that time, the reduction of fuels due to cattle grazing had likely already all but eliminated natural high frequency, low intensity fires (Touchan et al. 1995).

Other causes of expansion and infilling

In addition to the alterations of the fire regime, grazing suppressed grasses, giving woody species, which are not directly consumed by cattle, a direct competitive advantage (Barney and Frischknecht 1974, West 1984). Johnsen (1962) attributed competition from grasses and forbs as a major cause of the historic exclusion of juniper trees from semi-arid grasslands. With the reduction in vigor of grasses due to heavy grazing, their ability to compete with junipers was reduced. He argues that, neither fire nor competition alone could have accounted for the exclusion of junipers, however their combined effects could prevent the establishment of juniper trees. Additionally, cattle and sheep facilitate the

distribution of juniper seeds by consumption and defecation of the “berries” (Johnsen 1962, Arnold et al. 1964).

Climatic oscillations and global warming have also been proposed as mechanisms involved in the increasing abundance of *Juniperus* in the western U.S. (Soulé et al. 2004). Though climate is a primary factor affecting ecosystem assemblages world-wide, climate is unlikely a mechanism of the last 150 years of encroachment. Warmer, dryer conditions experienced through much of the 20th century would actually favor grasses over junipers (West 1984, Van Auken 2000) as has been shown by evidence from prehistoric periods of climatic oscillation (Miller and Wigand 1994). Although climate does not appear to be a direct factor involved in juniper encroachment, it’s important to view our present situation in the greater context of climate shifts and regional wide species migrations as they respond to these changing conditions.

Increased atmospheric CO₂ levels is another potential cause of encroachment. Although increased CO₂ should favor C3 woody plants over C4 grasses, there is little empirical evidence to support the CO₂ hypothesis. The period of greatest increase in CO₂ in the atmosphere (the latter half of the 20th century) does not correspond well to the period of greatest juniper establishment (around the turn of the 20th century) (Bond and Midgley 2000, Van Auken 2000, Knapp et al. 2001).

Though there are many potential causes of juniper encroachment into semi-arid grasslands, the one cause that can be most directly linked to juniper encroachment is grazing. Wright et al. (1979) stated that the three primary factors which historically prevented juniper trees from invading grasslands and shrublands were fire, competition and drought. Though cattle grazing has little effect on moisture availability, grazing does

cause the suppression of the historic fire regime and the reduction of the competitive ability of grasses and forbs. The magnitude of the impact of each these two effects of cattle grazing is debatable, the root cause is however, the same. It appears that cattle grazing is the primary catalyst driving widespread establishment of juniper trees in southwestern grasslands (Leopold, 1924, Arnold et al. 1964, West 1984, Van Auken 2000).

Stability and natural “succession” in piñon-juniper forests

It is important to note that not all PJ woodlands have been significantly impacted by the effects of grazing and fire suppression. Romme et al. (2003) describe the “piñon-juniper forest” community type as one that has seen little change as the result of intensive grazing and other modern impacts. These forests, such as those found at Mesa Verde National Monument in Colorado, appear to have maintained their historic high severity low frequency, stand replacing, fire regime (Floyd et al. 2000, Floyd et al. 2004). Additionally, some woodlands are experiencing infill as the natural part of the successional process. In these areas, historic PJ forests are simply reestablishing themselves after the most recent stand replacing fire (West and Van Pelt 1987, Dick-Peddie 1993). Therefore, it is important to understand the age distribution of trees and the management history of a site before restoration and other site manipulation activities are implemented (Romme et al. 2003, Baker and Shinneman 2004).

Juniper Allometrics

The relationship of various aspects of juniper tree growth to age will likely be different from trees in more mesic forest environments which are more commonly studied. Junipers typically live in arid environments often on sites with poor soil. They are particularly dominant in both highly arid and cold arid environments (Arnold et al. 1964, Lajtha and Getz 1993, Linton et al. 1998). Light is abundant in these environments, however moisture is limiting. Thus juniper trees do not often compete with each other for 'canopy' space as is the traditional model in more mesic forests, instead they compete for water. Even in mature, old-growth juniper woodlands, tree crowns rarely intermingle. Underground root competition, however, is fierce. Juniper root systems can extend up to 6 m away from the base of the tree (Everett *et al.* 1987). Thus, despite the fact that these trees are widely spaced, underground there is a dense 'root canopy' where trees are competing for moisture in much the same way many trees more typically have leaf canopies competing for light.

Very little research has been done on the relationship between age and size of *Juniperus* spp. and other trees of arid environments. One reason for this is likely due to the fact that many *Juniperus* put on ring growth in an inconsistent manner, and it is not often possible to create a chronology for cross reference (Fritts 1976, Gottfried et al. 1995, Landis and Bailey 2005). Previous literature has shown that height is the best predictor of age among *J. osteosperma*, with stem diameter also being a good predictor among mature trees (Brotherson et al. 1983, Landis and Bailey 2005) and seedlings (Miller 1921). Engle and Kulbeth (1992) found that among *J. virginiana* in Oklahoma, height was a good predictor of age whereas canopy area was a poor predictor. I have

found only two studies that have explored age/size relationships in *J. monosperma*. Looking at crown diameter, height and stem diameter, Calkins (1940) found that, once trees were established, the rate of growth of juniper trees was largely linear. Jameson (1965) focused on height, finding that *J. monosperma* trees increased in height 16 cm per decade on the Deadman's Flat area of the Coconino National Forest in Arizona, very near the study site for this thesis. Moisture and nutrient availability are the factors most strongly related to tree growth among *Juniperus* spp. and other trees in semi-arid environments (Johnsen 1962, Glock and Agerter 1962, Gottfried 1987). Therefore, trees in soils that hold moisture better or have higher nutrient availability will likely grow faster than others on poorer soils.

Research Questions

The purpose of my study was to assess the cover and density increase of *J. monosperma* via age/size distribution and stand structure at Wupatki National Monument and examine the pattern of increases in *J. monosperma* cover relative to key ecosystem properties. There were three primary research directions:

Question 1: Is there a correlation between tree age and tree size attributes? If so, are these correlations consistent across stands or is there variation in growth rates among stands?

Hypothesis 1: Previous literature has shown that height is the best predictor of age among *J. osteosperma*, with stem diameter also being a good predictor (Miller 1921, Brotherson et al. 1983, Landis and Bailey 2005). Engle and Kulbeth (1992) found that

among *J. virginiana* in Oklahoma, height was a good predictor of age whereas canopy area was a poor predictor. Calkins (1940) studied age/size relationships in *J. monosperma* and Jameson (1965) studied height growth in this species, but neither explored which size attribute would be most useful in predicting age. Based on what has been learned about similar species, I expect height will best predict age among *J. monosperma* at the Wupatki study site. Stem diameter will likely also reveal a useful correlation with age, and multivariable regression with stem diameter and tree height may prove to be the most useful predictor of all.

Question 2: What are the age distribution patterns of *J. monosperma* at Wupatki?

Does stand initiation correspond to Euro-American settlement and fire exclusion? Were there peaks in reproduction during years of favorable climatic conditions? What is the rate of increase of *J. monosperma* density?

Hypothesis 2: Based on a review of repeat aerial photos taken of the research site in 1936 and again in 1997, and the literature pertaining to juniper encroachment in the region (Leopold 1924, Johnsen 1962, Jameson 1965, West 1999, Van Auken 2000, Ffolliott and Gottfried 2002), I expect that almost all trees within the savanna stands in Wupatki were established after the initiation of intensive grazing and fire exclusion in the 1860's. The juniper woodlands on the national forest may also show a marked increase in tree establishment around this time. Moisture availability is most strongly linked to juniper seedling survival (Johnsen 1962, Arnold 1964, Fisher et al. 1986 Chambers et al. 1999), so periods of more moist conditions should correspond to periods of greatest establishment.

Question 3: Is there a correlation between juniper invasion rates, initiation dates and patterns and underlying bedrock composition?

Hypothesis 3: The bedrock underlying the study site includes limestone and basalt. Bedrock composition will not directly affect juniper establishment, but the soils derived from these parent materials may.

Literature Cited

- Archer, S. 1994. Woody plant encroachment into southwestern grasslands and savannas: rates, patterns and proximate causes. In: Ecological Implications of Livestock Herbivory in the West, ed. M Vavra, W. A. Laycock, R. D. Pieper. Denver: Society of Range Management: 13-69.
- Anderson, B. A. 1993. Wupatki National Monument: Exploring into prehistory. In: Noble, D. G., editor. Wupatki and Walnut Canyon: New Perspectives on History, Prehistory and Rock Art. Ancient City Press, Santa Fe, NM. Pp 13-19.
- Arnold, J. F., Jameson, D. A. and Reid, E. H. 1964. The pinyon-juniper type of Arizona: effects of grazing, fire, and tree control. Production Research Report, U.S. Department of Agriculture. 84, : 1-28
- Baker, W. L. and Shinneman, D. J. 2004. Fire and restoration of pinon-juniper woodlands in the western United States: a review. Forest Ecology and Management 189, 1-21.
- Barney, M. A., Frischknecht, N. C. 1974. Vegetation changes following fire in the pinyon-juniper type of west-central Utah. Journal of Range Management 27, 91-96.
- Bedell, T. E. 1987. Range management concerns on juniper woodlands. In: Everett, L., comp. Proceedings, pinyon-juniper conference; Gen. Tech Rep. INT-215. Ogden, UT: U.S. Department of Agriculture, Forest Service, Intermountain Research Station. pp. 436-439
- Bogan, M.A., Allen, C.D., Muldavin, E.H., Platania, S.P., Stuart, J.N., Farley, G.H., Melhop, P., and Belnap, J. 1998. Southwest. In Mac, M.J., Opler, P.A., and Doran, P.D. (eds.): Status and trends of the nation's biological resources. Reston, Va., U.S. Dept. of the Interior, U.S. Geological Survey ; Washington, DC
- Bond, W. J. and Midgley, G. F. 2000. A proposed CO₂-controlled mechanism of woody plant invasion in grasslands and savannas. Global Change Biology. 6, : 865-869
- Brotherson, J. D., Rushforth, S. R., Evenson, W. E., Johansen, J. R. and Morden, C. 1983. Population dynamics and age relationships of eight tree species in Navajo National Monument, Arizona. Journal of Range Management. 36, 2: 250-255

- Brown, D. E. 1994. Plains and Great Basin grassland. In *Biotic Communities: Southwestern United States and Northwestern Mexico*, Desert Plants 4 ed. D. E. Brown. University of Utah Press, Salt Lake City, Utah. pp. 115-121
- Brown, J. K., Smith, J. K., eds. 2000. Wildland fire in ecosystems: effects of fire on flora. Gen. Tech. Rep. RMRS-GTR-42-vol. 2. Ogden, UT: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station. 257 p.
- Budy, J.D., Meeuwig, R.O. 1987. Pinyon-juniper silvics and silviculture. In: Everett, R. L., editor Pinyon-juniper conference. General Technical Report INT-215. USDA Forest Service, Intermountain Research Station, Ogden, UT. pp. 244-248
- Burkhardt, J. W., Tisdale, E. W. 1976. Causes of juniper invasion in southwestern Idaho. *Ecology*. 57: 472-484
- Calkins, H. G. 1940. Pinon and juniper: a preliminary study of volume, growth and yield. Regional Bulletin No. 71. Forest Series No. 12. Pp 90.
- Chambers, J. C., Vander Wall, S. B., Schupp, E. W. 1999. Seed and seedling ecology of pinyon and juniper species in the pygmy woodlands of western North America. *The Botanical Review*. 65, 1: 1-37
- Cinnamon, S. K. 1988. The Vegetation Community of Cedar Canyon, Wupatki National Monument as Influenced by Prehistoric and Historic Environmental Changes. Master's Thesis, Northern Arizona University, Flagstaff, Arizona.
- Cinnamon, S. K. 1990. Wupatki grazing terminated. *Park Science: A Resource Management Bulletin*. 10, 1: p .20
- Cottam, W. P. and Stewart, D. 1940. Plant succession as a result of grazing and of meadow desiccation by erosion since settlement in 1862. *Journal of Forestry*. 38: 613-628.
- Davenport, D. W., Wilcox, B. P. and Breshears, D. D. 1996. Soil morphology of canopy and intercanopy sites in a piñon-juniper woodland. *Soil Science Society of America Journal*. 60, : 1881-1887
- Dick-Peddie, W.A. 1993. New Mexico vegetation, past, present and future. Albuquerque, NM: Univ. New Mexico Press.

- Engle, D.M., Kulbeth, J.D. 1992. Growth dynamics of crowns of eastern redcedar at three locations in Oklahoma. *Journal of Range Management*. 45, : 301-305
- Evans, R. A. 1998. Management of pinyon-juniper woodlands. Ogden, UT: USDA Forest Service Intermountain Research Station General Technical Report INT-249.
- Everett, R. L., Sharrow, S. H., Thran, D. F. 1987. Soil nutrient patterns and associations adjacent singleleaf pinyon. *Soil Science Society of American Journal*. 51: 81-88.
- Ffolliott, P. F., Gottfried, G. J. 2002. Dynamics of a piñon-juniper stand in northern Arizona: a half-century history. U.S. Department of the Agriculture, Forest Service, Rocky Mountain Research Station, Research Paper RMRS-RP-35.
- Fisher, J. T., Gregory, A. F., Neumann, R. W. 1986. Germination and field establishment of junipers in the southwest. New Mexico Agricultural Experimental Station Scientific Paper No. 253.
- Floyd, M. L., Romme, W. H., Hanna, D. D. 2000. Fire History and Vegetation Patterns in Mesa Verde National Park, Colorado, USA. *Ecological Applications* 10, 1666-1680.
- Floyd, M. L., Hanna, D. D. and Romme, W. H. 2004. Historical and recent fire regimes in Piñon–Juniper woodlands on Mesa Verde, Colorado, USA. *Forest Ecology and Management* 198, 269-289.
- Friederici, P. 2003. The “Flagstaff Model”. In: Peter Friederici ed. *Ecological Restoration in Southwestern Ponderosa Pine Forests*. Island Press, Washington, DC. pp. 7-25
- Fritts, H. C. 1976. *Tree Rings and Climate*. Academic Press, New York 567.
- Fuhlendorf, S. D., Smeins, F. E., Grant, W. E. 1996. Simulation of a fire-sensitive ecological threshold: a case study of Ashe juniper on Edwards Plateau of Texas, USA. *Ecological Modelling*. 90, : 245-255
- Glock, W. S. and Agerter, S. R. 1962. Rainfall and tree growth. *Tree Growth*. T. T. Kozlowski, ed., Ronald Press, New York: 23-56
- Gottfried, G. J. 1987. Regeneration of pinyon. In: Everett, L., comp. *Proceedings, pinyon-juniper conference*; Gen. TEch Rep. INT-215. Ogden, UT: U.S. Department of Agriculture, Forest Service, Intermountain Research Station. pp. 249-254

- Gottfried, G. J., Swetnam, T. W., Allen, C. D., Betancourt, J. L. and Chung-MacCoubrey, A. L. 1995. Pinyon-juniper woodlands. In: Finch, D. M., Tainter, J. A. (Eds.), Ecology diversity and sustainability of the Middle Rio Grande Basin. USDA Forest Service, General Technical Report: 95-132.
- Gottfried, G. J. 2004. Silvics and Silviculture in the Southwestern Pinyon-Juniper Woodlands. USDA Forest Service Proceedings RMRS-P-34.
- Grahame, J. D. and Sisk, T. D., editors. 2002. Canyons, cultures and environmental change: An introduction to the land-use history of the Colorado Plateau. [3/18/05]. <http://www.cpluhna.nau.edu/>
- Hannemann, M. Range Conservationist, Peaks Ranger District, Coconino National Forest, USDA Forest Service. Personal Communication. October 14th, 2004.
- Hansen, M. J. Coles, K.A. Thomas, D. Cogan, M. Reid, J. Von Loh, and K. Shulz. 2004. USGS-NPS National Vegetation Mapping Program: Wupatki National Monument. Final Report, U.S. Geological Survey, Southwest Biological Center, Flagstaff, Arizona.
- Hastings, J. R. 1959. Vegetation changes and arroyo cutting in southeastern Arizona. Journal of the Arizona Academy of Science. 1: 60-67.
- Heerwagen, A. 1956. Mixed prairie in New Mexico. In: J. E. Weaver and F. W. Albertson. Grasslands of the Great Plains. Johnson Publishing Company, Lincoln, Nebraska. pp. 284-300.
- Humphrey, R. R. 1958. The desert grassland: a history of vegetation change and an analysis of causes. Botanical Review. 24: 193-252.
- Jameson, D. A. 1965. Arrangement and growth of pinyon and one-seed juniper trees. Plateau 37: 121-127.
- Jeppesen, Darwin J. 1978. Comparative moisture consumption by the western juniper (*Juniperus occidentalis*). In: Proceedings of the western juniper ecology and management workshop; 1977 January; Bend, OR. Portland, OR: U.S. GTR-PNW-74 Department of Agriculture, Forest Service, Pacific Northwest Forest and Range Experiment Station: 83-90.

- Johnsen, T. N., Jr. 1962. One-seed juniper invasion of Northern Arizona grasslands. *Ecological Monographs*. 32, 3: 187-207
- Knapp, P. A. and Soule, P. T. 1998. Recent *Juniperus occidentalis* (Western Juniper) expansion on a protected site in central Oregon. *Global Change Biology*: 4, pp 347-357.
- Knapp, P. A., Soule, P. T. and Grissino-Mayer, H. D. 2001. Detecting potential regional effects of increase atmospheric CO₂ on growth rates of western juniper. *Global Change Biology*. 7: 903-917.
- Lajtha, K., Getz, J. 1993. Photosynthesis and water-use efficiency in pinyon-juniper communities along an elevation gradient in northern New Mexico. *Oecologia*. 94, : 95-101
- Landis, A. G. and Bailey, J. D. 2005. Reconstruction of age structure and spatial arrangement of piñon-juniper woodlands and savannas of Anderson Mesa, northern Arizona. *Forest Ecology and Management*. 205, : 221-236
- Laycock, W. A. 1991. Stable states and thresholds of range conditions of North American rangelands: a viewpoint. *Journal of Range Management*. 44: 427-433.
- Leopold, A. 1924. Grass, brush, timber, and fire in southern Arizona. *Journal of Forestry*. 22, 6: 1-10
- Linton, M. J., Sperry, J. S., Williams, D. G. 1998. Limits to water transport in *Juniperus osteosperma* and *Pinus edulis*: implications for drought tolerance and regulation of transpiration. *Functional Ecology*. 12, : 906-911
- Miller, F. H. 1921. Reclamation of grasslands by Utah juniper on the Tusayan National Forest, Arizona. *Journal of Forestry*. 19, : 647-651
- Miller, R. F. and Wigand P. E. 1994. Holocene changes in semiarid pinyon-juniper woodlands: response to climate fire and human activities in the Great Basin. *Bioscience*. 44: 465-474.
- Miller, R. F., Rose, J. A. 1995. Historic expansion of *Juniperus occidentalis* (western juniper) in southeastern Oregon. *Great Basin Naturalist*. 55, 1: 37-45

- Moir, W. H., Carleton, J. O. 1987. Classification of pinyon-juniper (p-j) sites on national forests in the southwest. Pinyon-Juniper Conference: 216-226
- Noble, D. G., editor. 1993. Wupatki and Walnut Canyon. Ancient City Press, Santa Fe, NM.
- O'Brien, R. A. 2002. Arizona's forest resources, 1999. Resour. Bull. RMRS-RB-2. Ogden, UT: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station. pp. 116
- Pieper, R. D. 1977. The southwestern pinyon-juniper ecosystem. In: Ecology, uses and management of pinyon-juniper woodlands. USDA, Forest Services General Technical Report. RM-39: 1-6.
- Pieper, R. D. 1990. Overstory-understory relations in pinyon-juniper woodlands in New Mexico.
- Price, K. P. 1993. Detection of soil erosion within pinyon-juniper woodlands using thematic mapper (TM) Data*. Remote Sens. Environ. 45, : 233-248
- Roberts, A. 1993. The Wupatki Navajos: An historical sketch. In: Noble, D. G., editor. Wupatki and Walnut Canyon: Ancient City Press, Santa Fe, NM. pp. 28-33.
- Romme, W. H., Floyd-Hanna, L., Hanna, D. D. 2003. Ancient piñon-juniper forests of Mesa Verde and the West: A cautionary note for the forest restoration programs. USDA Forest Service Proceedings RMRS-P-29: 335-350
- Short, M. S. 1988. Walnut Canyon and Wupatki: A History. M.S. Thesis. Northern Arizona University, Flagstaff, AZ. pp. 95
- Soulé, P. T., Knapp, P. A. and Grissino-Mayer, H. D. 2004. Human agency, environmental drivers, and western juniper establishment during the late Holocene. Ecological Applications. 14: 96-112.
- Sunset Crater Volcano National Monument, National Park Service (SU CR). 2005. Sunset Crater Volcano National Monument - Nature and Science.
<http://www.nps.gov/sucr/pphtml/nature.html> [Date accessed: September 13, 2005].
- Tausch, R. J., West, N. E. and Nabi, A. A. 1981. Tree age and dominance patterns in great basin pinyon-juniper woodlands. Journal of Range Management. 34, 4: 259-264

- Teidman, A. R., Eddleman, L. E. 1987. Establishment and stand development of western juniper in central Oregon. In: Everett, R. L., editor Pinyon-juniper conference. General Technical Report INT-215. USDA Forest Service, Intermountain Research Station, Ogden, UT. pp. 352-359
- Thybony, S. 1987. A guide to Sunset Crater and Wupatki. Southwest Parks and Monuments Association, Tucson, AZ. pp. 48
- Touchan, R., T. W. Swetnam, and H. Grissino-Mayer. 1995. Effects of livestock grazing on pre-settlement fire regimes in New Mexico. in J. K. Brown, R. W. Mutch, C. W. Spoon, and R. H. Wakimoto, technical coordinators. Symposium on fire in wilderness and park management. U.S. Forest Service General Technical Report INT-320: 268-272.
- Trimble, M. 1982. CO Bar Bill Owen Depicts the Historic Babbitt Ranch. Northland Press, Flagstaff. pp. 95.
- U. S. Department of Agriculture, Soil Conservation Service (USDA). 1971. Soil survey and range site and condition inventory Wupatki National Monument Arizona: a special report. Portland, Oregon.
- U.S. Department of Interior, National Park Service (NPS). 1990. The Wupatki Archeological Inventory Survey Project: Final report. Compiled by Bruce A. Anderson. Professional Paper No. 35; Division of Anthropology, NPS Southwest Regional Office, Santa Fe, New Mexico.
- Van Auken, O. W. 2000. Shrub invasions of North American semiarid grasslands. *Annu. Rev. Ecol. Syst.* , 31: 197-215.
- van Langevelde, F., van de Vijver, C. A. D. M., Kumar, L., van de Koppel, J., de Ridder, N., van Andel, J., Skidmore, A. K., Hearne, J. W., Stroosnijder, L., Bond, W. J., Prins, H. H. T., Rietkerk, M. 2003. Effects of fire and herbivory on the stability of savanna ecosystems. *Ecology*. 84: 337-350.
- West, N. E. 1999. Juniper-piñon savannas and woodlands of western North America. Roger C. Anderson, James S. Fralish and Jerry M. Baskin, eds Savannas Barrens, and Rock Outcrop Plant Communities of North America. Cambridge University Press, 288-307.

- West, N. E. 1984. Successional patterns and productivity potentials of pinyon-juniper ecosystems. In *Developing Strategies for Range Management: A Report*. Ed: National Research Council/National Academy of Science. Boulder, CO: Westview Press, 1301-1332.
- West, N. E., Tausch, R. J. and Tueller, P. T. 1998. A management-oriented classification of pinyon-juniper woodlands of the Great Basin. Ogden, UT: U.S. Dept. of Agriculture, Forest Service, Rocky Mountain Research Station. RMRS-GTR-12.
- West, N. E. and Van Pelt, N. S. 1987. Successional patterns in pinyon-juniper woodlands. In: Everett, L., comp. *Proceedings, pinyon-juniper conference*; Gen. Tech Rep. INT-215. Ogden, UT: U.S. Department of Agriculture, Forest Service, Intermountain Research Station. 43-52
- Western Regional Climate Center. 2005. Wupatki Natl Monument, Arizona – Climate Summary. [9/28/05]. <http://www.wrcc.dri.edu/>
- Wilcox, B. P. and Davenport, D. W. 1995. Juniper encroachment: potential impacts to soil erosion and morphology. Interior Columbia Basin Ecosystem Management Project.
- Wright, H.A., L.F. Newenschwander, and C.M. Britton. 1979. The role and use of fire in sagebrush-grass and pinyon-juniper plant communities: A state-of-the-art review. Intermountain Forest and Range Experiment Station. General Technical Report INT-58; 48pp.
- Wright, H. A. and Bailey, A. W. 1980. Fire Ecology and Prescribed Burning in the Great Plains-A Research Review. Washington DC: U.S. Department of Agriculture, Forest Service General Technical Report INT-77.
- Wupatki National Monument (WUPA). 2002. Final Environmental Impact Statement General Management Plan. NPS D-53a. Flagstaff, AZ, :
- Yorks, T.P., N.E. West, and K.M. Carpels. 1994. Changes in pinyon-juniper woodlands in western Utah's pine valley between 1933-1989. *Journal of Range Management* 47: 359-364.
- Young, J. A. and Evans, R. A. 1981. Demography and fire history of a western juniper stand. *Journal of Range Management* 34, 501-505.

Figures

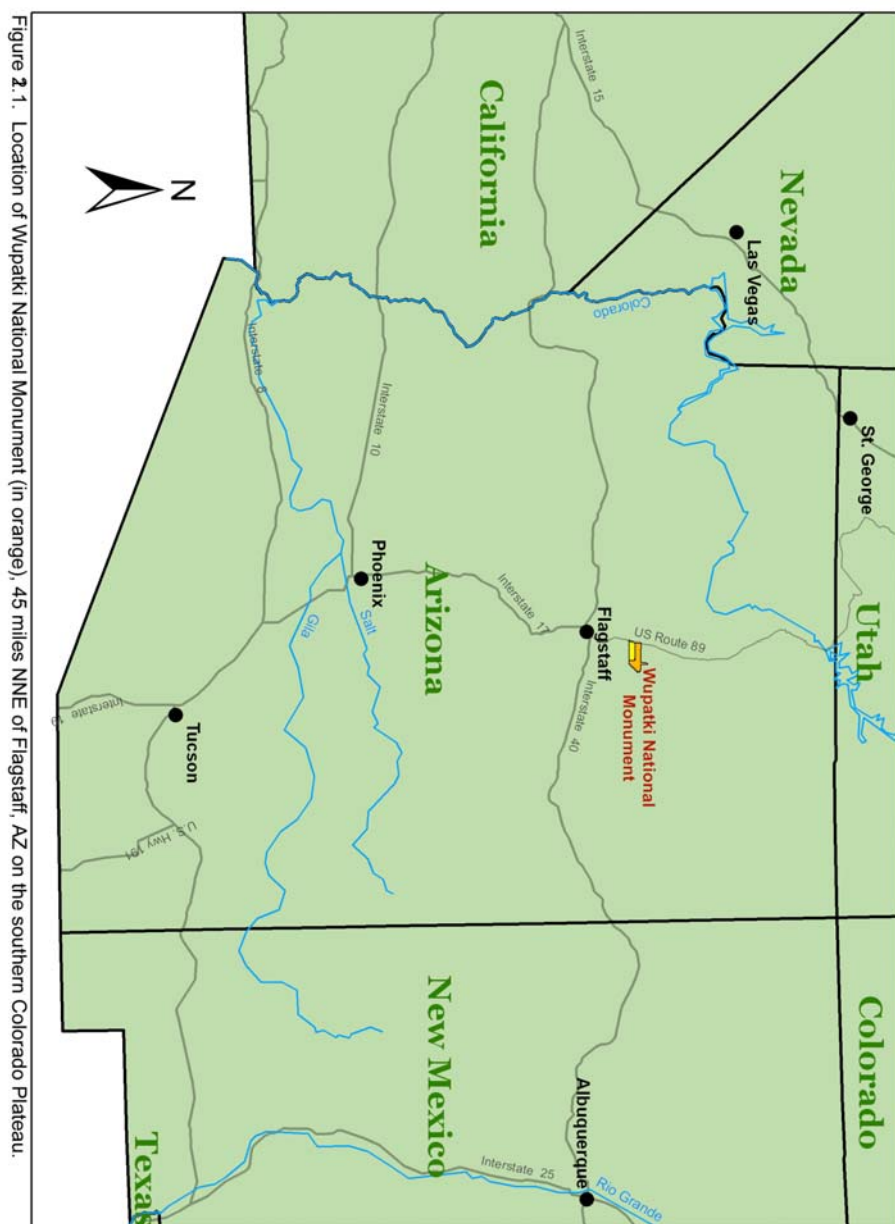


Figure 2.1. Location of Wupatki National Monument (in orange), 45 miles NNE of Flagstaff, AZ on the southern Colorado Plateau.

Chapter 2: Allometric Relationship for *Juniperus monosperma* In and Near Wupatki National Monument, Northern Arizona

Abstract

Understanding the age structure of *Juniperus monosperma* (Engelm.) Sarg. trees is important to land managers at Wupatki National Monument and throughout the Southwest, but removing cross section samples and conducting ring counts is difficult, time-consuming work. If allometric relationships for this species can be developed, then it could allow land managers to quickly estimate the age of junipers with simple field measurements. I explored the allometrics of *J. monosperma* at Wupatki National Monument in northern Arizona, USA. I measured the stem diameter, height and canopy radius of 216 trees in both savanna and woodland environments. I then removed cross section samples from these trees and determined their age by a ring count. The age of trees in more droughty environments was more difficult to predict than trees in less stressful environments. Overall, the most consistent correlation between age and size when analyzing all trees was a simple linear regression of stem diameter: $y = 0.689 + 0.0706 x$, where x = years of age and y = stem diameter in cm. This corresponds to a growth rate of .71 cm increase in stem diameter per decade. This regression had an R^2 value of .785. The strong correlation of stem diameter to age likely reflects the fact that growth patterns of *J. monosperma* are different than those of other tree species competing for resources in a forested environment. I recommend that land managers use the diameter of the largest stem of *J. monosperma* to evaluate tree age and stand age structure.

Introduction

There are many factors which affect tree allometrics. Traditional forestry research tells us that tree height will have a strong correlation with age. A tree in this environment will typically maintain its rate of height growth as it competes for space in the forest canopy with neighboring trees. Tree height will be limited primarily by site condition. Thus, while height growth will correspond well to age, the magnitude of this relationship will tend to change slightly from site to site.

Stem diameter is also typically strongly associated with age, however it is more strongly influenced by the effects of competition. As a tree competes with its neighbors it will maintain height growth at the expense of diameter growth. Thus, competition must be taken into account if one is attempting to evaluate tree age based on stem diameter.

The relationship of age to various aspects of juniper growth will likely be different from trees in more mesic forest environment. Junipers typically live in arid environments often on sites with poor soil. They are particularly dominant in both highly arid and cold arid environments (Arnold et al. 1964, Lajtha and Getz 1993, Linton et al. 1998). Soar radiation is typically not limiting in these environments instead moisture availability is typically the limiting agent. Thus, junipers do not often compete with each other for 'canopy' space, instead they compete for water and nutrients. Even in mature, old-growth juniper woodlands, tree canopies rarely intermingle. Underground root competition, however, is fierce. Juniper root systems can extend up to 6 m away from the base of the tree (Everett et al. 1987). Johnsen (1962) found that the roots of a 3 m tall juniper extended 2.5 to 3 times as far as the tree was tall. Thus, despite the fact that these trees are widely spaced, I can imagine that underground there is a dense 'root canopy'

where trees are competing for moisture in much the same way I typically see trees' leaf canopies competing for light.

Very little research has been done on the allometrics of *Juniperus* and other trees of arid environments. By studying the age/size relationships in these trees I can gain a better understanding of the physiology of these trees and how they cope with the harsh environmental conditions in which they thrive. By exploring juniper allometrics I also provide land managers with useful tools which will allow them to quickly assess the age of junipers in a stand as well as have a better understanding of the ecology and history of a stand.

Previous literature has shown that height is the best predictor of age among *Juniperus osteosperma*, with stem diameter also being a good predictor (Miller 1921, Brotherson et al. 1983, Landis and Bailey 2005). Engle and Kulbeth (1992) found that among *J. virginiana* in Oklahoma, height was a good predictor of age whereas canopy area was a poor predictor. Calkins (1940) studied age/size relationships in *Juniperus monosperma* (Engelm.) Sarg. and Jameson (1965) studied height growth in this species, but neither explored which size attribute would be most useful in predicting age. Based on what has been learned about similar species, I expect height will best predict age among *J. monosperma* at the Wupatki study site. Stem diameter will likely also reveal a useful correlation with age, and multivariable regression with stem diameter and tree height may prove to be the most useful predictor of all. Moisture and nutrient availability are the factors most strongly related to tree growth among junipers and other trees in semi-arid environments (Johnsen 1962, Glock and Agerter 1962, Gottfried 1987).

Therefore, trees in soils that hold moisture better or have higher nutrient loads will likely grow faster than others on poorer soils.

Methods

Site Description

Wupatki National Monument

Wupatki National Monument (WUPA) lies on the Colorado Plateau approximately 45 km (28 miles) northeast of Flagstaff, Arizona (Figure 1.1). The monument encompasses 14,335 hectares (35,422 acres). WUPA was established in 1924 to protect pre-historic Native American archeological sites. The monument also encompasses a sizable natural area including desert scrub, semi-arid grassland and juniper woodland.

The western half of the monument is a plains grassland/juniper savanna community known as Antelope Prairie. Hansen et al. (2004) specify these grasslands as being composed primarily of Galleta Mixed Grasslands, with several other community types intermixed, including Rabbitbrush Shrubland, Black Grama Coconino Plateau Shrubland, Galleta Mixed Shrublands and Needle-and-Thread Grassland. Hansen et al. define areas with significant populations of juniper trees simply as Oneseed Juniper Woodland. As designated for the purposes of this study, Antelope Prairie covers 7,000 hectares (17,000 acres). The elevation within Antelope Prairie ranges from 1,550 m (5,090 ft) to 1,740 m (5,710 ft) and the mean elevation of this portion of the park is 1,645 m (5,400 ft) (Figure 2.1).

In addition to the western portion of WUPA, the study area includes the adjacent portion of the Coconino National Forest (CNF) just to the south and upslope of Antelope

Prairie. Specifically the study site extends 4.8 km (3 miles) south from the WUPA southern boundary and covers 6,850 ha (16,900 ac). This area is bounded on the west by U. S. Highway 89 and extends eastwards an average of 15.1 km (9.4 mi) to the western boundary of the southern flank of WUPA. This portion of the CNF ranges in elevation from approximately 1640 m (5380 ft) to 1860 m (6100 ft), with a mean elevation of 1750 m (5740 ft) (Figure 2.1). The entire research area covers 13,850 ha (34,200 ac) ranging from 1,550 m (5,090 ft) to 1860 m (6100 ft) in elevation.

The climate is most often described as semi-desert or semi-arid with an average annual precipitation of 20.8 cm (8.2 inches) and a mean annual temperature of 14.4 C (57.9 F). Over 50% of this precipitation falls between late July and early September during the summer rain or monsoon season. The average high in July is 35.2 C (95.3 F) and the average low in January is -4.2 C (24.5 F). All climatic data for the monument is recorded at a National Weather service Cooperative Station at the Wupatki Visitor Center (elevation 1,490 m (4,900 ft)) (Western Regional Climate Center 2005). Precipitation and temperature can vary widely in the monument with higher elevation locations, such as the study site, being cooler and more moist than lower elevation sites (USDA 1971). Various estimates place the average annual precipitation in the study area to be between 20 cm (8 inches) and 40 cm (16 inches) (USDA 1971, ALIC 2001).

Geology

The underlying bedrock of the study area is Kaibab Formation of silty dolomite limestone of Triassic and Permian origin (USDA 1971). On about half of the study site, this bedrock is overlaid by low basalt mesas formed of lava flows from the San Francisco Volcanic Field during the Later Tertiary and Quaternary (McCormack 1989). The

limestone itself is broken in places due to geological faulting in the area, resulting in raised outcroppings and sunken valleys (USDA 1971).

The soil in the area is strongly influenced by an overlay of volcanic cinders. These cinders are primarily from the nearby Sunset Crater with its eruptions between A.D. 1064 and 1180 and from Doney Mountain, within the Monument, which erupted considerably earlier in the late Pleistocene (Amos 1987, Hooten et al. 2001). These soils range in depth from deep to shallow. Soil textures include cindery loams and gravelly loams, sandy loams and loamy sands (Taylor 1983, ALIC 2001).

Ecology

The majority of Antelope Prairie is semi-arid grassland or juniper savanna. According to Brown (1994) the grassland of Antelope Prairie in WUPA is of the plains grassland type, though they are in the region of transition to the Great Basin grassland type. Dick-Peddie (1993) terms this same type as plains-mesa grassland. Both authors agree that the defining attribute of this grassland type is the domination of short (< .5 m), drought tolerant grasses, specifically *Bouteloua gracilis* (Willd. ex Kunth) Lag. ex Griffiths (blue grama). Other common grasses include *Hilaria jamesii* Torr. (galleta grass), *Achnatherum hymenoides* (Roemer and J.A. Schultes) Barkworth (indian ricegrass) and *Hesperostipa comata* (Trin. and Rupr.) Barkworth (needle-and-thread grass) (Dick-Peddie 1993). Other common plants include sub-shrubs such as *Chrysothamnus* Nutt. spp. (rabbitbrush) and *Gutierrezia* Lag. spp. (snakeweed), forbs that are most strongly represented by the sunflower family (Asteraceae), and succulents such as cactus (Cactaceae) (Brown 1994). However, these shrubs and forbs constitute less than 10% of the flora (Heerwagen 1956). In cases of excessive grazing, shrubs,

snakeweed in particular, will be more conspicuous, as will rabbitbrush and less palatable “weedy” forbs (Brown 1994).

To the south of Antelope Prairie on National Forest land the landscape is dominated by juniper and juniper-piñon woodland. These woodlands are composed of an overstory of *Juniperus monosperma* (Engelm.) Sarg. (one-seed juniper) with occasional *Pinus edulis* Engelm. (piñon pine), especially at higher elevations. Understory vegetation is sparse to barren, including grass, shrub and forb species of similar composition to that of the adjacent grassland.

There are also patches of isolated juniper woodland and shrublands within the grassland/savanna matrix. These juniper and shrub refugia populations are most often found on cinder slopes and rocky outcroppings, sites which would be sheltered from the direct impacts of frequent, low intensity fires. These isolated woodland and shrubland refugia were not included in the research study due to a sampling restriction within WUPA.

Figure 2.2 shows the vegetation types in the study site as mapped by Hansen et al. (2004). Their survey does not recognize juniper savanna as a cover type. As a result this map is not directly comparable to my description of the community types in the study area.

Site History

Wupatki grasslands were impacted by Navajo sheep herding as early as the mid 1800’s (Short 1988). Anglo cattle grazing began to have an impact as early as 1886 when the C O Bar ranch grazed the public domain land that would later become Wupatki National Monument (Trimble 1982). For the following 140 years, grassland fires in

WUPA were rare and covered only a very small area. Since 1924, NPS administrative records report only two fires other than localized lightening strikes - in 1956 and 1989. Cattle grazing was removed from WUPA in 1989 (Cinnamon 1990). Since then, the herbaceous plants in Antelope Prairie have been able to recover from grazing. As a result, approximately 1000 ha (2,600 acres) have burned in four fires in 1995, 2000 and 2002.

Stands

For the purposes of this study, stands (population units) were defined as an area on level to gently-rolling terrain on the same basalt shelf or limestone bedrock, with a fairly consistent elevation. There are two types of juniper stands in the study area. Woodland stands were defined as areas with greater than 30 trees per hectare (tph) and in fact have a mean density of 118 tph (292 trees per acres (tpa)). Savanna stands were defined as having between 30 tph and 1 tph, with an average of 8 tph (19 tpa) in the study area. Areas with 1 tph or less are considered grasslands.

Within the National Monument, sampling was limited by two factors. First, I was not allowed to cut any live trees. Second, my permit allowed for no more than 150 dead trees to be destructively sampled within WUPA. Therefore, savanna stands were necessarily further defined by the outline of several recent wildfires that had killed significant numbers of *J. monosperma*. It is believed that savanna areas were historically a fire maintained grassland habitat (Cinnamon 1988). Land managers initially inferred from aerial photography and historical account that most of these savanna stands have developed within the past 150 years. All of the four savanna stands in this study were located within WUPA.

Woodland stands have higher tree densities and are believed to have been established for a longer period of time than the savanna stands. There were no sampling restrictions on the CNF, where these stands were located; therefore woodland stands encompass entire basalt shelves and areas of limestone bedrock within the boundaries of the study area.

Stand Description

There were six stands in this research study, four within WUPA (Figure 2.1). The four savanna stands within the park are known as Antelope/State Fire (AF), West Fire South (WFS), West Fire North (WFN) and Moon Fire (MF). Two woodland stands were sampled in the southern portion of the research site on the CNF. These stands are known as Antelope Prairie South (APS) and Powerline Mesa (PM) (see Figure 2.1). See Table 2.1 for a brief summary of the stand attributes.

The Antelope Fire stand is the largest savanna stand at 543 ha (1342 acres) and is the result of the Antelope/State complex fire in 2002. This stand lies on a basalt shelf at a median elevation of 1710 m (5610 ft). A portion of the area impacted by the Antelope Fire was not included in this stand because it did not fall on the same basalt shelf as the majority of the fire, and this area was too small to be considered a stand of its own. There were an average of 9.1 tph (3.7 tpa) dead and live trees in the stand at the time research was conducted. The soils in AF are moderately deep gravelly loams and very gravelly loams (Taylor 1983) with cinders present on the soil surface.

The West Fire in 1995 was split into two stands due to differences in bedrock and elevation. WFS is also on a basalt shelf with a median elevation of 1690 m (5545 ft) and covers 105 ha (260 acres). There is an average of 4.9 tph (2.0 tpa) in the WFS stand.

The soils in WFS are a deep, very gravelly loam (Taylor 1983) with cinders present on the soil surface. WFN is just north of WFS and at a lower median elevation (1665 m (5463 ft)) on the limestone bedrock covering 204 ha (505 acres). There were an average of 5.8 tph (2.4 tpa) dead and live trees in the WFN stand. The soils in WFN are a deep, very cindery loam (Taylor 1983) with cinders present on the soil surface.

The Moon Fire stand is the smallest of the stands at only 58 ha (143 acres) in size, having burned in 2000. This area is also at the lowest median elevation (1630 m (5350 ft)) on the limestone bedrock. Finally, the MF stand is unique in that it has the lowest tree density of only 1.7 tph (.7 tpa). The soils in MF are shallow, gravelly fine sandy loams and gravelly loams (Taylor 1983) with sparse cinders present on the soil surface.

Antelope Prairie South is a large juniper woodland stand on the CNF immediately south of the Antelope Prairie area in WUPA. This stand is on limestone bedrock and covers 2,144 ha (5298 acres), with a median elevation of 1660 m (5446 ft). There are an average of 106.7 tph (43.2 tpa) in APS, and less than 1% of these trees are piñon pines. The soils of APS are extremely cindery, moderately deep, loamy sands and sandy loams with a thin cinder surface layer (2-4 cm) overlying the A horizon (ALIC 2001).

Powerline Mesa is the highest elevation stand at 1780 m (5840 ft), sitting on top of the next basalt shelf above the one that underlies AF and WFS. PM covers 1922 ha (4749 acres). The total average tree density is 131.2 tph (53.1 tpa). This is composed primarily of *J. monosperma* with an average of 117.6 tph (47.6 tpa). Only 10.4% of the trees are *P. edulis* numbering an average of 13.6 tph (5.5 tpa). The soils of PM are extremely cindery, shallow to moderately deep, loamy sands and sandy loams with a cinder surface layer (5-15 cm) overlying the A horizon (ALIC 2001).

Sample Plots

Sample points were randomly assigned within each stand using ArcView 3.2 GIS software. Each stand was delineated as a polygon shapefile and plot center points randomly assigned within each polygon using the Random Point Generator 1.27 extension developed by Jenness Enterprises (2005). More plots than necessary were generated. Plot center points were turned into Global Positioning Satellite (GPS) waypoints using the ArcView script `export_GPS_to_trimble` developed by David Kimball (2002). These waypoints were downloaded to a Trimble GeoExplorer3 GPS unit and used to locate plot centers in the field. Plots were visited in numerical order. Sites that were substantially altered by recent anthropogenic activities such as wood cutting, mining or road building or where the plot center fell within an archeological site, where excluded from the study.

The center of each plot was located using a Trimble GeoExplorer 3 GPS unit and marked with a flag. The perimeter of the plot was initially determined with distance tape. However, it was soon found that the GeoExplorer 3, in the navigation mode, was able to determine the distance to the center of the plot with equal or greater accuracy than the distance tape and with greater convenience. Thus the GPS unit was used to determine the plot boundaries used for the majority of the study.

In juniper woodland stands, sample plots consisted of a 0.238 ha circular sample area (radius of 27.5 m) centered on a randomly placed plot center. In stands considered to be juniper savanna or “grassland with scattered junipers”, plots consisted of a 3.80 ha circular sample area (radius of 110 m). Presampling determined that there was a far greater density of trees in the woodland stands as compared to the savanna stands.

Therefore, this variation in plot size is necessary to maintain a consistent sample size, and a consistent ratio of trees measured to samples taken per plot, across habitat types. Sample plots were used instead of a transect or other sampling method in order to accurately survey tree density within each stand.

A total of 94 sample plots were used in this study, 57 in WUPA and 37 on the CNF. After a small number of plots were sampled in each stand, I carried out a preliminary analysis of juniper age/size relationships. Based on the strength of these correlations, I calculated the number of plots and trees needing to be sampled per stand in order to maximize the accuracy of each stand's respective age/size regressions and provide consistent precision between stands.

Tree Measurements

Within each plot, several size parameters were measured for each tree. These parameters include stem diameter, height, crown radius (drip line) and percent live crown. A circular sweep starting at true north and proceeding clockwise determined the order trees would be sampled and the assigned tree number.

Largest Stem Diameter: The diameter of the largest stem at 30 cm off the ground (or as close as is practicable), to the nearest centimeter was measured with diameter tape. A similar method was used in previous studies in the area (Calkins 1940, Ffolliott and Gottfried 2002). This largest stem method appears to be more practical and accurate than attempting to measure diameter at the root collar.

Height: Height was measured to nearest tenth of a meter with a Haglof Vertex hypsometer. The highest stem on the tree was regarded as the top of the tree, regardless of whether this branch was live or dead. For live branches or branches with dead foliage

present, the measurement was taken at the point which appeared to be the highest point of woody stem. For recently dead branches without foliage, the measurement was taken at the highest point of the stem. For long dead branches which appeared to have lost the more delicate upper portion of the highest branch, the height measured at the top of the remaining stem was rounded up 0.1 meters to compensate for this post-mortem decrease in height. Three or more measurements were made with the hypsometer for each tree with the most frequent or mean measurement being recorded.

Crown Radius: Crown radius was measured to the nearest 0.1 meter with loggers tape or a height stick. Two canopy radius measurements were taken per tree. I took the first measurement at the branch which appeared to terminate at the greatest distance from the bole of the tree. A second drip line measurement was taken 90 degrees clockwise from that first branch. These measurements were later averaged to calculate a mean crown radius or drip line.

Percent Live Crown: The percentage of live crown for each tree was made by a visual estimate of the tree from at least two perspectives and divided into five classes (0 % 25%, 50%, 75%, 100%) and recorded. See Table 2.2 for a detailed description of these percent live crown categories.

The canopy on the majority of trees extended to the ground, making a height to live crown measurement impractical.

Fire Evidence: Any trees that appeared to have damaged that could have been the result of a pre-Euro-American settlement fire were noted. A cursory search was made in each plot for additional fire scarred materials. Samples were taken of trees that appeared

to harbor fire evidence. However these samples were so few in number that they were not useful to this study.

Tree Cross Section Samples

Trees were divided into four size classes based on height (0-1.5 m, 1.5-3.0 m, 3.0-4.5 m and 4.5 and greater). In each plot, one tree per species in each size class closest to the center of the plot was selected to remove a cross section for analysis. Within WUPA savanna stands, this included only fired killed *Juniperus monosperma*. On the CNF, these included both live *J. monosperma* and live and recently deceased *P. edulis*. Two additional *J. monosperma* in each size class in each plot were sampled in the MF stand due to the low number of trees, and thus low number of samples for analysis, in this stand. One additional tree in each size class in each plot was sampled in the WFS stand due to the low correlation in preliminary allometric analysis in this stand.

The stem cross sections were removed from the tree with the aid of a chain saw, cutting as low to the ground as conditions would safely allow. It was most desirable to get a bole cut on both junipers and piñons; in some cases, this required digging through duff and soil to reach the root collar. Often it was not possible to remove a sample at the bole of a one-seed juniper due to the multi-branching structures of these trees. In these cases, a cross section was removed from the largest stem on the tree as close to the ground as possible in order to get the oldest cross section possible for analysis. The unintended benefit of the latter method was that it only damaged and did not kill live trees. For live piñon pines, an increment borer was used whenever possible to extract an increment core instead of removing a stem cross section. This allowed me to collect the tree age data I needed without killing the sample tree.

Sample Preparation: Each cross section sample “disc” was sanded using an electric belt sander in order to better reveal ring patterns. Sanding began with a coarse sanding (36 grit), and was repeated with incrementally finer grit (Stokes and Smiley 1968)s. The final sanding was with a 400 or 320 grit sand paper. The increment cores were prepared in a similar fashion, however sanding began with a less coarse, 220 grip paper and then was repeated with finer grits.

Sample Age Determination: A binocular microscope with 7x to 80x magnification was used to analyze the samples. The number of rings in each disc was counted with great care being taken to account for false and missing rings. Marking of rings during counting was done in a manner consistent with Stokes and Smiley (1968).

Due to the lobed growth form of *J. monosperma* stems, a cross section of an entire stem is necessary for an accurate ring count. In some years, *J. monosperma* will put on new wood around the entire circumference of the stem. However, in most years “rings” are only accumulated on the most consistently growing portion of the stem (Tausch and West 1988), which creates the distinctive lobes found in juniper cross sections. Ring counts were conducted along the most vigorously and consistently growing lobe for each disc.

For the purposes of this study true rings were defined as rings with a strong distinction between one year’s late wood and the following year’s early wood. The latewood must end abruptly and not fade into latter early wood or it was considered a false ring and not counted. Also, rings which faded out along their longitudinal axis before reaching the terminus of the lobe were considered false rings and thus not counted even if they appeared to have a definitive transition from late to early wood.

Care was also taken to carefully observe any especially prominent rings which might contain missing rings. In some cases rings were found that contained only two or three layers of cells. Though it is likely some missing rings were not counted, it is also likely that some false rings were misperceived as true rings and counted.

Age Correlation: Due to the inconsistent manner in which many *Juniperus* put on ring growth, it was not possible to create a chronology for cross reference (Fritts, 1976, Gottfried et al., 1995, Landis and Bailey, 2005). It is likely that the accuracy of the counted age of the tree decreases with increasing age because tree rings were only counted and not cross dated. In general, junipers, especially *J. osteosperma* and *J. monosperma*, are difficult if not impossible to cross date (Grissino-Mayer 2005). It is worth noting that there are no chronologies for these species in the International Tree Ring Data Bank (NCDC 2005). However, due to the diligence and care taken while counting growth rings of the samples I am highly confident in the usefulness of these results. Since we cannot be certain that the number of rings counted accurately corresponds to tree age, for the purpose of this study, I define “tree age” as the number of rings counted in the cross section sample for that tree.

Fire Evidence: In addition, each sample was searched for potential fire scars which might harbor evidence of a historic fire regime.

Data Analysis

The allometric relationships for each stand were independently analyzed using SAS JMP software. They were also grouped into categories including basalt bedrock, limestone bedrock, woodland stands, savanna stands and all stands.

Using linear and non-linear regression, I correlated tree age and tree size attributes. I recognized that the decrease in accuracy with the increase in the number of rings counted results in unequal error variances. Also, older trees tend to have more variability in their size attributes. However, the coarseness of scale when measuring small trees also causes error in modeling allometric relationships. This made a weighted least squares approach to the regression unfavorable.

There were many possible ways to analyze this data. Initial data analysis included simple linear regressions, transformations of variables in simple linear regression, multivariate regressions as well as combinations of various transformations within multivariate regression. I also explored a small subset of biological growth models. There were literally dozens of permutations of allometric relationships to analyze. In general, multivariate analysis showed little to no improvement in predictive ability over univariate linear regressions, and therefore due to their increased complexity they were not as useful in predicting age/size correlations. In the end three correlations were chosen based on three criteria. All of these correlations had a strong relationship between age and size, they were simple formulas with a single predictor variable that are easy to reproduce, and they had a relatively even distribution of residuals.

Model A was the simple linear regression of *J. monosperma* age predicting stem diameter. Preliminary analysis showed that though this relationship was rarely the strongest correlation in any particular stand (compared to simple linear regressions in which age predicted height or canopy radius), it was the most consistent predictor of age when looking at the results as a whole. This model takes the form of $y = b + a \cdot x$, where

“y” is stem diameter, “x” is age, and “a” is the growth rate (cm/year) and “b” is the y intercept.

Model B was the relationship between the natural log of tree age and tree height. This regression took the form of $y = y(x) + a \cdot \ln(x)$ where “y” is height, “x” is age, “y(x)” is the y intercept, and “a” is the rate constant.

Model C was developed using the monomolecular growth model (Seber and Wild 1989) in order to relate tree height to tree age. In order to constrain the intercept to zero, I simplified the model to the following form: $y = a + -a \cdot e^{(-c \cdot x)}$, where “y” is height, “x” is age (time) and “a” and “c” are parameters within the model.

See Table 2.3 for a summary of these models.

Results

The simple linear regression with age predicting stem diameter (Model A) produced stronger correlations than the other two models (Table 2.4). The linear regression using the natural log of age to predict height (Model B) and the monomolecular model using age to predict height (Model C) produced similar quality results (Table 2.5 and 2.6). In the regression including all trees (Figure 2.3), Model A produced an R^2 value of .785. For all trees, models B and C (Figures 2.4 and 2.5) produced R^2 values of .686 and .695 respectively. When blocked by habitat type, Model A proved more reliable at predicting stem diameter in woodland stands (Figure 2.6). Model A was not as strongly correlated in savanna stands (Figure 2.7) when compared to Models B and C (Figures 2.8, 2.9, 2.10 and 2.11).

I expected to find that a multiple variable regression using stem diameter and tree height would produce the strongest correlation with age. This was indeed the case, for

the regression including all trees the adjusted R^2 value was only .786. However, this model was only a slightly better predictor of age than simple linear regression with stem diameter ($R^2 = .785$). Due to the added complication of this model and the negligible increase in predictive ability, I decided not to report on this model in this paper.

Correlations were significant for all models in all stands and blocks of stands, except for the WFS and MF stands. In these stands Model A performed poorly, with stem diameter having no significant correlation to age. Model C performed best in these stands, though it also had a low correlation (WFS, $R^2 = .252$ and MF $R^2 = .189$), the results were significant. Model B produced mixed results in these stands with poor but significant results in WFS and an insignificant correlation in MF. See Tables 2.4, 2.5 and 2.6 for the complete result of these regression models.

Discussion

Best Model Forms

A simple linear relationship between age and stem diameter had as good or better fit than more complicated transformations in most cases. After initial establishment one would expect a tree to grow quickly when it is young but have its growth rate decrease as it ages, generally following a logarithmic curve. Calkins (1940) attributed the more or less linear rate of growth even among mature junipers to the fact that older, more dominant trees likely receive light from the side, which allows them to maintain their growth rate. However, I feel that in the arid environment in which junipers grow that moisture is more likely to be a limiting resource than is light.

The primary resource that *J. monosperma*, and other trees that grow in extreme arid environments compete for is soil moisture (Breshears et al. 1997). Though in some

habitats young *J. monosperma* may compete with other trees for resources, often these young *J. monosperma* are in competition with grasses, forbs and shrubs (Johnsen 1962). In other cases they might have a commensial relationship with other trees which can provide shade and thus reduce moisture loss. Instead of growing in height, canopy area or stem mass, they instead focus a greater portion of their energy towards developing a more substantial root structure which is less easily measured by researchers.

As individual *J. monosperma* age the number of live stems typically decreases as some of the stems die off. The loss of these stems may simply be the result of injury due to insect attack or fire. However, this also may be an adaptation to environmental stresses. The tree may passively or actively sacrifice branches which are less efficient in their use of water or production of carbohydrates. At very least it is clear that juniper trees as a whole are able to survive even when portions of the tree are killed due to environmental stress. The overall photosynthetic potential of the tree will be reduced by such diebacks (Kaufmann 1990). However, with these less productive stems eliminated the mean vigor of the tree increases. This will result in the growth of the tree, as seen in measurable attributes such as the diameter of the surviving stems, slowing less with age than one might expect from what we know of typical tree allometrics. Future research may wish to focus on the structure and size of juniper roots as a means to better understand juniper establishment and growth.

My findings, that the diameter of the largest stem had, on average, the best correlation with age, differ from previous studies. Landis and Bailey (2005) and Despain (1989) found that height had the strongest correlation with age among *J. osteosperma*.

These differences could be due to genetic differences among these two closely related species or differences in site conditions.

It is however important to note that the use of the allometric equations derived in this chapter may be dubious when applied to young trees. Since measurements of stem diameter were taken at 30 cm up the stem from the ground, trees less than 30 cm in height were recoded as having a stem diameter of zero. As a result the age prediction for the youngest and smallest trees, those with a stem diameter of less than 3 cm at 30 cm above the ground, might not be as accurate as the age prediction for larger trees.

Understanding predictability

Generally for all models, but specifically looking at Model A, better fitting regressions were derived from the block of Woodland stands ($R^2=.712$) compared to the block of Savanna stands ($R^2=.367$) (Figures 2.6 and 2.7). The older woodland trees may not vary as much in their size attributes with age as did the younger savanna trees. Or, this may be because the lower elevation savanna areas have a harsher and less predictable environment when compared to the woodland areas. It may also simply be that data covering a larger range of ages better display the allometric relationships than the limited range of ages seen in the younger savanna trees. The WFS and MF had the lowest predictability among all stands. When one blocks only two savanna stands, WFS and AF, the increased R^2 value (.622) suggests that the age of savanna trees is nearly as predictable as trees in a woodland environment.

Tausch (1980) suggested that site quality was a critical factor influencing variation in allometric relations. Therefore, I conclude that the reason that tree size in MF is so difficult to predict is that these trees are growing in shallow soil on the lower

limit in elevation and moisture at which *J. monosperma* exists in the study site. The WFS stand is for the most part on a mild slope with a southern aspect, which would increase irradiance and evapotranspiration. Also, the soils on WFS are relatively coarse and thus will not hold moisture well. Differences in fitness among individual trees and microsite conditions will likely result in a much more variable growth rate between trees in these harsh environments. These differing growth rates create a poor correlation between age and size.

Consistency in site conditions might help explain why WFN, AF and APS have a stronger correlation between size and age than other stands. WFN and APS in particular are on flat to gently sloping areas underlied by limestone. The soil microtopograph of AF is less consistent than that of WFN and APS, but more consistent than that of other basalt stands such as PM and WFS. PM in particular is more topographically diverse than other stands, with high points and rock outcroppings where soil is thin and lower depressions and slopes where deeper soils could develop. Therefore, I can generally state that harsher living conditions and greater variability in site conditions will make predicting the age of *J. monosperma* more difficult.

Comparing growth rates

Bedrock type does not have a significant effect on the growth rate of *J. monosperma* on this study site. Looking at the stem diameter growth equation (Table 2.4) it appears that the slopes of the regression, and thus the growth rate of the trees in each stand differ. I blocked the stands by both bedrock type and habitat type for growth rate analysis. The stands on the limestone derived soil had a mean growth rate of .73 mm increase in stem diameter per year. Stands on basalt derived soil had a mean growth rate

of .69 mm increase in stem diameter per year. These values are not significantly different (probability > t = .2861).

When blocked by habitat type, woodland stands (PM and APS) had a mean growth rate of .70 mm increase in stem diameter per year (Figure 2.7) and the savanna stands had a mean growth rate of .69 mm per year (Figure 2.6). These values are not significantly different (probability > t = .9076). It is important to note that the assumptions of this t-test were violated in that the distribution of the residuals was not normal. However, considering the extremely high p-value, it is still reasonable to assume that the growth rates of savannas and woodlands do not differ. In another test, WFS and MF were not blocked with AF and WFN in the savanna block due to their insignificant correlation between age and stem diameter in WFS and MF. The remaining savanna stands had a mean growth rate of .96 mm increase in stem diameter per year (Figure 2.12). This value is also not significantly different (probability > t = .0656) from the growth rate of woodland trees. Therefore habitat type had no substantial effect on *J. monosperma* growth rates. This supports the use of a single growth rate equation for all *J. monosperma* in the study area. This is contrary to anecdotal evidence suggesting that junipers in woodland environments grow more slowly than those in savanna environments or that trees at the lower elevation limits of *J. monosperma* range grow more slowly than those at more moderate elevations. However, this lack of variation in growth rates is at least hinted at in previous research. Lymbery and Pieper (1983) found no difference among the mean stem diameters of the *J. monosperma* the measured on variously graded slopes and aspects in central New Mexico.

Calkins (1940) also found that among *J. monosperma* stem diameter increased in a linear fashion over time, with a growth rates between 0.4 and 0.6 inches (1.02 and 1.52 cm) per decade among trees surveyed across northern Arizona and northern New Mexico. At my study site junipers grew at just over half this rate, increasing in diameter approximately .71 cm per decade. Jameson (1965) focused on height, finding that *J. monosperma* trees increased in height 16 cm per decade on the Dead Man's Flat are of the Coconino National Forest in Arizona, very near the study site for this thesis, but at a slightly higher elevation. Although a simple linear regression of height is not a relationship I explored in detailed, my initial data analysis found that junipers at Wupatki increased in height of approximately 12.2 cm per decade ($R^2=.619$). Although this data is too limited to draw any sound conclusions, it appears that the *J. monosperma* at the Wupatki study site grow more slowly then average. This may be due to reduced moisture availability at the research site compared to the sites survey in these other studies, however further research, studying juniper growth rates at various sites with differing site conditions, would be needed to confirm this assertion.

Conclusion

It is more difficult to correlate age to size among *J. monosperma* in more stressful environments. Overall, a simple linear relationship between age and stem diameter was the most consistent among the many allometric relationships tested for *J. monosperma* at my study site. For a land manager in the field the most practical and efficient way to estimate the age of *J. monosperma* is to measure and compare the diameter of the largest stem of each tree. Although my study found a consistent growth rate across the entire

study site, future research should focus on determining what factors might affect juniper growth rates. It is likely that moisture availability is a primary limiting factor, but we can learn more about juniper ecology and physiology by determining how elevation, competition, rainfall, soil type or other factors affect juniper growth rates.

Literature Cited

- Amos, R.C. 1987. Sunset Crater, Arizona: Evidence for a large magnitude strombolian eruption. M.S. Thesis, Arizona State University.
- Arid Lands Information Center (ALIC). 2001. Terrestrial Ecosystem Survey of the Coconino National Forest. <http://alic.arid.arizona.edu/tes/tes.html>. Date accessed: 10/24/05:
- Arnold, J. F., Jameson, D. A. and Reid, E. H. 1964. The pinyon-juniper type of Arizona: effects of grazing, fire, and tree control. Production Research Report, U.S. Department of Agriculture. 84: 1-28
- Breshears, D. D., Myers, O.B., Johnson, S. R., Meyer, C. W. and Martens, S. N. 1997. Differential use of spatially heterogeneous soil moisture by two semiarid woody species: *Pinus edulis* and *Juniperus monosperma*. Journal of Ecology. 85: 289-299
- Brotherson, J. D., Rushforth, S. R., Evenson, W. E., Johansen, J. R. and Morden, C. 1983. Population dynamics and age relationships of eight tree species in Navajo National Monument, Arizona. Journal of Range Management. 36: 250-255
- Brown, D. E. 1994. Plains and Great Basin grassland. In Biotic Communities of the American Southwest-United States and Northwest Mexico, ed D. E. Brown. Desert Plants 4: 115-121
- Calkins, H. G. 1940. Pinon and juniper: a preliminary study of volume, growth and yield. Regional Bulletin No. 71. Forest Series No. 12. Pp 90.
- Cinnamon, S. K. 1988. The Vegetation Community of Cedar Canyon, Wupatki National Monument as Influenced by Prehistoric and Historic Environmental Changes. Master's Thesis, Northern Arizona University, Flagstaff, Arizona.
- Cinnamon, Steve. 1990. Wupatki grazing terminated. Park Science: A Resource Management Bulletin. 10: p .20
- Despain, D. W. 1989. Radial growth relationships in Utah juniper (*juniperus osteosperma*) and Pinyon pine (*Pinus edulis*). The University of Arizona.

- Dick-Peddie, W.A. 1993. New Mexico vegetation, past, present and future. Albuquerque, NM: Univ. New Mexico Press.
- Engle, D.M., Kulbeth, J.D. 1992. Growth dynamics of crowns of eastern redcedar at three locations in Oklahoma. *Journal of Range Management*. 45: 301-305
- Everett, R. L., Sharrow, S. H., Thran, D. F. 1987. Soil nutrient patterns and associations adjacent singleleaf pinyon. *Soil Science Society of American Journal*. 51: 81-88.
- Ffolliott, P. F., Gottfried, G. J. 2002. Dynamics of a piñon-juniper stand in northern Arizona: a half-century history. U.S. Department of the Agriculture, Forest Service, Rocky Mountain Research Station, Research Paper RMRS-RP-35
- Fritts, H. C. 1976. *Tree Rings and Climate*. The Blackburn Press: Caldwell, NJ
- Glock, W. S. and Agerter, S. R. 1962. Rainfall and tree growth. *Tree Growth*. T. T. Kozlowski, ed.: 23-56
- Gottfried, G. J. 1987. Regeneration of pinyon. In: Everett, L., comp. *Proceedings, pinyon-juniper conference*; Gen. Tech Rep. INT-215. Ogden, UT: U.S. Department of Agriculture, Forest Service, Intermountain Research Station: 249-254
- Gottfried, G. J., Swetnam, T. W., Allen, C. D., Betancourt, J. L. and Chung-MacCoubrey, A. L. 1995. Pinyon-juniper woodlands. In: Finch, D. M., Tainter, J. A. (Eds.), *Ecology diversity and sustainability of the Middle Rio Grande Basin*. USDA Forest Service, General Technical Report: 95-132
- Grissino-Mayer, Henri D. 2005. Species used in Tree-Ring Research. Ultimate Tree-Ring Web Pages. <http://web.utk.edu/%7egrissino/>: Date accessed: 10/23/05
- Hansen, M. J. Coles, K.A. Thomas, D. Cogan, M. Reid, J. Von Loh, and K. Shulz. 2004. USGS-NPS National Vegetation Mapping Program: Wupatki National Monument. Final Report, U.S. Geological Survey, Southwest Biological Center, Flagstaff, Arizona.
- Heerwagen, A. 1956. Mixed prairie in New Mexico. In: J. E. Weaver and F. W. Albertson. *Grasslands of the Great Plains*. Johnson Publishing Company, Lincoln, Nebraska. pp. 284-300.

- Hooten, J. A. Ort, M. H. and Elson, M. D. 2001. The Origin of Cinders in Wupatki National Monument. Technical Report 200 1-12. Desert , .Archaeology, Inc., Tucson
- Jameson, D. A. 1965. Arrangement and growth of pinyon and one-seed juniper trees. Plateau 37: 121-127.
- Johnsen, T. N., Jr. 1962. One-seed juniper invasion of Northern Arizona grasslands. Ecological Monographs. 32: 187-207.
- Kaufmann, M. R. 1990. Ecophysiological processes affecting tree growth: water relationships. In: Process Modeling of Forest Growth Responses o Environmental Stress, Dixon, et al. ed. Timber Press Inc, Portland, USA, 441.
- Kimball, David. 2002. GIS point to Trimble waypoint(GPS.WriteWaypointTextFile) AVENUE Script for ArcView 3.x. Available from: <http://arcscrips.esri.com>.
- Lajtha, K., Getz, J. 1993. Photosynthesis and water-use efficiency in pinyon-juniper communities along an elevation gradient in northern New Mexico. Oecologia. 94, : 95-
- Landis, A. G. and Bailey, J. D. 2005. Reconstruction of age structure and spatial arrangement of piñon-juniper woodlands and savannas of Anderson Mesa, northern Arizona. Forest Ecology and Management. 205: 221-236
- Linton, M. J., Sperry, J. S., Williams, D. G. 1998. Limits to water transport in Juniperus osteosperma and Pinus edulis: implications for drought tolerance and regulation of transpiration. Functional Ecology. 12, : 906-911
- McCormick, D. 1989. The geology of Wupatki National Monument, northern Arizona. PhD Dissertation, Northern Arizona University
- Lymbery, G. A., and R. D. Pieper. 1983. Ecology of pinyon-juniper vegetation in the northern Sacramento Mountains. Bulletin, (New Mexico State University) Agricultural Experiment Station, 698.
- Miller, F. H. 1921. Reclamation of grasslands by Utah juniper on the Tusayan National Forest, Arizona. Journal of Forestry. 19: 647-651
- National Climatic Data Center (NCDC). 2005. WDC for Paleoclimatology – Tree-Ring Data Search. <http://www.ncdc.noaa.gov/paleo/ftp-treering.html> Date accessed: 10/23/05.

- Seber, G. A. F., Wild, C. J. 1989. Nonlinear Regression. John Wiley and Sons, Inc., New York.
Pp. 768
- Short, M. S. 1988. Walnut Canyon and Wupatki: A History. M.S. Thesis. Northern Arizona University, Flagstaff, AZ. pp. 95.
- Stokes, M. A. and Smiley, T. L. 1968. Introduction to tree-ring dating. University of Chicago Press, Chicago.
- Tausch, R. J. and West, N. E. 1988. Differential establishment of pinyon and juniper following fire. American Midland Naturalist. 119: 174-184
- Tausch, R., J. 1980. Allometric analysis of plant growth in woodland communities. Logan, UT, Utah State University.
- Taylor, D. R. 1983. Soil Survey of Coconino area, Arizona, central part. United States Department of Agriculture, Soil Conservation Service, Washington D.C.
- Trimble, M. 1982. CO Bar Bill Owen Depicts the Historic Babbitt Ranch. Northland Press, Flagstaff. pp. 95.
- U. S. Department of Agriculture, Soil Conservation Service (USDA). 1971. Soil survey and range site and condition inventory Wupatki National Monument Arizona: a special report. Portland, Oregon.
- Western Regional Climate Center. 2005. Wupatki Natl Monument, Arizona – Climate Summary. <http://www.wrcc.dri.edu/> Date Accessed: 9/28/05.

Figures

<u>Stand</u>	<u>Antelope Fire</u>	<u>West Fire, South</u>	<u>West Fire, North</u>	<u>Moon Fire</u>	<u>Antelope Prairie South</u>	<u>Powerline Mesa</u>
<u>Abbreviation</u>	AF	WFS	WFN	MF	APS	PM
<u>Type</u>	Savanna	Savanna	Savanna	Savanna	Woodland	Woodland
<u>Bedrock</u>	Basalt	Basalt	Limestone	Limestone	Limestone	Basalt
<u>Size</u>	543 ha	105 ha	204 ha	58 ha	2144 ha	1922 ha
<u>Mean Elevation</u>	1710 m	1690 m	1665 m	1630 m	1660 m	1780 m
<u>Elevation Range</u>	1670-1745 m	1678-1700 m	1652-1687 m	1629-1642 m	1634-1698 m	1709-1868 m
<u>Mean Density</u>	9.1 tph	4.9 tph	5.8 tph	1.7 tph	106.7 tph	117.6 tph
<u>Soil Texture</u>	gravelly loams-very gravelley	very gravelly loam	very cindery loam	gravelly fine sandy laom, gravelly loam	extremely cindery loamy sands/sandy loams	extremely cindery loamy sands/sandy loams
<u>Soil Depth</u>	moderately deep	deep	deep	shallow	moderately deep	shallow to moderately deep

Table 2.1. Attributes of the six stands included in this study.

<u>% Live Crown Class</u>	<u>Description</u>
0%	Entirely or almost entirely and imminently dead
25%	2% to 37.4% live crown
50%	37.5% to 63.4% live crown
75%	63.5% to 90% live crown
100%	At least a 90% live crown

Table 2.2. Detailed description of percent live crown categories as defined for this study.

<u>Model</u>	<u>Formula</u>	<u>Variables</u>	<u>Description</u>
A	$y = b + a \cdot x$	y = stem diameter (cm) x = age a = growth rate (cm/year) b = y intercept y = height (m)	The simple linear regression of tree age predicting stem diameter.
B	$y = y(x) + a \cdot \ln(x)$	x = age y(x) = y intercept a = rate constant y = height (m)	The regression of the natural log of tree age predicted by tree height.
C	$y = a + -a \cdot e^{(-c \cdot x)}$	x = age (time) a and c are model parameters	The monomolecular growth model relating tree height to tree age.

Table 2.3. Chart of the growth models used in this chapter displaying the formula, variables used and a brief description of the model.

<u>Stand</u>	<u>Regression Equation</u>	<u>R² value</u>	<u>n</u>	<u>Slope prob>t</u>	<u>y intercept prob>t</u>
All	$y = 0.6890578 + 0.0706339 x$	0.785	216	<.0001	0.2066
Savanna AF and WFN only	$y = 0.815772 + 0.0688178 x$	0.367	126	<.0001	0.3361
Woodland	$y = -0.635024 + 0.0961257 x$	0.622	79	<.0001	0.4537
Basalt	$y = 0.8828239 + 0.0701818 x$	0.712	90	<.0001	0.5513
Limestone	$y = 1.3331608 + 0.069268 x$	0.778	118	<.0001	0.0627
PM	$y = -0.309903 + 0.0732417 x$	0.8	98	<.0001	0.7152
APS	$y = 3.8631983 + 0.0624121 x$	0.576	39	<.0001	0.1942
AF	$y = -0.794616 + 0.0748311 x$	0.807	51	<.0001	0.6057
WFS	$y = -0.960562 + 0.098982 x$	0.662	49	<.0001	0.3072
WFS	$y = 0.1597881 + 0.089918 x$	0.521	30	<.0001	0.9304
WFS	$y = 5.1136552 + 0.0251909 x$	0.069	30	0.16	0.0101
MF	$y = 2.5984437 + 0.0182039 x$	0.169	17	0.101	0.06

Table 2.4. Results of simple linear regression of age (x) predicting stem diameter in cm (y) for each stand and blocks of stands. The gray numbers in the columns "Slope prob>t" and "y intercept prob>t" highlight that those numbers indicate the slope is not different from zero or that the y intercept is not different from zero.

<u>Stand</u>	<u>Regression Equation</u>	<u>R² value</u>	<u>n</u>	<u>Slope prob>t</u>	<u>y intercept prob>t</u>
All	$y = -4.362558 + 1.4089478 \ln(x)$	0.686	216	<.0001	<.0001
Savanna AF and WFN only	$y = -3.208374 + 1.1414852 \ln(x)$	0.464	126	<.0001	<.0001
Woodland	$y = -4.280392 + 1.4417076 \ln(x)$	0.693	79	<.0001	<.0001
Basalt	$y = -5.017151 + 1.53838 \ln(x)$	0.601	90	<.0001	<.0001
Limestone	$y = -4.30034 + 1.4078637 \ln(x)$	0.695	118	<.0001	<.0001
PM	$y = -4.608078 + 1.4442686 \ln(x)$	0.674	98	<.0001	<.0001
APS	$y = -6.385367 + 1.7747244 \ln(x)$	0.579	39	<.0001	<.0001
AF	$y = -4.316673 + 1.4153001 \ln(x)$	0.634	51	<.0001	<.0001
WFS	$y = -4.567149 + 1.5247729 \ln(x)$	0.693	49	<.0001	<.0001
WFS	$y = -4.076366 + 1.3731896 \ln(x)$	0.708	30	<.0001	<.0001
WFS	$y = -2.515612 + 0.9493768 \ln(x)$	0.252	30	0.0047	0.0879
MF	$y = -0.533371 + 0.4195058 \ln(x)$	0.179	17	0.091	0.6355

Table 2.5. Results of regression of ln of age (x) predicting tree height in meters (y) for each stand and blocks of stands. The gray numbers in the columns "Slope prob>t" and "y intercept prob>t" highlight that those numbers indicate the slope is not different from zero or that the y intercept is not different from zero.

Stand	Regression Equation	R2 value	n
All	$y = 4.7997400608 + -4.7997400608 * e^{(-0.005321994528 * x)}$	0.695	216
Savanna	$y = 3.3127882564 + -3.3127882564 * e^{(-0.0094880041 * x)}$	0.457	126
AF and WFN only	$y = 5.2968457881 + -5.2968457881 * e^{(-0.0056546692 * x)}$	0.685	79
Woodland	$y = 4.9177783638 + -4.9177783638 * e^{(-0.0049981976 * x)}$	0.613	90
Basalt	$y = 4.7301379497 + -4.7301379497 * e^{(-0.0057307917 * x)}$	0.697	118
Limestone	$y = 4.935676084 + -4.935676084 * e^{(-0.0048270663 * x)}$	0.695	98
PM	$y = 5.2882642188 + -5.2882642188 * e^{(-0.0041221061 * x)}$	0.585	39
APS	$y = 4.709488196 + -4.709488196 * e^{(-0.0056440291 * x)}$	0.601	51
AF	$y = 7.6145110501 + -7.6145110501 * e^{(-0.0037281896 * x)}$	0.684	49
WFN	$y = 4.783830592 + -4.783830592 * e^{(-0.0060971376 * x)}$	0.71	30
WFS	$y = 2.4595928472 + -2.4595928472 * e^{(-0.0142565165 * x)}$	0.252	30
MF	$y = 1.5822616304 + -1.5822616304 * e^{(-0.0236430703 * x)}$	0.189	17

Table 2.6. Results using age (x) in the monomolecular growth model to predict tree height in meters (y) for each stand and blocks of stands.

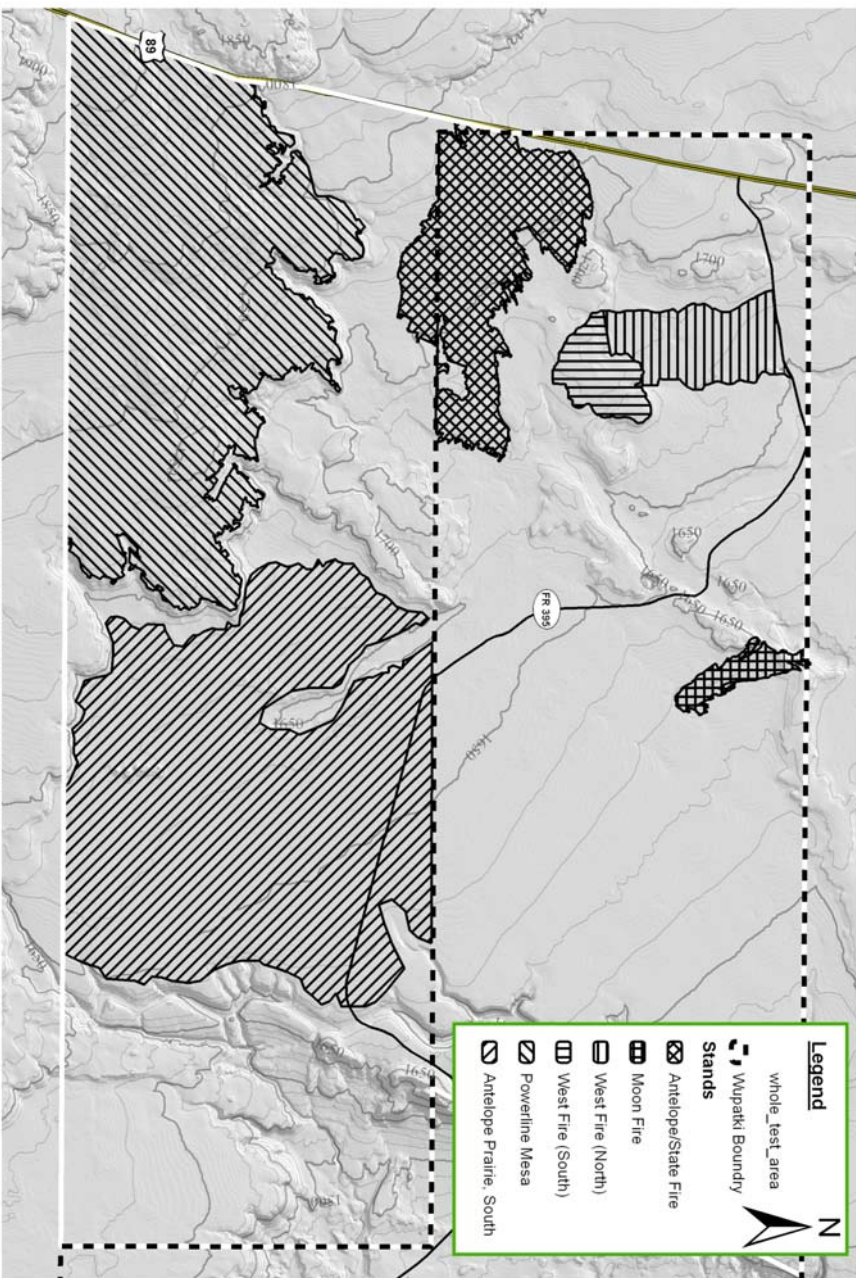
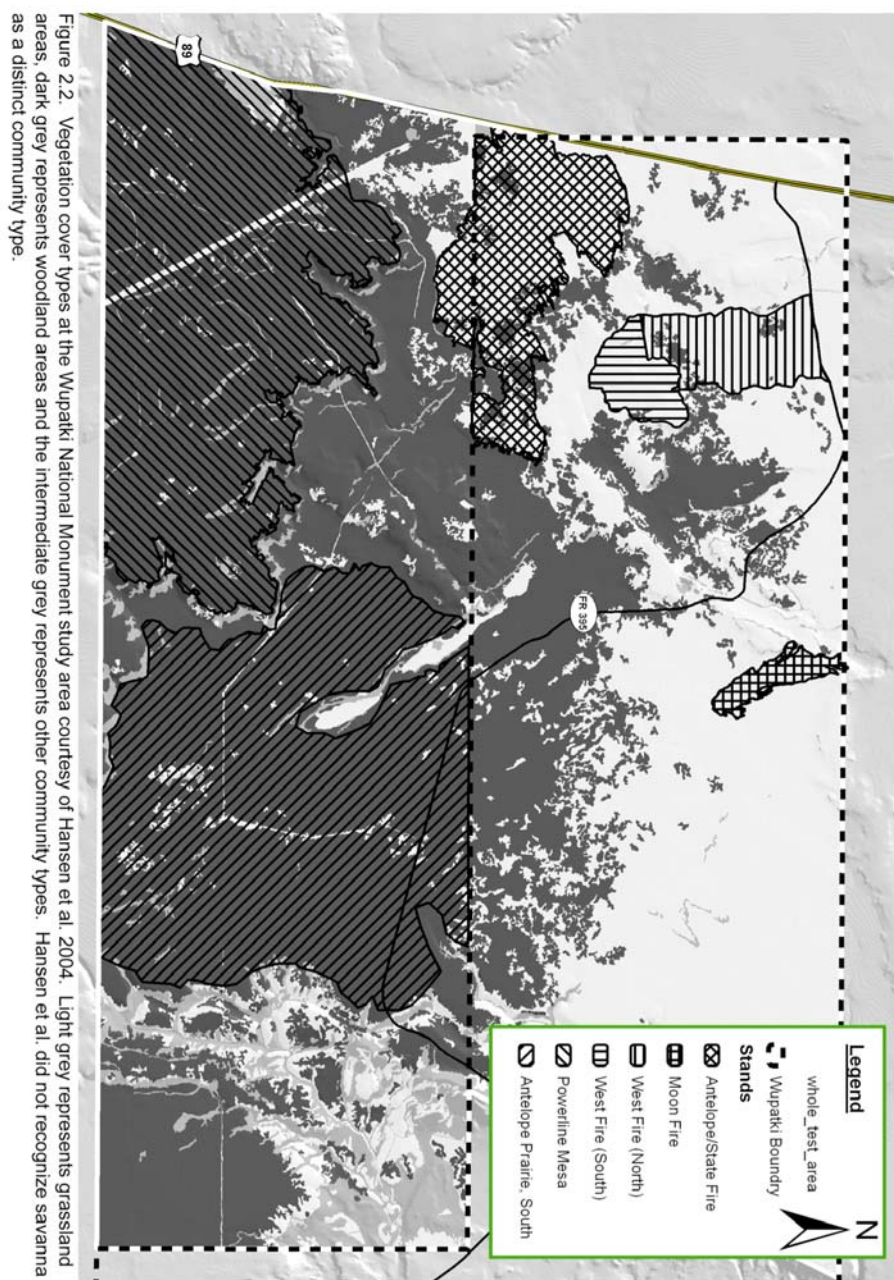


Figure 2.1. Wupatki National Monument Test area with stands, sample plots and elevation.



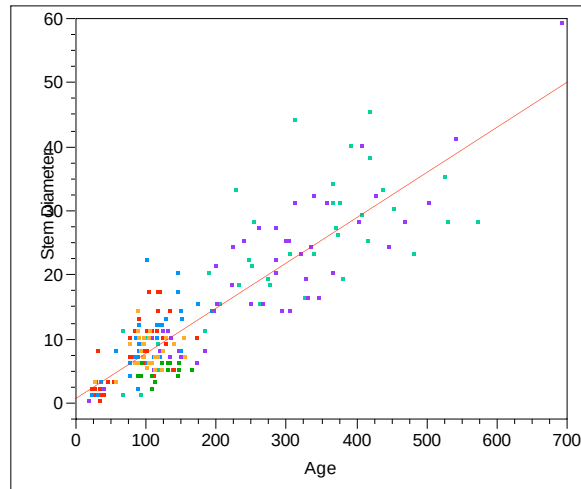


Figure 2.3. Graph of Model A, the linear fit of stem diameter as predicted by age, for the block of All stands. The regression equation is $y = 0.6890578 + 0.0706339x$, $R^2 = .785$. Solid line indicates the linear fit of the regression.

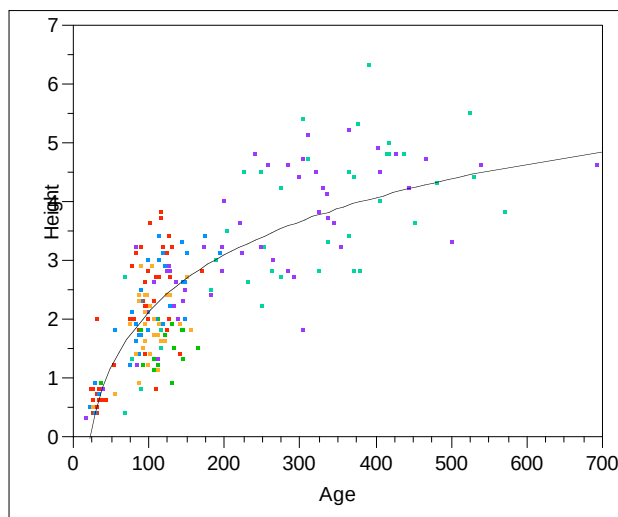


Figure 2.4. Graph of Model B, the regression of height as predicted by the log of age, for the block of all stands. $R^2 = .686$.

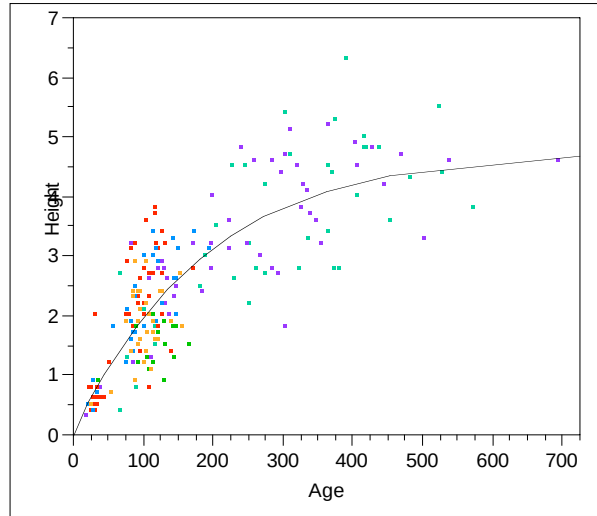


Figure 2.5. Graph of Model C, height as predicted by age using the monomolecular growth model, for the block of all stands. $R^2 = .695$.

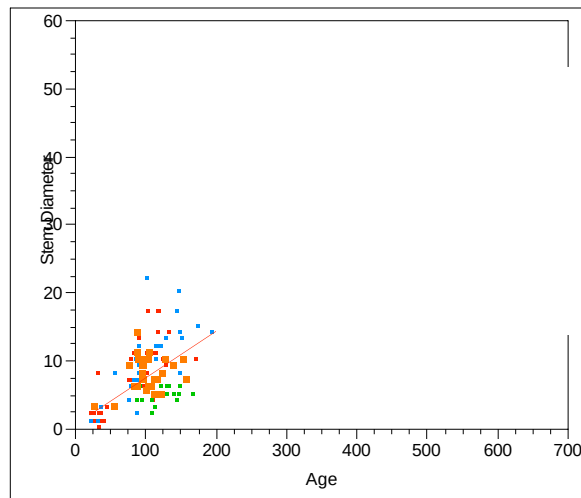


Figure 2.6. Graph of Model A, the linear fit of stem diameter as predicted by age, for the block of savanna stands. The regression equation is $y = 0.815772 + 0.0688178 x$, $R^2 = .367$. Solid line indicates the linear fit of the regression.

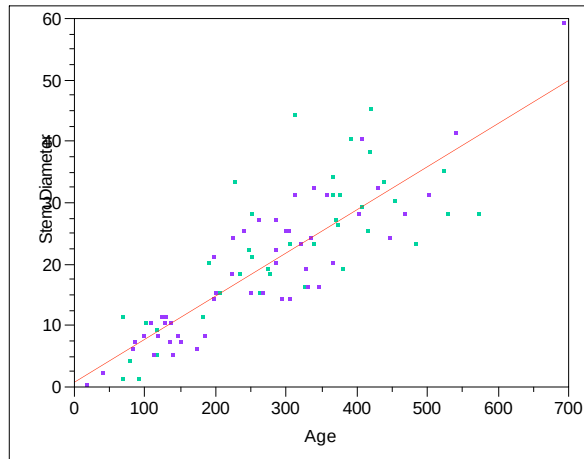


Figure 2.7. Graph of Model A, the linear fit of stem diameter as predicted by age, for the block of woodland stands. The regression equation is $y = 0.8828239 + 0.0701818x$, $R^2 = .712$. Solid line indicates the linear fit of the regression.

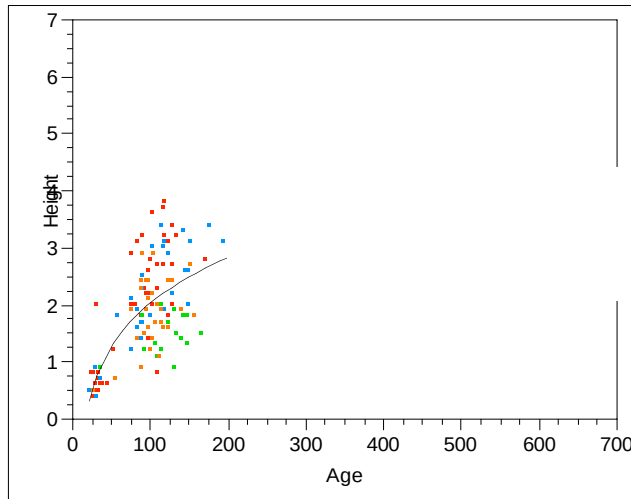


Figure 2.8. Graph of Model B, the regression of height as predicted by the log of age, for the block of savanna stands. $R^2 = .464$.

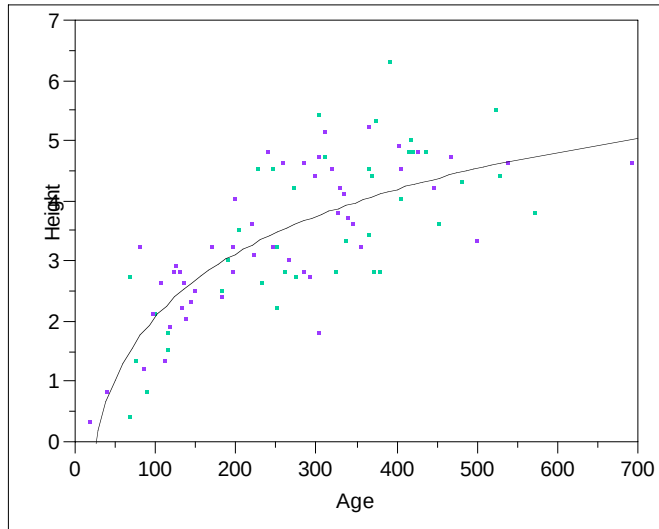


Figure 2.9. Graph of Model B, the regression of height as predicted by the log of age, for the block of woodland stands. $R^2 = .601$.

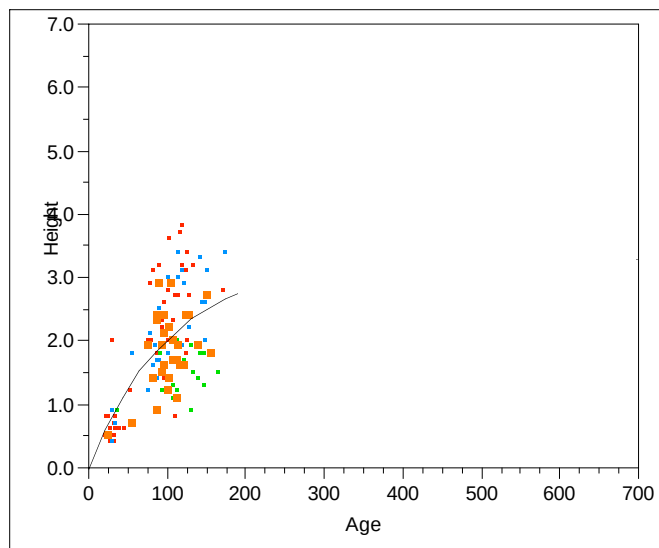


Figure 2.10. Graph of Model C, the regression of height as predicted by age using the monomolecular model, for the block of savanna stands. $R^2 = .457$.

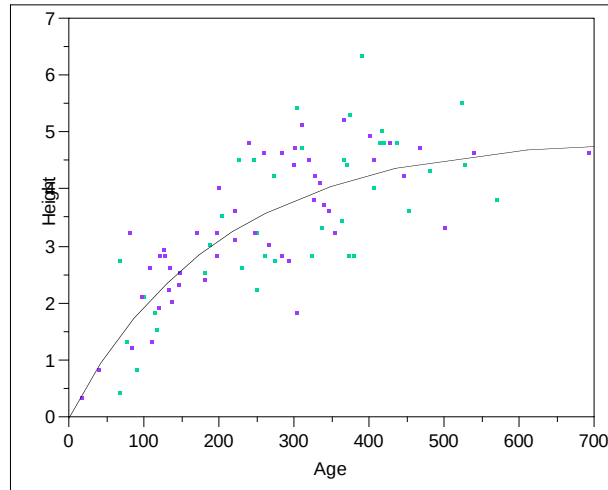


Figure 2.11. Graph of Model C, height as predicted by age using the monomolecular model, for the block of woodland stands. $R^2 = .613$.

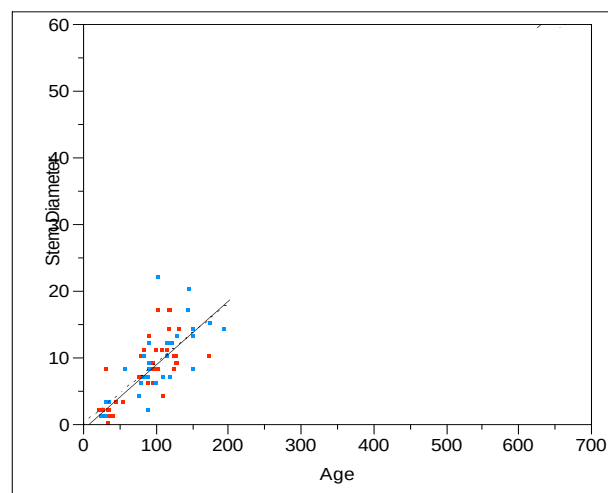


Figure 2.12. Graph of Model A, the linear fit of stem diameter as predicted by age, for the block of AF and WFN (solid line). Slope = 0.0961257, $R^2 = .622$. Solid line indicates the linear fit of the regression. Dashed line indicates the linear fit when the intercept is forced to zero, with a slope of 0.0903055.

Chapter 3: Establishment of *Juniperus monosperma* in Invaded Grasslands and Old-Growth Woodlands In and Near Wupatki National Monument, Northern Arizona

Abstract

Evidence suggests that, during the last 140 years, *Juniperus monosperma* (Engelm.) Sarg.) (one-seed juniper) woodland has expanded both downward in elevation and northward into Antelope Prairie in Wupatki National Monument in Northern Arizona, USA. I evaluated and compared the establishment dates and densities of the juniper trees in several stands in both the juniper savanna within Wupatki N. M. and the juniper woodland on the adjacent Coconino National Forest in order to determine if the establishment of these stands, or an increase in tree density, follows the regional pattern corresponding to Euro-American settlement. The density of *J. monosperma* in 94 plots and the age of 216 sample trees were analyzed. Stands were blocked for analysis according to habitat type and bedrock composition. I removed cross section samples from these trees and determined their age by a ring count. Bedrock type had little to no effect on the tree density or establishment patterns of stands of *J. monosperma* in my study site. Woodlands were substantially denser than savannas with 118 tph in woodlands and 7.6 tph in savannas. The juniper woodlands on the Coconino National Forest are long established, with trees as old as 700 years, and a mean establishment date of 1730. *J. monosperma* establishment within savanna stands is relatively recent; these stands have become established within the past 200 years with a mean establishment date of 1902. It is likely that these savanna stands were semi-arid grassland communities previous to grazing impacts which disturbed the historic frequent fire regime. Prescribed

fire will be an important tool in restoring these savannas to their historic grassland condition. Conversely, thinning or prescribed fire would be misguided management actions within the juniper woodland community.

Introduction

The total area of grassland habitat in the southwestern United States has significantly declined during the past 150 years (Kearney and Peebles 1960, Dick-Peddie 1993, Brown 1994). Historically, semi-arid grasslands were maintained by wildfires. It appears that the reduction of fine fuels due to cattle grazing and subsequent fire suppression, has favored the establishment of juniper woodland in the upper elevation range of grassland habitat (Foster 1917, Leopold 1924, Johnsen 1962, Bogan et al. 1998).

Increased shading by juniper trees and competition for resources, especially water, has led to a dramatic reduction in grass and forbs diversity and abundance in these grasslands (Arnold, 1958; Tausch and West, 1994). This loss of grassland habitat threatens already imperiled grassland dependant species such as black-footed ferrets (*Mustela nigripes* (Audubon and Bachman)), prairie dogs (*Cynomys* (Rafinesque) *spp.*), burrowing owls (*Athene cunicularia* (Molina)) and pronghorn antelope (*Antilocapra americana* (Ord)) (Lowe 1964, Neff 1986). Not only can juniper encroachment reduce the size of remaining grassland habitat, it also increases the fragmentation of these grasslands (Coppedge et al. 2001).

Repeat photography, packrat midden analysis, historic vegetation maps, and limited vegetation plot data suggest that, during the last 140 years, *Juniperus monosperma* (Engelm.) Sarg.) (one-seed juniper) has expanded both downward in

elevation and northward into Antelope Prairie in Wupatki National Monument (WUPA) in Northern Arizona (Merriam 1898, Cinnamon 1988, Ffolliott and Gottfried 2002). Several grassland-dependent vertebrates and grassland associated plants inhabit Antelope Prairie. Land manager are concerned that if the entire grassland community succeeds to juniper woodland, many of these species may be at risk of extirpation from the Monument (Wilcox and Murphy 1985).

In this study I evaluated and compared the establishment dates and densities of the trees in several stands in both the juniper savanna within Wupatki and in denser juniper woodlands on the adjacent Coconino National Forest. My goal was to evaluate the age structure of these stands and determine if their establishment, or an increase in tree density, follows the regional pattern corresponding to Euro-American settlement. Based on a review of repeat aerial photos taken of the research site in 1936 and again in 1997, and the literature pertaining to juniper encroachment in the region (Leopold 1924, Johnsen 1962, Jameson 1965, West 1999, Van Auken 2000, Ffolliott and Gottfried 2002), I expect that almost all trees within the savanna stands in Wupatki were established after the initiation of intensive grazing and fire exclusion in the 1860's. I also expect to find that the juniper woodlands on the national forest will also show a marked increase in tree establishment around this time.

Methods

Site Description

Wupatki National Monument (WUPA) lies on the Colorado Plateau approximately 45 km (28 miles) northeast of Flagstaff Arizona (Figure 1.1). The study

area includes in the western half of monument and the adjacent portion of the Coconino National Forest (CNF) just to the south and upslope of this portion of the monument.

The portion of the study site within WUPA is known as Antelope Prairie and is a plains grassland and juniper savanna. The portion of the study area on the CNF is best described as a juniper woodland. *Juniperus monosperma* is the most common tree species, with a small number of *Pinus edulis* Engelm. in the highest elevation portions of the study site.

The research area covers 13,850 ha (34,200 ac) ranging from 1,615 m (5,300 ft) in elevation at the lowest point in Antelope Prairie to 1860 m (6,100 ft) at the highest point within the research area within the CNF (Figure 2.1). Various estimates place the average annual precipitation in the study area to be between 20 cm (8 inches) and 40 cm (16 inches) (USDA 1971, ALIC 2001).

The underlying bedrock of the study area is Kaibab limestone. On about half of the study site, this bedrock is overlaid by low basalt mesas. The soil in the area is strongly influenced by an overlay of volcanic cinders (Hooten et al. 2001).

Site History

The Sinagua people settled in and farmed the Wupatki Basin and surrounding area including Antelope Prairie in the late 11th century (Short 1988, Anderson 1993, SUCR 2005). The ancestral Hopi culture flourished here for about 150 years before these Pueblo sites were abandoned around 1250 A. D. (Short 1988, Anderson 1993). The Navajo grazed their sheep in the area in the mid to late 19th century (Cinnamon 1988, Short 1988). By 1886, the Navajo were supplanted by Euro-American cattle operations such as the C O Bar ranch that heavily grazed the land that would later become WUPA

(Trimble 1982, Cinnamon 1988). For the following 140 years grassland fires in Wupatki were rare and covered only a very small area. Since 1924, NPS administrative records report only two fires other than localized lightening strikes - in 1956 and 1989. Cattle grazing was removed from Wupatki in 1989 (Cinnamon 1990). Since then, the herbaceous plants in Antelope Prairie have been able to recover from grazing. As a result, approximately 1000 ha (2,600 acres) have burned in four lightning and human caused fires in 1995, 2000 and 2002.

Stand Description

For the purposes of this study, stands were defined as populations of juniper trees on level to gently-rolling terrain on the same basalt shelf or limestone bedrock, with a fairly consistent elevation. A stand was defined as a woodland if there were greater than 30 trees per hectare (tph), and as a savanna if there were fewer than 30 tph. There are six stands in this research study, four being in WUPA (Figure 2.1). Two woodland stands were sampled in the southern portion of the research site on the CNF. These CNF stands are known as Antelope Prairie South (APS) and Powerline Mesa (PM). Due to sampling limitations within WUPA, the savanna stands were limited to areas burned by recent lightning and human caused wildfires. The four savanna stands within the park are known as Antelope/State Fire (AF), West Fire South (WFS), West Fire North (WFN) and Moon Fire (MF) (Table 2.1).

Tree Measurements and Samples

The size attributes of each tree in each plot were measured and recorded. The percentage of live crown for each tree was made by a visual estimate of the tree from at least two perspectives and divided into five classes (0 % 25%, 50%, 75%, 100%) and

recorded. See Table 2.2 for a detailed description of these percent live crown categories. Trees with 0% live crown were considered dead. It was assumed that direct and indirect fire induced mortality was the cause of death for all dead trees within the savanna stands.

Trees were divided into four size classes based on height (0-1.5 m, 1.5-3.0 m, 3.0-4.5 m and 4.5 and greater). In each randomly placed plot, the tree in each size class closest to the plot center was selected to be sampled and have a cross section removed for analysis. Two additional trees in each size class in each plot were sampled in the MF stand due to the low number of trees (and thus samples for analysis) in this stand. One additional tree in each size class in each plot was sampled in the WFS stand due to the low correlation in preliminary allometric analysis in this stand. The stem cross sections were removed from the tree with a chain saw, cutting as low to the ground as conditions would safely allow. Due to sampling limitations, only dead trees killed in recent wildfires were allowed to be removed from savanna stands within WUPA. There were no sampling restrictions on the CNF, where only live trees were removed so that the year of death could be known.

Any trees that appeared to have damaged that could have been the result of a pre-Euro-American settlement fire were noted. A cursory search was made in each plot for additional fire scarred materials. Samples were taken of trees that appeared to harbor fire evidence. However these samples were so few in number that they were not useful to this study.

Lab Methods

Each cross section sample “disc” was prepared using standard techniques (Stokes and Smiley 1968). A cross section of an entire stem is necessary for an accurate ring

count due to the lobed growth form of juniper stems. Among some *Juniperus* species new wood growth around the entire circumference of the stem will only occur years most conducive to growth. In most years, “rings” are only accumulated on the most consistently growing portion of the stem (Tausch and West, 1988), which creates the distinctive lobes found in the cross sections of many *Juniperus* species. Ring counts were conducted along the most vigorously and consistently growing lobe for each disc.

Due to the inconsistent manner in which many *Juniperus* put on ring growth, it was not possible to create a chronology for cross reference (Fritts, 1976, Gottfried et al., 1995, Landis and Bailey, 2005). It is likely that the accuracy of the counted age of the tree decreases with increasing age because tree rings were only counted and not cross dated. In general, junipers, especially *J. osteosperma* and *J. monosperma*, are difficult if not impossible to cross date (Grissino-Mayer 2005).

The number of rings in each disc was counted with great care being taken to account for false and missing rings. Though it is likely that some missing rings were not counted, it is also likely that some false rings were misperceived as true rings and counted. Due to the diligence and care taken while counting growth rings of the samples I am highly confident in the usefulness of these results. Since we cannot be certain that the number of rings counted accurately corresponds to tree age, for the purpose of this study, I define “tree age” as the number of rings counted in the cross section sample for that tree.

Data Analysis

Stands were blocked according to habitat type and bedrock composition for analysis. The density of *J. monosperma* in 94 plots and the age of 216 sample trees were

analyzed. The Wilcoxon Rank-Sum procedure was applied to analyze these blocks as populations since both the density of trees in plots and the age of trees in stands are not normally distributed. T-tests were used to compare the mean densities and ages of these blocks of plots and trees. According to the central limit theorem, the use of t-tests was appropriate in light of the large number of samples, despite the non-normality of the populations.

Results

Comparing *J. monosperma* densities

J. monosperma densities in plots was not normally distributed as there were more low density plots than high density plots. The Wilcoxon Rank-Sum test reveals that there is no difference in the distribution of tree density in plots between stands on limestone soil compared to those on basalt soil ($p = .8999$) (Figure 3.1). Stands on limestone bedrock had mean density of 54.6 tph, while those on basalt bedrock had a mean density of 48.3 tph. A t-test showed no significant difference in these mean values. See Table 3.1 for a summary of results.

When blocked by habitat type I found that woodland stands differed in the distribution of tree density in plots ($p = <.0001$) (Figure 3.2). Woodland plots ranged in density from a minimum density of 33.7 tph to a maximum of 256.8 tph with a mean density of 118.0 tph. Plots within savanna stands ranged from 0 tph to 37.9 tph with a mean of 7.6 tph (Figure 3.3). The mean density of woodland stands was significantly greater than that of savanna stands (p -value of $<.0001$).

Comparing *J. monosperma* Establishment

The distribution of *J. monosperma* ages was not normal, with there being more young trees than old trees. An additional factor resulting in non-normal distribution of tree ages was the inconsistent establishment of trees over time as climate varied. The Wilcoxon Rank-Sum test reveals a significant difference between the populations of *J. monosperma* establishment dates on limestone soil compared to those on basalt soil ($p = .0059$) (Figure 3.4). Trees on limestone bedrock had a mean establishment date of 1814 and those on basalt bedrock had a mean establishment date of 1841 and a t-test revealed no significant difference in these mean values.

I found that trees in woodland stands established significantly earlier than trees in savanna stands ($p = <.0001$) (Figure 3.5) when blocked by habitat type. Among the trees that were sampled, the oldest tree in woodland stands was established in 1310, while the most recently established was 1985, with a mean establishment date of 1730 (Figure 3.6). The oldest tree establishment date sampled among savanna stands was in 1800 and the youngest in 1980 with a mean establishment date of 1902 (Figure 3.7). The mean establishment date of trees in woodland and savanna habitats was significantly different (p -value of $<.0001$).

Fire Evidence

Very little evidence of historic fires in the form of fire scars is apparent in the juniper savanna. A small number of trees among those sampled were found with damage that may have been the result of fire, but no char was present so the cause of the damage was unclear. These trees were few enough in number to make it impractical to attempt to reconstruct a fire return interval. Mortality from recent wildfires was 96% in the Moon

Fire (MF), 46% in West Fire North (WFN), 66% in West Fire South (WFS), and 55% in the Antelope/State Fire (AF) with a mean mortality due to fire of 55%. Trees of all sizes, including those over 4 m in height were susceptible to mortality due to fire.

In the woodland stands I observed several individual trees and small patches of trees which had been burned and killed, apparently by lightning ignited fires. However, these fires are limited to a very small area, typically 1-5 trees. A small number of samples containing damage consistent with fire scars were also found in the woodland stands, but I could not confirm that the damage was the result of fire, and cross dating was not possible.

Discussion

The effects of bedrock type on *J. monosperma* populations

There was no difference in the mean establishment date of *J. monosperma* across bedrock types, however the Wilcoxon Rank-Sum test revealed a significant difference in the distribution of tree establishment dates across bedrock types. Areas underlied by limestone bedrock had a broader range of establishment dates, containing both the oldest and youngest trees. This broader distribution of establishment dates occurred despite the fact that the number of trees sampled on limestone soils (n=107) was much less than the number of trees sampled on basalt soils (n=160). These differences, though significant, are minor and I believe they are artifacts of the limited number of stands sampled in this project.

The non-normal distribution of stand densities across bedrock type is a result of my sampling technique. There was a larger number of low density plots on both basalt

and limestone bedrock types since more plots were sampled within the savanna stands in WUPA. This is clearly visible in Figure 3.1. Also visible is the clumping of stands into less dense savanna and more dense woodland types. Looking at Figure 3.1, one also sees that there tends to be more higher density savanna and woodland stands among the basalt soil types. Indeed, the four densest stands were found on areas of basalt bedrock. I attributed these anomalies to the fact that basalt stands were typically at slightly higher elevation compared to those of limestone stands of the same habitat type, and not to a difference in *J. monosperma* densities between bedrock types. In any event, a Wilcoxon Rank-Sum test should have revealed any differences in the density of these populations and none were found.

Overall, bedrock types had little to no effect on the tree density or establishment patterns of stands of *J. monosperma* in my study site.

Densities of woodlands and savannas

Since it is the density of trees which determined whether a particular stand was considered a savanna or woodland population it was expected that woodland stands would be significantly more dense than savanna stands, as seen in Figure 3.2. With the exception of one plot, the density of woodland plots was distinctively higher than that of savanna stands. There are no woodland plots with fewer than 70 tph and no savanna plots with more than 40 tph. The exception is a plot in the APS stand that happened to be placed in a seasonally wet area which has developed a hard clay surface where very little vegetation grows.

I originally defined juniper woodlands stands as those with greater than 30 trees per hectare (tph), and juniper savannas as stands with fewer than 30 tph. Based on my

results, 55 tph might be a more biologically sound definition of this threshold between savannas and woodlands. West (1999) states that savannas are communities in which the non-tree phase dominates the “matrix” or “major fraction of the landscape”, and woodlands have higher tree densities. From personal observations in Antelope Prairie I could argue that at 30 tph trees dominate the “matrix”. Moir and Carleton (1987) review the UNESCO (1973) definition of woodlands and that of Driscoll et al. (1984). These definitions are based on canopy cover of > 40% and 26-60% respectively. Unfortunately canopy cover is difficult to assess from the ground especially short junipers and piñons. I am unaware of any delineation of these community types based on tree density.

Future research in this area should focus on the relationship between tree density, herbaceous cover and fire dynamics. Specifically, how does tree density affect vegetation cover, especially in cases of juniper encroachment? Is there a size or density threshold where trees such as *J. monosperma* become dominant over grasses forbs and shrubs? At what point does increased density or decreased vegetation cover promote the switch from a frequent surface fire regime to an infrequent crown fire regime? And lastly, how do we define the boundaries between grasslands, savannas and woodlands based on what is learned about the ecology, botany and structure of these communities?

Establishment of juniper woodlands and savannas at Wupatki

J. monosperma establishment within savanna stands in Wupatki National Monument is relatively recent. All of the trees sampled within savanna stands have become established within the past 200 years with over 71% of the sampled trees becoming established after the initiation of heavy grazing impacts around 1880. Contrary to what Ffolliott and Gottfried (2002) found at a study site nearby, my research suggests

that junipers continued to become established in Antelope Prairie throughout the 20th century, albeit at a lower rate. The 1960's and 1970's saw the highest rate of *J. monosperma* establishment in the latter half of the 20th century, suggesting that conditions such as climate or reduced competition were favorable for establishment at this time. It is difficult to tell from my data however whether the establishment rate is now slowing, or whether there is only a temporary lull until climatic conditions are more favorable for establishment.

It is likely that these savanna stands were semi-arid grassland communities previous to grazing impacts. Considering that 29% of *J. monosperma* establishment in savanna stands seems to predate the heaviest grazing impacts, it is possible that initial juniper establishment in these grasslands is a regular occurrence, with mortality of these newly established (highly fire sensitive) trees occurring regularly as high frequency grassland fires consume above ground vegetation. This condition is consistent with the "piñon-juniper grass savanna community type proposed by Romme et al. (2003).

Previous studies (Jameson 1962, Dwyer and Pieper 1967) have reported that trees under 1.2 m in height are most susceptible to fire induced mortality, however I found that trees of all sizes, including those over 4 m in height were equally susceptible to fire. The limited amount of fire evidence found among savanna trees suggests that few of the *J. monosperma* alive today have experienced wildfires. It appears that intense grazing in the late 19th century removed fine fuels, excluded fire and thus allowed the juniper invasion to continue unrestricted, and intensify around the turn of the 20th century.

The juniper woodlands to the south of Wupatki in the Dead Man Flat area of the Coconino National Forest have been established for a long period of time. The oldest

woodland tree sampled became established in 1310, and the mean establishment date is in 1730. These stands are clearly “old growth” juniper woodlands. Figure 3.6, indicates that more sampled trees became established in the 1880’s than in any other decade in the woodland stands. It is possible that intense grazing impacted these woodlands and reduced competition from grasses and forbs spurring the establishment of many young *J. monosperma* at this time. Favorable climatic conditions during this period are also a possible cause in this surge in establishment. However, it is difficult to determine, based on this limited data, if these old growth juniper woodland communities have been affected significantly by grazing and other land-use impacts over the past 120 years.

The lack of fire evidence on the Coconino National Forest suggests a low frequency, high intensity, stand replacing fire regime. The evidence of spot fires I observed suggests that there is not sufficient light fuel in the juniper woodlands to carry frequent, low intensity fires. However, these spot fires may be an important disturbance type in juniper woodlands and other woodland types that is not often recognized.

Historically, there was a rather sharp ecotone between juniper woodland, primarily to the south and upslope on the Coconino National Forest and semi-arid grassland, which is primarily within Wupatki National Monument and areas further north and downslope. The boundary of this ecotone was largely defined by topographical features that would prevent the continuation of surface fires as suggested by West (1999) and Romme et al. (2003). At times juniper savanna would invade the grassland, only to be removed regularly by frequent, high-intensity grassland fires. The juniper woodlands themselves however, were not affected by these fires due to low fuel load.

Anthropogenic disturbances in the fire regime correspond strongly to the establishment of juniper savannas in Antelope Prairie. If land managers wish to preserve the preserve and restore the grassland habitat in this portion of Wupatki, management action will need to be taken to prevent further juniper establishment of junipers into Antelope Prairie. However, looking at Figure 3.7, it appears that the establishment of a juniper woodland is a slow process that will likely take several hundred years to complete. Considering an average of 55% *J. monosperma* mortality in the wildfire areas, the regular application of prescribed fire and prescribed natural fire should be an adequate juniper control method, with no need for mechanical thinning. While restoring semi-arid grasslands at sites such as these by removing junipers we must also be mindful that there are ancient woodlands on the landscape that should be preserved. In these woodlands prescribed fire and thinning activities would not be advisable management practices if the intent is ecological restoration.

Literature Cited

- Anderson, B. A. 1993. Wupatki National Monument: Exploring into prehistory. In: Noble, D. G., editor. Wupatki and Walnut Canyon: New Perspectives on History, Prehistory and Rock Art. Ancient City Press, Santa Fe, NM. Pp 13-19.
- Arid Lands Information Center (ALIC). 2001. Terrestrial Ecosystem Survey of the Coconino National Forest. <http://alic.arid.arizona.edu/tes/tes.html>. Date accessed: 10/24/05.
- Arnold, J. F. 1958. Effects of juniper invasion on forage production and erosion. In: Your range-its management. Special Rept. No 2, Agr. Ext. Ser., Univ. of Arz. 17-18.
- Brown, D. E. 1994. Plains and Great Basin grassland. In Biotic Communities of the American Southwest-United States and Northwest Mexico, ed D. E. Brown. Desert Plants. 4, 115-121
- Bogan, M.A., C.D. Allen, E.H. Muldavin, S.P. Platania, J.N. Stuart, G.H. Farley, P. Melhop, and J. Belnap. 1998. Southwest. In M.J. Mac, P.A. Opler, and P.D. Doran (eds.): Status and trends of the nation's biological resources. Reston, Va. : U.S. Dept. of the Interior, U.S. Geological Survey ; Washington, DC.
- Cinnamon, S. K. 1988. The Vegetation Community of Cedar Canyon, Wupatki National Monument as Influenced by Prehistoric and Historic Environmental Changes. Master's Thesis, Northern Arizona University, Flagstaff, Arizona.
- Cinnamon, Steve. 1990. Wupatki grazing terminated. Park Science: A Resource Management Bulletin. 10:1, 20.
- Coppedge, B. R., Engle, D. M., Fuhlendorf, S. D., Masters, R. E., and Gregory, M. S. 2001. Landscape cover type and pattern dynamics in fragmented southern Great Plains grasslands, USA. Landscape Ecology. 16, 677-690.
- Dick-Peddie, W.A. 1993. New Mexico vegetation, past, present and future. Albuquerque, NM: Univ. New Mexico Press.
- Driscoll, R. S., Merkel, D. L., Radloff, D. L., Snyder, D. E. and Hagihara, J. S. 1984. An ecological classification framework for the United States. USDA Forest Services Miscelaneous Publication 1439, vi, 56 p.

- Dwyer, D. D. and Pieper, R. D. 1967. Fire effects on blue grama-pinyon-juniper rangeland in New Mexico. *Journal of Range Management*. 20: 359-362.
- Ffolliott, P. F., Gottfried, G. J. 2002. Dynamics of a piñon-juniper stand in northern Arizona: a half-century history. U.S. Department of the Agriculture, Forest Service, Rocky Mountain Research Station, Research Paper: RMRS-RP-35.
- Foster, J. H. 1917. The Spread of timbered areas in central Texas. *Journal of Forestry* 15, 442-445.
- Fritts, H. C. 1976. *Tree Rings and Climate*. Academic Press, New York, 567.
- Grahame, John D. and Thomas D. Sisk, editors. 2002. "Canyons, cultures and environmental change: An introduction to the land-use history of the Colorado Plateau". <http://www.cpluhna.nau.edu/> Date accessed: 3/18/05.
- Grissino-Mayer, Henri D. 2005. Species used in Tree-Ring Research. Ultimate Tree-Ring Web Pages. <http://web.utk.edu/%7egrissino/>: Date accessed: 10/23/05
- Gottfried, G. J., Swetnam, T. W., Allen, C. D., Betancourt, J. L. and Chung-MacCoubrey, A. L. 1995. Pinyon-juniper woodlands. In: Finch, D. M., Tainter, J. A. (Eds.), *Ecology diversity and sustainability of the Middle Rio Grande Basin*. USDA Forest Service, General Technical Report: 95-132.
- Hooten, J. A., Ort, M. H. and Elson, M. D. 2001. The origin of Cinders in Wupatki National Monument. Technical Report 200 1-12. Desert Archaeology, Inc., Tucson.
- Jameson, D. A. 1962. Effects of burning on a galleta-black grama range invaded by juniper. *Ecological Monographs*. 32:187-207.
- Jameson, D. A. 1965. Arrangement and growth of pinyon and one-seed juniper trees. *Plateau* 37: 121-127.
- Johnsen, T. N., Jr. 1962. One-seed juniper invasion of Northern Arizona grasslands. *Ecological Monographs*. 32:3, 187-207.
- Kearney, Thomas H and Robert H. Peebles. 1960. *Arizona Flora*. University of California Press, Berkeley, Los Angeles, London.

- Landis, A. G. and Bailey, J. D. 2005. Reconstruction of age structure and spatial arrangement of piñon-juniper woodlands and savannas of Anderson Mesa, northern Arizona. *Forest Ecology and Management*. 205, : 221-236
- Leopold, Aldo. 1924. Grass, brush, timber, and fire in southern Arizona. *Journal of Forestry*. 22:6, 1-10.
- Lowe, C. H. 1964. *The Vertebrates of Arizona*. University of Arizona Press, Tucson.
- Merriam, C. H. 1898. Life zones and crop zones of the United States. U. S. D. A. Div. Biol. Surv. Bull. 10, 9-79.
- Moir, W. H., Carleton, J. O. 1987. Classification of pinyon-juniper (p-j) sites on national forests in the southwest. In: Everett, L., comp. *Proceedings, pinyon-juniper conference*; Gen. Tech Rep. INT-215. Ogden, UT: U.S. Department of Agriculture, Forest Service, Intermountain Research Station. 216-226.
- Neff, D. J. 1986. Pronghorn habitat description and evaluation: a problem analysis report. Federal Aid in Wildlife w-78-R, Work Plan 4, Arizona Game and Fish Department, Phoenix, Arizona.
- Romme, W. H., Floyd-Hanna, L., Hanna, D. D. 2003. Ancient pinon-juniper forests of Mesa Verde and the West: a cautionary note for the forest restoration program. *USDA Forest Service Proceedings RMRS-P-29*, 335-350.
- Short, M. S. 1988. *Walnut Canyon and Wupatki: A History*. M.S. Thesis. Northern Arizona University, Flagstaff, AZ. pp. 95
- Sunset Crater Volcano National Monument, National Park Service (SU CR). 2005. *Sunset Crater Volcano National Monument - Nature and Science*.
<http://www.nps.gov/sucr/pphtml/nature.html> [Date accessed: September 13, 2005].
- Stokes, M. A. and Smiley, T. L. 1968. *Introduction to tree-ring dating*. University of Chicago Press, Chicago.
- Tausch, R. J. and West, N. E. 1988. Differential establishment of pinyon and juniper following fire. *American Midland Naturalist*. 119, 174-184.

- Tausch, R. J. and West, N. E. 1994. Plant species composition patterns with differences in tree dominance on a southwestern Utah piñon-juniper site. *Desired Future Conditions for Piñon-Juniper Ecosystems*. USDA Forest Service. General Technical Report RM-258, 16-23.
- Trimble, M. 1982. CO Bar Bill Owen Depicts the Historic Babbitt Ranch. Northland Press, Flagstaff. pp. 95.
- United Nations Educational, Scientific and Cultural Organization (UNESCO). 1973. International classification and mapping of vegetation, Series 6, Ecology and conservation. Paris. 93 p.
- U. S. Department of Agriculture, Soil Conservation Service (USDA). 1971. Soil survey and range site and condition inventory Wupatki National Monument Arizona: a special report. Portland, Oregon.
- Van Auken, O. W. 2000. Shrub invasions of North American semiarid grasslands. *Annu. Rev. Ecol. Syst.* 31, 197-215.
- West, N. E. 1999. Juniper-pi non savannas and woodlands of western North America. In Roger C. Anderson, James S. Fralish and Jerry M. Baskin, eds: *Savannas Barrens, and Rock Outcrop Plant Communities of North America*. Cambridge University Press. 288-307.
- Wilcox, B. A. and Murphy, D. D. 1985. Conservation Strategy: The Effects of Fragmentation on Extinction. *American Naturalist*, 125:6. pp. 879-887.

Research Question	Stand Block	Mean	Minimum	Maximum	Test of Means (P value of t-test)	Test of non-normal pop. (P value of WRS test)	Results
Does juniper density differ between limestone and basalt bedrock types?	Limestone	54.6	0.0	176.8	0.6136	0.8968	no
	Basalt	48.3	0.0	256.8			
Does juniper density differ between savanna and woodland habitat types?	Woodland	118.0	33.7	256.8	<.0001	<.0001	yes
	Savanna	7.6	0.0	37.9			
Does juniper establishment differ between limestone and basalt bedrock types?	Limestone	1814	1985	1310	0.1131	0.0059	Mixed results. means do not differ, but population structure does.
	Basalt	1841	1980	1432			
Does juniper establishment differ between savanna and woodland habitat types?	Woodland	1730	1985	1310	0.0000	<.0001	yes
	Savanna	1902	1980	1800			

Table 3.1. Summary of research questions, data and results of analysis. Density is in units of trees per hectare (tph), establishment is in units of calendar years.

Figures

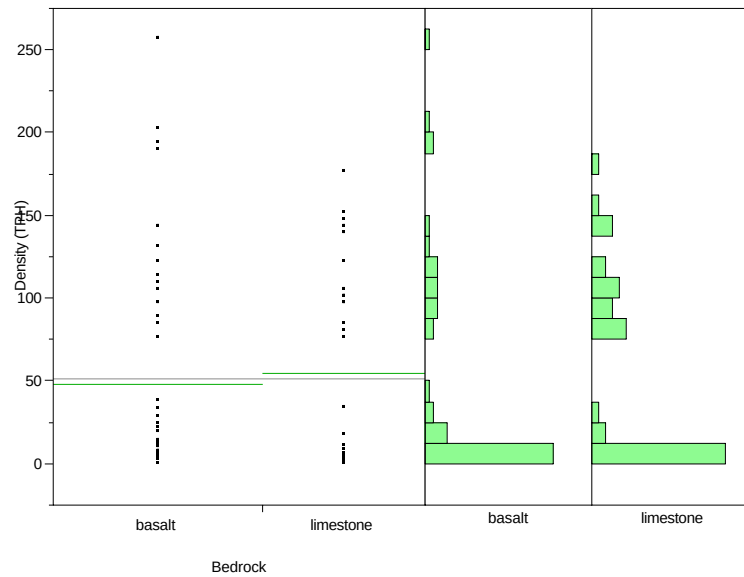


Figure 3.1. Distribution of plots by density when blocked by basalt and limestone bedrock types. Note the substantial separation between higher density woodland plots and lower density savanna plots. Histograms are not to scale.

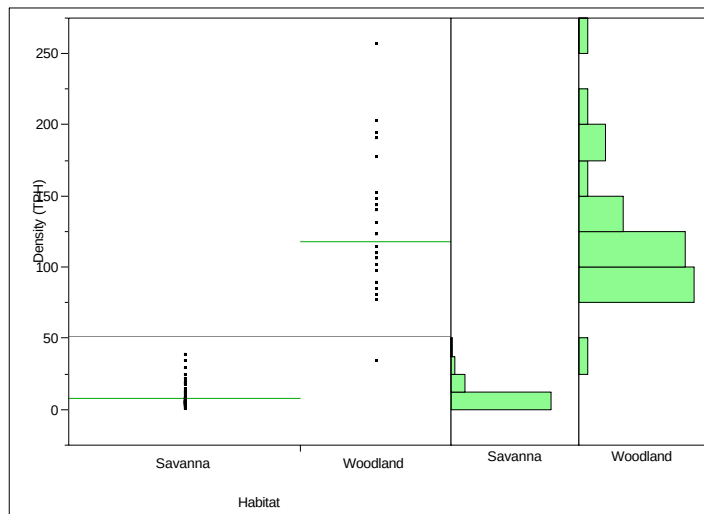


Figure 3.2. Distribution of plots by density when blocked by habitat type. Histograms are not to scale.

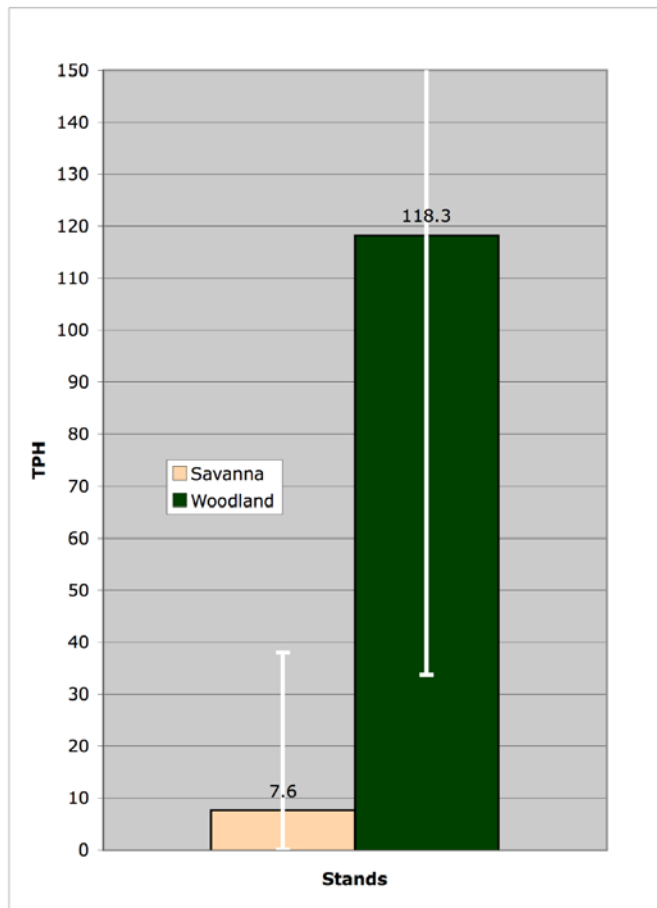


Figure 3.3. Mean density of stands in woodland and savanna environments in trees per hectare (tph). Error bars represent the maximum and minimum densities observed in each habitat type (maximum value for woodland is 256.8 tph).

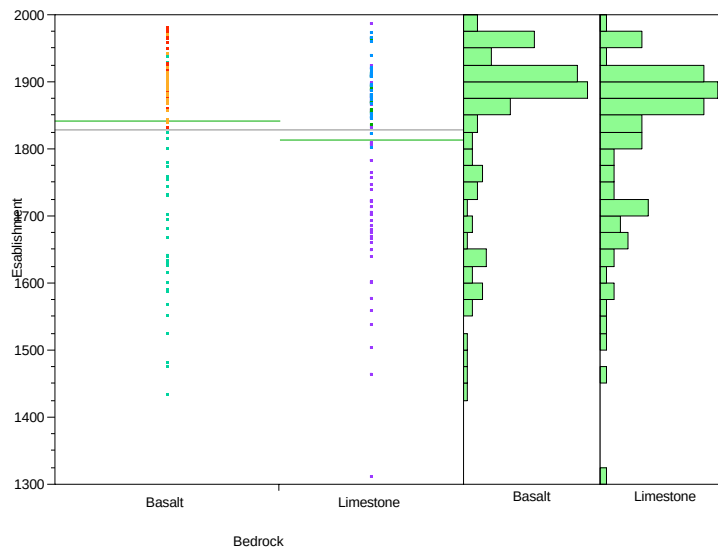


Figure 3.4. Distribution of juniper tree establishment dates when blocked by bedrock type. Histograms are not to scale.

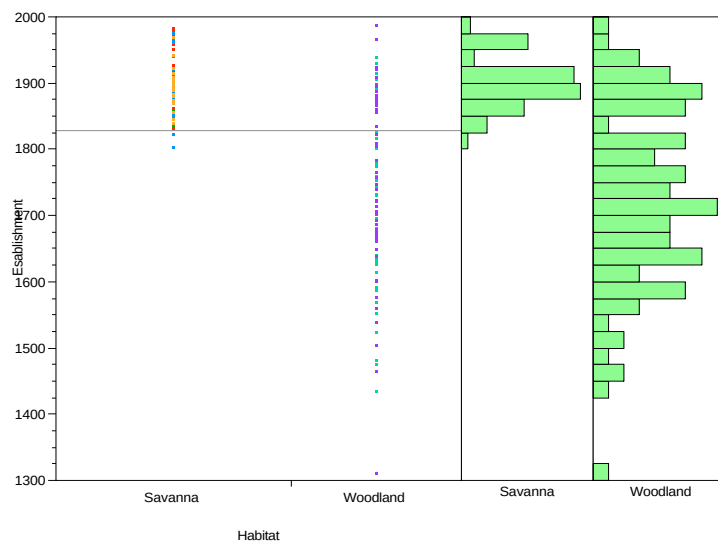


Figure 3.5. Distribution of juniper establishment dates when blocked by habitat type. Note that all of the savanna trees have become established within the past 200 years. Histograms are not to scale.

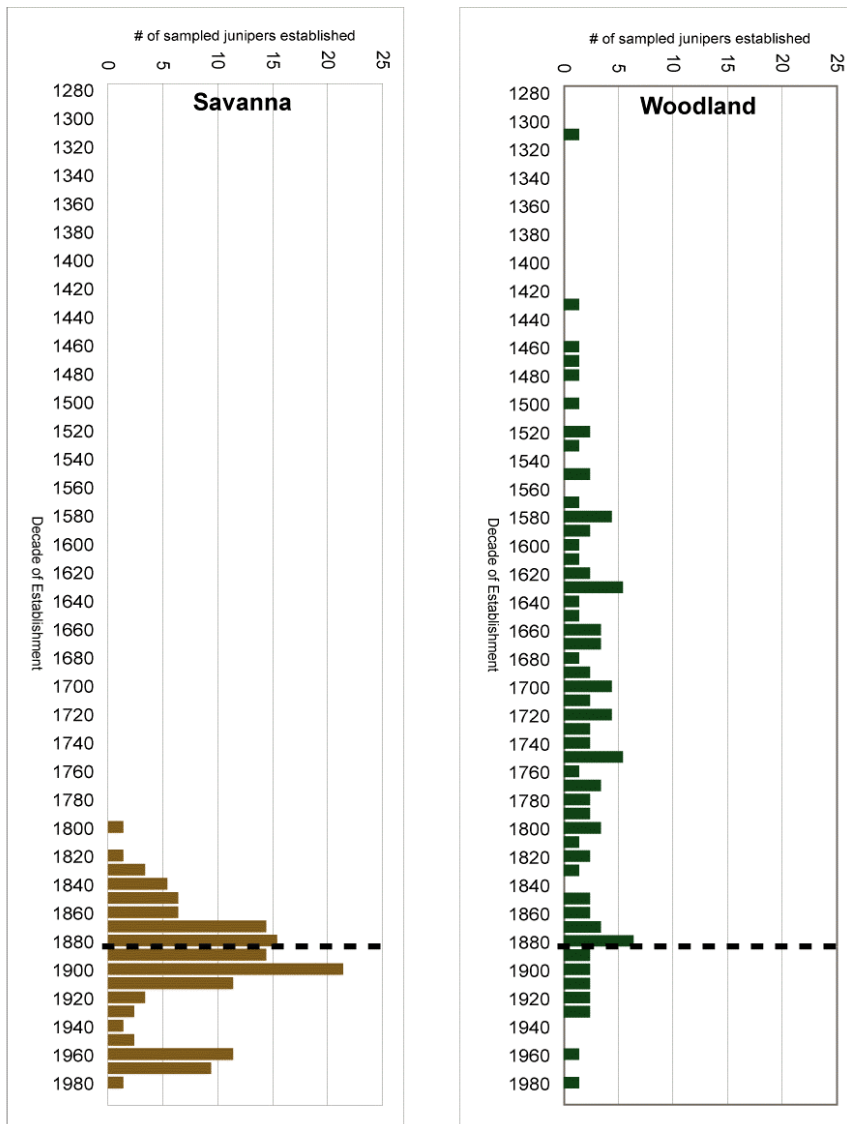


Figure 3.6 a & b. Establishment dates of junipers sampled from savanna stands (3.6 a, left, n=90) and woodland stands (3.6 b, right, n=126). The dotted lines indicate the approximate date of initial heavy grazing impacts in the vicinity.

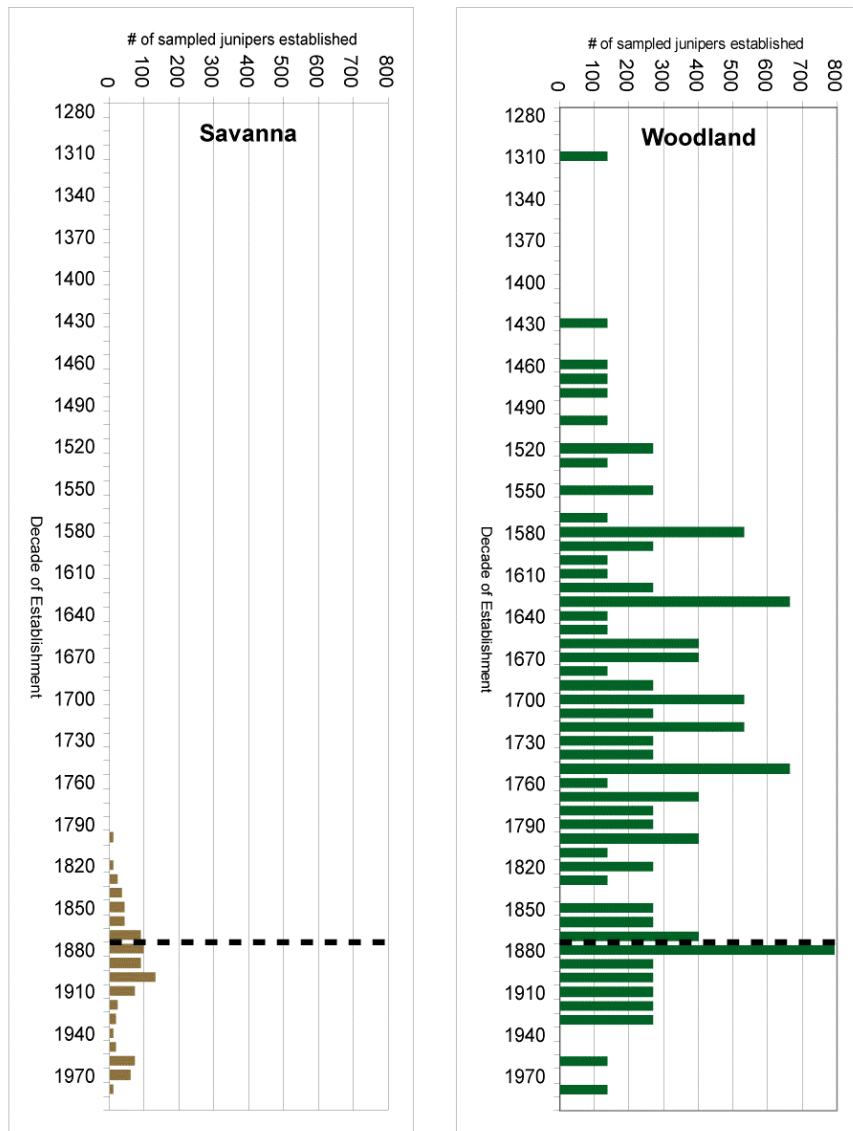


Figure 3.7 a & b. The average juniper establishment per decade based on frequency of establishment and average juniper density in savanna (3.7 a, left) and woodland (3.7 b, right) stands. The dotted lines indicate the approximate date of initial heavy grazing impacts in the vicinity.

Chapter 4: Future Trends and Management Considerations of *Juniperus monosperma* Savannas and Woodlands In and Near Wupatki National Monument, Northern Arizona

Introduction

Euro-American settlement has brought many changes to the arid southwest. Land uses such as grazing, water development and logging have had a substantial impact on the biological communities in the region. Riparian degradation, widespread soil erosion and forest compositional and structural changes receive much of the attention of conservationists. The encroachment of woody species into semi-arid grasslands is another critical conservation issue which until recently has received less attention.

Semi-arid grasslands on the Colorado Plateau are typically situated between piñon-juniper woodlands at higher elevations and semi-arid scrub communities at lower elevations (Bogan et al. 1998). Historically, fire maintained these semi-arid grasslands. *Juniperus* sp. L. were excluded at higher elevations (Johnsen 1962), while at lower elevations fire kept shrub species at bay (Van Auken 2000). However, this all began to change shortly after the arrival of white settlers and their cattle. The overstocking of both cattle and sheep in semi-arid grasslands appears to have eliminated the grass fuels required to carry low intensity wildfires (Leopold 1924, Johnsen 1962, West 1984). Aldo Leopold first suggested these changes in 1924. Leopold observed both trees, such as piñon pines and *Juniperus*, and shrubs, such as manzanita (*Arctostaphylos uva-ursi* (L.) Spreng. Kinnikinnick sp.), snakeweed (*Gutierrezia* spp. Lag.) and sagebrush (*Artemisia* sp. L.), were invading areas which were once grassland. He also noted the dramatic soil erosion associated with this change in cover type.

Later research (Burkhardt and Tisdale 1976, Bedell 1987, Van Auken 2000) suggests that this brush invasion was a continuing process. It appears that junipers and woody shrubs can out-compete grasses for soil moisture in the absence of fire. In addition to the alterations of the fire regime, grazing suppressed grasses, giving woody species a direct competitive advantage (West 1984). Furthermore, once the density of shrubs and trees reaches a certain level, the low fuel loads of these species should eliminate surface fires from the system, thus preventing reestablishment of grasslands by means of natural or prescribed fire. With fire unable to impact the system and return grass dominance, these ecosystems may cross an ecological threshold, becoming increasingly shrub dominated; eventually the grassland is replaced with scrubland or woodland (Fuhlendor et al. 1996, Bock and Bock 1997).

As a result of this shrub encroachment, the total area of grassland habitat in the southwestern United States has significantly declined during the last 150 years (Kearney and Peebles 1960, Dick-Peddie 1993, Brown 1994). The increase in shrub and piñon-juniper tree density across the Southwest has generally had a negative impact on other elements of these grassland ecosystems. Increased shading and competition for resources, most notably water, has lead to a dramatic reduction in grass and forbs diversity and abundance (Arnold 1958, Tausch and West 1994). This loss of grassland habitat has had a negative impact on many grassland dependant species such as pronghorn antelope (*Antilocapra americana* (Ord)) (Neff 1986, Bogan et al. 1998).

Evidence suggests that juniper encroachment is occurring at Wupatki National Monument, in northern Arizona (Cinnamon 1988) (Figure 4.1). Several grassland-dependent vertebrates inhabit the Antelope Prairie, including pronghorn antelope

Antilocapra americana), Gunnison's prairie dog (*Cynomys gunnisoni* (Baird)), Burrowing Owl (*Athene cunicularia* (Molina)), Ferruginous Hawk (*Buteo regalis* (Gray)), Golden Eagle (*Aquila chrysaetos* (Linnaeus)), and Little-striped Whiptail Lizard (*Cnemidophorus inornatus* (Baird)). If the entire grassland biome succeeds to juniper woodland, several of these species may eventually be at risk of extirpation from the Monument. In addition, certain herbaceous plant species may also be at risk of local extirpation from the lack of fire disturbance and increased shading by *Juniperus monosperma* (Engelm.) Sarg..

In previous chapters, I have determined how juniper encroachment has transpired in and Near Wupatki National Monument in the past. In this chapter, I will use population growth modeling to predict how this increase in juniper establishment might unfold in the future.

Methods

Field Work

The study area for this project includes both Wupatki National Monument and a portion of the Coconino National Forest to the south of the monument. For the purposes of my research project, stands of *J. monosperma* are defined as areas sharing the same bedrock (either base limestone or one of several basalt shelves) and having a fairly consistent elevation. Within Wupatki, I was limited to removing samples only from dead trees. Therefore, the only juniper stands I was able to study within the monument were savanna stands defined by the outline of several recent wildfires, which resulted in significant *J. monosperma* mortality (see Figure 2.1). For the portion of the study area on

the Coconino National Forest there are no such restrictions, therefore the woodland stands encompass an entire basalt shelf.

A total of 94 sampled plots were sampled over the course of this project. These plots were randomly distributed within each stand. The number of plots per stand varied according to the variability within each stand. In juniper woodland stands, plots consisted of a .238 ha circular sample area (diameter of 27.5 m) centered around a sample point. In stands considered to be juniper savanna or “grassland with scattered junipers”, plots consisted of a 3.80 ha circular sample area (diameter of 110 m). This variation in plot size is necessary to maintain a consistent sample size, and a consistent ratio of trees measured to samples taken per plot, across habitat types.

In each plot, one *J. monosperma* from each of four arbitrary size classes based on height (0-1.5 m, 1.5-3.0 m, 3.0-4.5 m and 4.5 and greater) was selected and cut to remove cross sections for analysis. These cross sections were aged using dendrochronological methods in the lab. In addition, I measured tree heights, crown diameters (drip line), and diameter of the largest stem for all 2,479 trees within the sample plots. By gathering this information I was able to correlate size class to tree age, allowing me to make inferences regarding the age distribution of the stand while removing a minimal number of trees.

Modeling *J. monosperma* establishment

The ages of all measured trees in each stand were calculated using age/size correlations determined by the 216 trees sampled. By using the allometric relationship developed in Chapter 3 (Table 2.4), I have been able to estimate the age of all trees in the sample plots for each stand. Based on these results, rates and patterns of juniper savanna

and woodland population growth were examined using the logistic population growth model (Gotelli 1998).

I made several assumptions in order to develop a model that would fit. First, I set the carrying capacities for the woodland stands to 11,100 trees per km^2 (t/km^2). I based this assumption on the fact that the population is currently estimated to be 10,820 (t/km^2) and appears to be stabling, as seen in Figure 4.2. This carrying capacity is just above the current mean densities of these stands. Second, I assumed these woodland populations could have been established in the year 1000 AD, and thus I modeled the growth of these stands for 100 decades. I chose this date because, according to the allometric relationship I developed in Chapter 3, the age of the oldest tree I measured in the woodland stands became established around 1060 AD. Also, this was during the Sunset Crater eruption period, and this disturbance could have substantially reduced or even eliminated the juniper population at this site.

I then applied this model framework to the data I had for the juniper savanna stands in Wupatki and attempted to mimic the population growth they had experienced over the past 150 years. This period roughly corresponds to the time of the elimination of fire impacts and initiation of grazing impacts at Wupatki until the present day. Juniper establishment peaked around the turn of the 20th century (as seen in Figure 4.3), likely due to climatic conditions, and was low for most of the 20th century. Therefore, I had to assume that the 150 year period was a long enough modeling period to balance out the highs and lows in the instantaneous rates of population growth.

I assigned carrying capacities (K) of the savanna population to 9000 t/km^2 . I chose this number because it is slightly less than the carrying capacity of the higher

elevation woodland stands. The Wupatki savanna stands, being at lower elevation, likely receive less rainfall and thus would be able to support fewer trees at capacity. I also reduced the intrinsic population growth rate for the savanna population to .009. I did this under the assumption that establishment would be slightly less likely for trees in this exposed, slightly more arid environment (Meagher 1943, Jameson 1965) and because it matched the data well. Lastly, I based the initial population size on the average number of trees the allometric relationship suggested were alive (per km²) in the savanna stands in 1850, thus $N_0=275$.

I also modeled fire impacts to project what the impacts of future land management practices might be. To do this, I added a survivorship variable to the model. In decades in which there was no mortality due to fire this variable was set to 1. In a decade that would have 45% mortality due to fire (or 55% survivorship) the variable was set to .55. Using this method I could test many possible fire return intervals and fire severities.

Results and Discussion

Modeling Juniper Encroachment

The results of modeling for the savanna stands can be seen in Figures 4.3 and 4.4. When the population growth model is plotted against the population growth projected from allometric relationship of age and size (Figure 4.3), it is clear that the instantaneous population growth rates vary dramatically over time. These *J. monosperma* populations have growth spurts during periods of favorable climatic conditions and periods of little to no increase in population when the climate is less favorable.

Modeling Management Effects

As seen in Figures 4.5 and 4.6, it is likely that the reintroduction of fire to the savanna areas of Antelope Prairie will push the community back towards a semi-arid grassland state. Figure 4.5 represents a scenario that might match a 'hands-off' prescribed natural fire management plan with a fire return interval of 30 years and a relatively high 45% mortality rate. This model might represent how juniper density in the savanna stands would change over time in the event that wildfires are allowed to burn during the historic summer burn season. Figure 4.6 represents a prescribed burning scenario with a fire return interval of 10 years for the first 40 years and a 20 year return interval for the following period. The mortality rate for this scenario is lower at 35% since land managers would likely choose to conduct prescribed burns during periods of decreased fire intensity.

For comparison's sake, I will call a juniper stand a 'grassland' when it is reduced to fewer than 5 tph (or 500 t/km²). I chose this number because pronghorn are a primary management concern in Antelope Prairie and it has been found that tree density in good pronghorn habitat is 5 per hectare or less (Alexander and Ockenfels 1994). It will take approximately twice as long for the juniper density to be reduced to grassland levels as it would under the prescribed fire scenario if the prescribed natural fire scenario is followed. Although these scenarios are hypothetical, it is clear that increased fire intensity and frequency will enhance the removal of excess junipers from Antelope Prairie.

It is also important to note that juniper encroachment is not as heterogeneous as one might be lead to believe by this modeling exercise. In Figure 4.1 you can see that

some areas are more heavily impacted by encroachment than others. As a result, fire may be the only management tool necessary to restore grassland conditions over much of Antelope Prairie. Mechanical thinning may be necessary in some historical grassland locations where the juniper population has increased to the point that the grasses and forbs are suppressed, thereby allowing in trees that are less susceptible to surface fires.

Juniper Encroachment as Succession

One might consider juniper encroachment as a step towards a climax state when looking at juniper encroachment in the framing of the traditional succession approach. Fire cessation, whether short term or long term, allows the community to begin moving out of the grassland condition as a sub-climax state, towards a juniper or piñon-juniper woodland as the climax community, as seen in Figure 4.7. It would then take a stand replacing fire to act as a disturbance and return the community to an early successional state. This view of a piñon-juniper woodland as a climax community requires us to characterize the semi-arid grassland as a sub-climax community maintained by fire.

However, it seems misguided to consider the dominant, pre-settlement community condition as simply a sub-climax community. Another construction allows us to view semi-arid grasslands and the “climax” community. In this case, fire maintains the stability of the grassland in its climax condition and prevents further change to the system (Figure 4.7). With this model in mind, one could argue that fire is not a disturbance, but instead is a regular and integral process within the community. Indeed, in this community, you could argue that the *absence* of fire is a disturbance.

It seems apparent that the piñon-juniper climax model is applicable to many woodlands in the southwest such as those described on Mesa Verde by Floyd et al. (2000), and these cases are excellent examples of the succession framework. However, the successional model does not apply well to communities which naturally experience frequent disturbances. In semi-arid grasslands the piñon-juniper climax requires human intervention to alter natural processes to redirect the successional trajectory towards that of a different community. The complexity of these community dynamics were explored by Jameson (1987). He suggested that a variety of natural and human caused factors affected the successional dynamics of these communities. Land managers must be mindful that both natural and anthropogenic forces are now integral components of the community dynamics of these arid ecosystems.

Juniper Encroachment as a Biological Invasion

In many ways, juniper encroachment can be compared to a biological invasion. The term 'biological invasion' however, usually refers to the introduction of an exotic species. *J. monosperma* is a common native in the southwest, and in the greater Wupatki landscape matrix. Pre-settlement trees are not only found in the woodlands to the south of Wupatki, but also interspersed within the grassland community on isolated rocky outcroppings and slopes where they were presumably sheltered from frequent fires (Van Auken 2000, West 1984). However, in order to continue following this line of thinking one may argue that these trees are locally exotic, alien to the grassland habitat itself.

J. monosperma are not particularly fast growing nor do they reproduce quickly. It takes several years for *J. monosperma* to reach sexual maturity. These attributes would seem to suggest that they'd be poor invaders (Meffe 1997). However, they are a long-

lived, with lifespans approaching 1,000 years (personal observation) and once they do reach maturity, they produce large amounts of seed (Chambers et al. 1999). Though they aren't excessively common or particularly persistent in the seed bank, their perseverance within the landscape matrix allows for quick invasion of grasslands when conditions permit. These are attributes that would normally be associated with a successful invasive species (Meffe 1997).

At Wuptaki and throughout the Southwest, junipers are expanding their populations at a time when human caused disturbances, namely fire suppression and reduced competition from grasses, a direct result of cattle grazing (West 1984) allow for favorable reproductive conditions. Junipers are strong competitors for nutrients and moisture and sequester these resources within their tissue and the soil surrounding the plant (Teidman 1987). Once established, junipers can alter the patterns of nutrient distribution on the soil, leaving few resources available for herbaceous species persistence in the inter-space between the trees (Wilcox and Davenport 1995).

By these means they can out-compete grasses and forbs for resources, which is what invasive species can do when they enter a suitable environment. However, the difference is that these junipers are simply native species responding to changes in their environment. Some of these changes, such as climate change, are naturally occurring processes that have been altering the distribution of ecosystems for millions of years. Others, such as intense grazing are very recent and likely unprecedented changes to the ecosystem. Juniper encroachment happens in the greater context of a millennial scale 'shifting mosaic' of various habitats. But it is also quite poignantly associated with human caused disturbances localized to our present time.

Literature Cited

- Alexander, A., and R. A. Ockenfels. 1994. Juniper densities relative to pronghorn use in central Arizona. Proceedings of the Biennial Pronghorn Antelope Workshop 16: 76-85.
- Arnold, J. F. 1958. Effects of juniper invasion on forage production and erosion. Your range-its management. Special Rept. No 2, Agr. Ext. Ser., Univ. of Arz.: 17-18
- Bedell, T. E. 1987. Range management concerns on juniper woodlands. In: Everett, L., comp. Proceedings, pinyon-juniper conference; Gen. Tech Rep. INT-215. Ogden, UT: U.S. Department of Agriculture, Forest Service, Intermountain Research Station. 436-439.
- Brown, D. E. 1994. Plains and Great Basin grassland. In Biotic Communities: Southwestern United States and Northwestern Mexico, Desert Plants 4 ed. D. E. Brown. University of Utah Press, Salt Lake City, Utah. pp. 115-121
- Burkhardt, J. W., Tisdale, E. W. 1976. Causes of juniper invasion in southwestern Idaho. Ecology. 57: 472-484.
- Bock, C. E. and Bock, J. H. 1997. Shrub densities in relation to fire, livestock grazing, and precipitation in an Arizona desert grassland. The Southwestern Naturalist 42(2): 188-193.
- Bogan, M.A., C.D. Allen, E.H. Muldavin, S.P. Platania, J.N. Stuart, G.H. Farley, P. Melhop, and J. Belnap. 1998. Southwest. In M.J. Mac, P.A. Opler, and P.D. Doran (eds.). National Status and Trends Report, U.S. Geological Survey, Washington, D.C.
- Chambers, J. C., Vander Wall, S. B., Schupp, E. W. 1999. Seed and seedling ecology of pinyon and juniper species in pygmy woodlands of western North America. The Botanical Review 65(1): 1-37.
- Cinnamon, Steve. 1988. The Vegetation Community of Cedar Canyon, Wupatki National Monument, as Influenced by Prehistoric and Historic Environmental Change. Master's Thesis, Northern Arizona University.
- Dick-Peddie, W.A. 1993. New Mexico vegetation, past, present and future. Albuquerque, NM: Univ. New Mexico Press.

- Floyd, M. L., Romme, W. H., Hanna, D. D. 2000. Fire History and Vegetation Patterns in Mesa Verde National Park, Colorado, USA. *Ecological Applications*. 10, 6: 1666-1680
- Fuhlendor, S. D., Smeins, F. E. and Grant, W. E. 1996. Simulation of a fire-sensitive ecological threshold: a case study of Ashe juniper on Edwards Plateau of Texas, USA. *Ecological Modelling* 90: 245-255.
- Gotelli, N. J. 1998. *A Primer of Ecology*, Second Edition. Sinauer Associates, Inc. Sunderland, MA, 236.
- Jameson, D. A. 1965. Arrangement and growth of pinyon and one-seed juniper trees. *Plateau* 37: 121-127.
- Jameson, D. A. 1987. Climax or alternative steady states in woodland ecology. In: Everett, L., comp. *Proceedings, pinyon-juniper conference; Gen. Tech Rep. INT-215*. Ogden, UT: U.S. Department of Agriculture, Forest Service, Intermountain Research Station. 9-13.
- Johnsen, T. N., Jr. 1962. One-seed juniper invasion of Northern Arizona grasslands. *Ecological Monographs* 32; 3, 187-207.
- Kearney, T. H and Peebles, R. H. 1960. *Arizona Flora*. University of California Press, Berkeley, Los Angeles, London.
- Leopold, A. 1924. Grass, brush, timber and fire in southern Arizona. *Journal of Forestry* 6, 1-10.
- Meagher, G. S. 1943. Reaction of pinyon and juniper seedlings to artificial shade and supplemental watering. *Journal of forestry*. 41: 480-482.
- Meffe G. K., Carroll C. R., and Contributors. 1997. *Principals of Conservation Biology*, Second Edition. Sinauder Associates, Inc. Publishers: Sunderland, MA. 729 pp.
- Neff, D. J. 1986. Pronghorn habitat description and evaluation: a problem analysis report. Federal Aid in Wildlife w-78-R, Work Plan 4, Arizona Game and Fish Department, Phoenix, Arizona.
- Tausch, R. J. and West, N. E. 1994. Present species composition patterns with differences in tree dominance on a southwestern Utah pinyon-juniper site. *Desired Future Conditions for Pinyon-Juniper Ecosystems*. USDA Forest Service, General Technical Report RM-258: 16-23

- Teidman, A. R. 1987. Nutrient accumulations in pinyon-juniper ecosystems--managing for future site productivity. 1987. In: Everett, L., comp. Proceedings, pinyon-juniper conference; Gen. Tech Rep. INT-215. Ogden, UT: U.S. Department of Agriculture, Forest Service, Intermountain Research Station. pp. 352-359.
- Van Auken, O. W. 2000. Shrub invasions of North American semiarid grasslands. *Annu. Rev. Ecol. Syst.*: 31. 197-215.
- West, N. E. 1984. Successional patterns and productivity potential of pinyon-juniper ecosystems. In *Developing Strategies for rangeland management*. National Research Council/National Academy of Science. Boulder, CO: Westview Press: pp. 1301-1332.
- Wilcox, B. P. and Davenport, D. W. 1995. Juniper encroachment: potential impacts to soil erosion and morphology. Interior Columbia Basin Ecosystem Management Project.

Figures

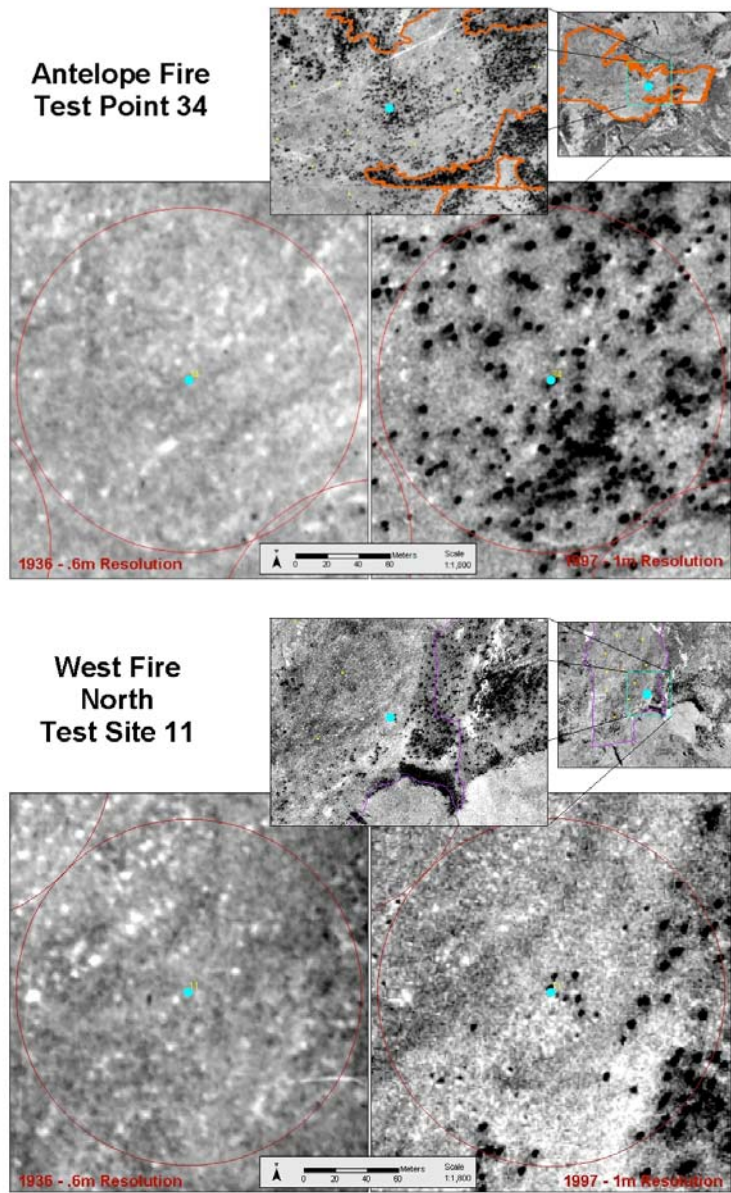


Figure 4.1 (a and b): Two research plots in savanna stands as seen from aerial photographs in 1936 (left) and again in 1997 (right). Encroaching junipers appear in these photos as black dots. Juniper encroachment is more intense in some sites than in others.

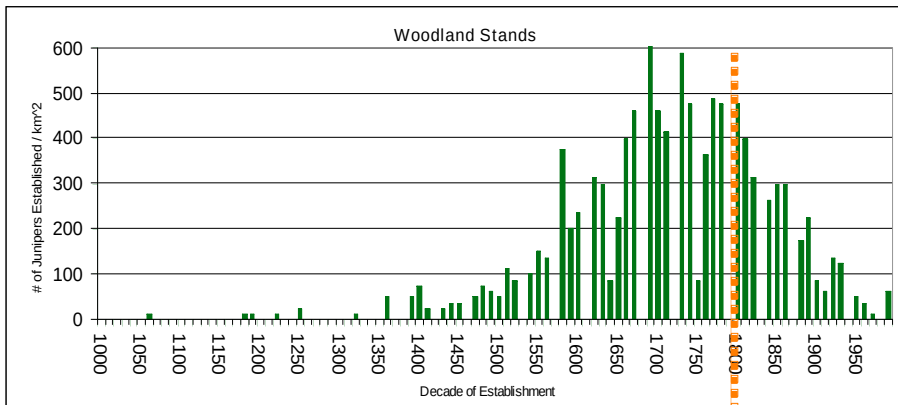


Figure 4.2 Establishment of woodland trees as projected by allometric relationships (grey bars) in t/km^2 per decade. The dotted line indicates the approximate date of the initiation of grazing impacts.

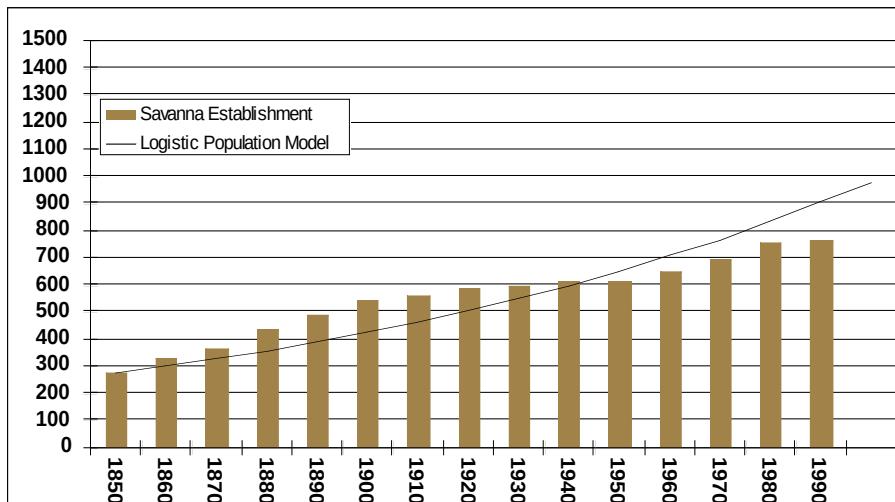


Figure 4.3. Establishment of savanna trees as projected by allometric relationships (grey bars) in t/km^2 per decade and a population growth model for juniper woodland stands since 1850 AD to 2000 AD (black line) in units of t/km^2 and calendar year. The population model is based on an intrinsic growth rate of .010, a population carrying capacity of 9,000 t/km^2 and with an initial population of $n=275$.

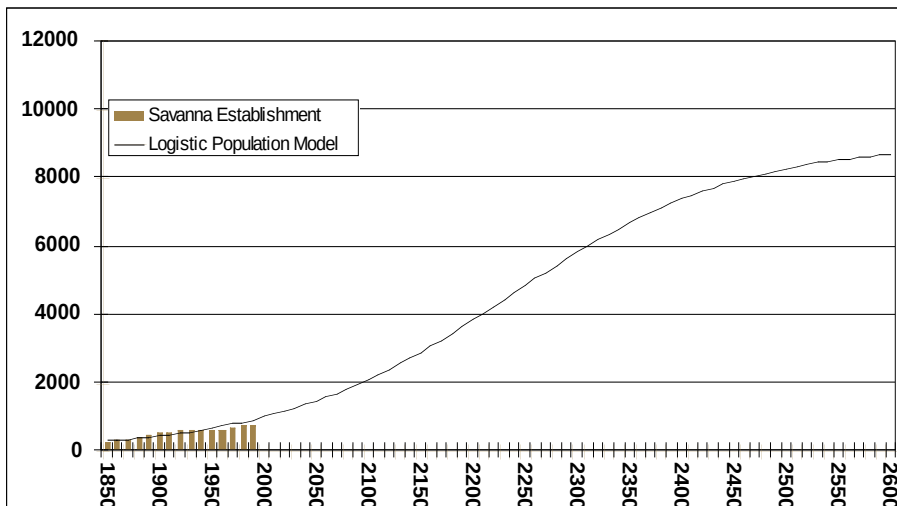


Figure 4.4: Establishment of savanna trees as projected by allometric relationships (grey bars) in t/km^2 per decade and a population growth model for juniper woodland beginning in 1850 AD and projected to 2600 AD (black line) in units of t/km^2 and calendar year. The population model is based on an intrinsic growth rate of .010, a population carrying capacity of 9,000 t/km^2 and with an initial population of $n=275$.

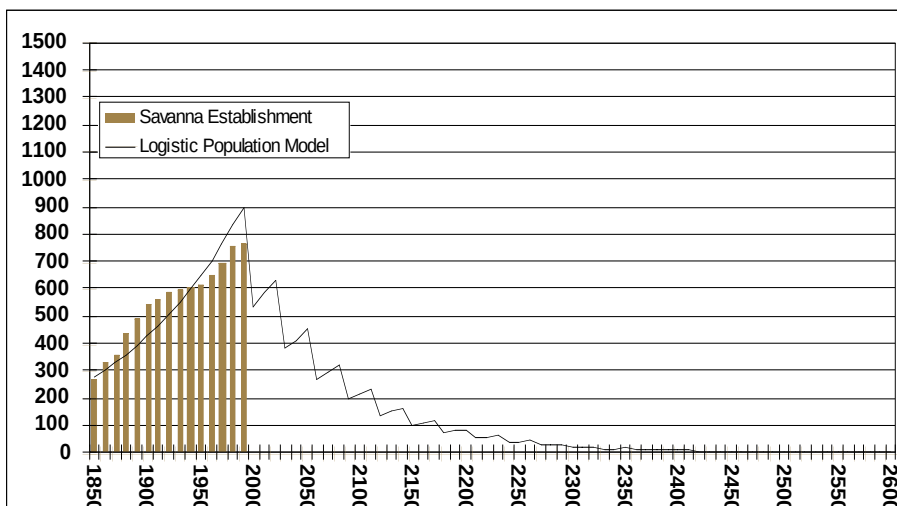


Figure 4.5: Population growth model for juniper savanna stands beginning in 1850 AD and projected to 2600 AD (black line) with compensation for 45% mortality due to fire with a fire return interval of 30 years. The logistic models for Powerline Mesa and Antelope Prairie South stands are included for comparison.

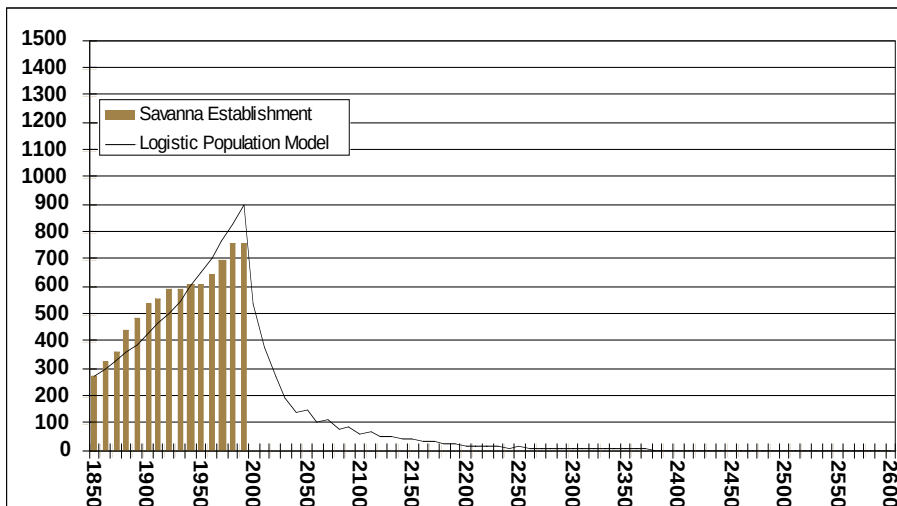
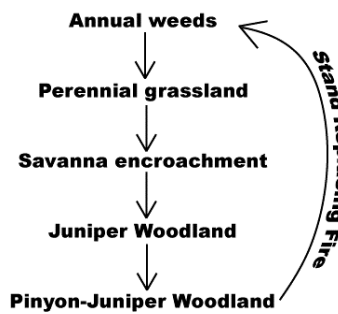


Figure 4.6: Population growth model for juniper savanna stands beginning in 1850 AD and projected to 2600 AD (black line) with compensation for 35% mortality due to a fire return interval of 10 years for the first 40 years and a 20 year fire return interval following that. The dotted line represents the present time. Note the slow but steady increase in population size.

Deleted: fire with

Pinyon-Juniper Woodland as Climax



Semi-Arid Grassland as Climax

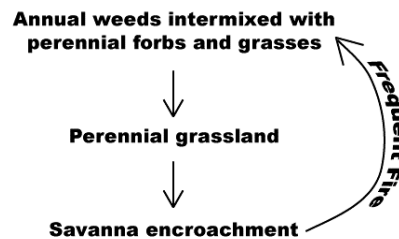


Figure 4.7. Two models of succession in juniper encroached systems.