EFFECTS OF SLASH ARRANGEMENTS AND TREATMENTS ON THE PINYON-JUNIPER WOODLAND UNDERSTORY COMMUNITY

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ABSTRACT

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MARIA IRWIN

Pinyon-Juniper woodlands represent a dominant ecosystem in the American Southwest and have been increasing in density and range. Land managers are concerned about the resulting effects on wildlife habitat, forage production for livestock, and wildfire risk. In many places, the only treatment has been total tree removal. This study presents an alternative to wholesale tree removal, by using historic reference conditions to determine tree densities and using the resulting slash to try and increase understory diversity and abundance. We thinned twenty-three hectares of *Juniperus osteosperma* (Torr.) Little and *Juniperus monosperma* (Engelm.) Sarg. to simulate 1860 (pre-livestock grazing) age structure and density, over three sites. Each site was comprised of either limestone, sandstone or basalt parent soil materials. For each site there was a control plot and three slash treatments. Slash was either piled, broadcasted, or clustered. The control plots were not thinned. Each of these slash arrangements received one of four treatments: 1) prescribed fire, 2) seeding, 3) prescribed fire and seeding, 4) no treatment. Understory plant species richness and abundance was measured before thinning in June of 2005 and then again in June of 2006, after the slash arrangements and treatments were implemented. In 2005, we identified 115 plant species in the understory over all three sites. January to June of 2006 was the driest period in the last 30 years and species richness decreased by an average of 40% from the previous year in control plots. We

found variable understory responses to the slash arrangements, burning and seeding. Plant species abundance was generally low and not influenced by slash arrangement, burning, or seeding at any of the three sites. Plant species richness was significantly different due to slash arrangement at the basalt site, where broadcasting the slash produced the greatest richness. Plant richness was not affected by slash arrangement at the limestone site or at the sandstone site. Burning and or seeding did not affect species richness at any of the sites. This study demonstrates that extensive ecosystem manipulation (thinning, slash arrangements, burning, and seeding) in the pinyon-juniper woodlands of northern Arizona does not affect understory richness or abundance the first year after treatment.

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PREFACE

This thesis is divided into 4 chapters. The first chapter is a literature review of the scientific work that is pertinent to my thesis. The second chapter was written to be submitted to the journal Forest Ecology and Management and describes my main research work. The third chapter describes a smaller clearcut case study, and the forth chapter contains management recommendations. Plant nomenclature followed the USDA Plants Database (http://plants.usda.gov/).

Chapter 1

Literature Review

Ecology of Pinyon-Juniper Woodlands

Pinyon *(Pinus* subsection Cembroides*)* and juniper *(Juniperus)* savannas, woodlands and forests currently occupy close to 30 million hectares in the western United States and are some of the largest ecosystems in the American Southwest (West 1999). Pinyon-juniper woodlands are usually found from elevations of 1,370 to 2,290 m and receive 25-50 cm of precipitation a year (West and Young 2000). Both pinyon and juniper trees are relatively small compared to other trees, averaging less than 12 m in height and can be very long lived. Pinyon trees may live up to 500 years and juniper trees may live to be over 1,000 years old (Sweatnam and Brown 1992, Graumlich 1993). Pinyon and juniper tree canopy is usually discontinuous, generally comprising less than 50% cover (Gottfried *et al.* 1995). Pinyon-juniper woodlands are the most xeric forest type in the United States and often form the lower tree line between forests and desert grasslands.

Pinyon-juniper woodlands across the West are quite variable, depending on overstory and understory structure and composition, location, management history, and site potential. Pinyon-juniper woodlands are usually composed of one species of pinyon pine and one to several species of juniper trees (Gottfried *et al.* 1995). There are two species of pinyon pine (*P. edulis and P. monophylla*) and four dominant species of juniper (*J. monosperma, J. osteosperma, J. deppeanna, and J. scopulourum*) in the southwestern pinyon-juniper woodlands (Gottfried 2004). The particular combination of tree species depends on the regional climate patterns (Neilson 1987). Pinyon-juniper woodlands are found in three western climate regimes: northern Great Basin (which includes Washington, Oregon, Idaho, Wyoming and Montana), Great Basin (which includes California, Nevada, and Utah), and the Southwest (which includes New Mexico, Arizona and Colorado). Each area has a unique assemblage of pinyon and juniper species.

In northern Arizona, pinyon-juniper woodlands are dominated by Utah juniper (*Juniperus osteosperma* (Torr.) Little), and or one-seed juniper (*Juniperus monosperma* (Engelm.) Sarg.), with a smaller pinyon pine (*Pinus edulis* Engelm.) component. At the lowest end of the elevational gradient, pinyon-juniper woodlands transition into semi-arid grasslands. At the highest end of their elevational range, pinyon-juniper woodlands transition into ponderosa pine forests.

Pinyon trees are generally monoecious, but may be dioecious in stands stressed by drought or insect attack (Cobb *et. al* 2001). Pinyon pines produce relatively large wingless seeds that are very valuable for wildlife and are also collected for human consumption. Seed crops are produced every four to seven years. Juniper "berries" contain one to four seeds, depending on the species and are important to wildlife and are sometimes gathered for human consumption. *J. osteosperma* are monoecious and *J. monosperma* are dioecious. Their heavy mature seeds fall to the ground, not far from the tree. Birds, especially the corvids, and small mammals are important for the widespread dispersal of both pinyon and juniper seeds (Balda 1987, Johnsen 1962). Both pinyon and juniper are shade-intolerant, but germination is greater under mature trees or logging debris. Germination requirements are not well understood, and seem to be episodic (Gottfried 2004). Growth of both pinyon and juniper trees is very slow, although pinyon grows at twice the rate of juniper under the same environmental conditions (Conner *et al*. 1990). Most natural stands have an uneven-aged structure (Gottfried 2004).

The understory composition of pinyon-juniper woodlands varies tremendously depending on site specific conditions (West *et al.* 1975). The United States Forest Service recognizes 32 plant community types dominated by pinyon pine and 23 dominated by juniper species (Bogen *et al*. 1998). West *et al*. (1998) classifies pinyon-juniper woodlands into 45 series, 183 associations and 326 sub-associations. Moir and Calreton (1987) distinguish 70 plant associations within the pinyon-juniper woodland type. Overall, the understory vegetation is similar to adjacent grasslands and shrub steppe communities. In the northern and western range of the Great Basin, cool-season bunchgrasses and sagebrushes prevail, fed by winter moisture. In the Colorado Plateau and upper Rio Grande basin, there are fewer shrubs and more warm-season grasses, possibly due to the monsoonal weather patterns (West and Young 2000).

In general, understory plant cover is low compared to other forested ecosystems and varies by location and past management history. At Bandelier National Monument, understory cover is very low and tree interspaces are almost barren, leading to trees on mounded topography, with rills and gullies in the interspaces (Davenport *et al*. 1998). In Mesa Verde National Park, there is very little evidence of erosion and relatively high shrub, grass and forb cover and diversity (Floyd 2003). Since we lack sufficient historical documentation of pinyon-juniper understory communities, it is difficult to interpret the status and health of current range conditions.

Pinyon-juniper Woodland Disturbance and Expansion

Many studies have documented the expansion and contraction of pinyon-juniper woodlands over thousands of years due to long-term changes in climate (Van Devender *et al*. 1984, Mehringer and Wigand 1990, Gottfried *et al.,* 1995, Woolfenden 2003). The previous 150 years has been a period of rapid expansion and densification in some pinyon-juniper areas (Cottam and Stewart 1940, Johnsen 1962, Burkhardt and Tisdale 1969, Blackburn and Tueller 1970, Tausch *et al.* 1981, Landis and Bailey 2005). Until recently, most researches thought that the current expansion and densification of pinyon-juniper woodlands was due to over grazing and the subsequent elimination of frequent fires which had been thought to maintain an open savanna-like condition (Eisenhart 2004). This conventional model has been used to guide pinyon and juniper removal throughout the West. The assumptions behind this model are that: 1) the historic fire regime was dominated by frequent, low intensity fires; 2) Over grazing by livestock in the late 1800's and early 1900's eliminated the fine fuels that used to carry these frequent, low intensity fires; 3) Fire exclusion and reduced competition from grasses facilitated tree invasion; 4) Fire exclusion and tree invasion has created to many mature stands and reduced early-seral stages; 5). High tree density has caused insect and disease outbreaks and high parasite loads; 6) High tree density has caused a shift to high-intensity, stand-replacing fire regime with potential replacement of native vegetation by invasive and undesirable species (Eisenhart 2004).

The role of fire in pinyon-juniper woodlands has been the subject of several recent research papers. Baker and Shinneman (2004) conducted a literature review and synthesis of all the research relating to fire regimes in pinyon-juniper and found no reliable data to support the notion of a frequent, low-intensity fire regime in pinyon-juniper woodlands. In fact, they found many woodlands were naturally subject to long rotation, high-severity fires. Baker and Shinneman (2004) report that the role of fire as a general mechanism maintaining woodland character remains poorly supported. Romme *et al.* (2003) suggests a model of fire regimes for contrasting types of pinyon-juniper communities, ranging from savanna, to shrub-woodland, to forest. They hypothesize that: 1) savanna communities have deep, fine textured soils with frequent, low severity fire regimes; 2) Shrub-woodland communities have deep, fine textured soils with moderate fire frequency and high severity; 3) Forests have shallow, rocky, or course-textured soils with very infrequent fires and very high severity. Any classification of pinyon-juniper woodlands generalizes the complexity encountered in the regional woodland mosaic (Eisenhart 2004).

Drought, insects, and disease may be major disturbance agents in pinyon-juniper woodlands dynamics. Prolonged drought can decrease woodland extent directly through tree mortality (Betancort *et al.* 1993, Swetnam and Betancourt 1998), or increase the woodland extent by mortality of the species that compete with the trees (Allen and Breshears 1998). Drought may also cause mortality by causing stress, which makes trees more susceptible to insects, disease, and parasites (Rogers 1995). Breshears *et al.* (2005) documented a rapid, regional scale mortality of pinyon pine in 2002-2003 across the Southwest. In some places mortality was as high as 90%. The pinyon trees died from bark beetle attack, which is directly tied to water stress.

The last major drought in the Southwest was in the 1950's. All though some regional die-off was recorded, the recent drought was greater in magnitude and extent than the mortality response to the 1950's drought. Warmer than normal temperatures combined with the lack of precipitation increased the energy load and water stress demands on the trees and may account for the greater mortality of the 2002 drought (Breshears *et al.* 2005). Droughts have influenced the range and extent of pinyon-juniper woodlands in the past and no doubt will continue to be an important disturbance in the future. Since global climate change is predicted to raise temperatures and change precipitation patterns, the potential for such die-off events may be even greater in the future (Breshears *et al.* 2005).

Management of Pinyon-Juniper Woodlands

Native Americans have lived in pinyon-juniper woodlands for over a thousand years. They used pinyon-juniper woodlands for hunting, farming, and tree harvesting (Samuels and Betancourt 1982). From the 1940's to the 1970's, the typical land management objective for pinyon-juniper woodlands was tree elimination to increase forage production for livestock (Evans 1988). The Pinyon-Juniper Treatment Inventory Database of BLM Land on the Colorado Plateau (http://www.mpcer.nau.edu/pj/pjwood/) reports that over 700,000 acres of pinyon-juniper woodlands have been "treated" on the Colorado Plateau alone. This area encompasses 786 kinds of treatments, ranging from chaining to single tree selection.

After the oil crisis of the mid-1970's demand for firewood and the price of gas increased, thus changing and broadening the management objectives in pinyon-juniper woodlands. Silviculturists began creating prescriptions in pinyon-juniper woodlands to maintain their productivity for wood products, including fuel wood, posts for fences and pinyon nut harvesting (Gottfried 2004). Basset (1987) found single tree selection protected the site from wind and water erosion, maintained vertical diversity which is important for wildlife, and was aesthetically pleasing. Two and three-step shelterwood and group selection are used in the Southwest to maintain fuel wood productivity (Gottfried 2004). Uneven-aged forest structure control can be accomplished through a BDQ prescription, which stands for basal area, maximum diameter, and q-ratio (Nyland, 1996). The technique is based on the reverse-J shaped diameter frequency distributions that are naturally found in forests throughout the world. The q-factor produces an inverse J-shaped distribution because it is the ratio of trees in a diameter class to the number of trees in the next largest diameter class. Thus, as the diameter classes get smaller, the number of trees increases (Bailey and Covington 2002). Clearcuts, although simple to administer and effective at increasing browse for wildlife, are discouraged because of difficulty regenerating the site and concerns about erosion (Gottfried 2004).

Currently, rural pinyon-juniper woodlands are managed for multiple uses, including grazing livestock, hunting wildlife, and collecting pinyon nuts and firewood. Pinyon-juniper woodlands are increasingly valued for their ecological, recreational and aesthetic values (Floyd 2003). The current expansion and densification of pinyon-juniper woodlands is considered an undesirable trend for some land managers. These managers may thin or remove pinyon-juniper woodlands for a variety of reasons including: wildlife habitat improvements, watershed issues, increased forage for livestock, and fuels mitigation. Most managers remove pinyon and juniper trees by chaining, hydro-axing, or mulching to a predefined lower density, or remove all the trees entirely (Campbell 1999).

The inverse relationship between overstory tree and understory plant cover in pinyon-juniper woodlands has been well documented (Parker 1945, Pieper 1990, Erramouspe 1994, Tausch and West 1995, White *et al.* 1997). Even though the tree crowns rarely touch, the junipers root systems extend two and three times as far as their crown diameters (West and Young 2000), leading to intense competition for water. Removing pinyon and juniper trees has been shown to increase understory abundance in Arizona (Clary and Jameson 1981), New Mexico (Brockway *et al.* 2002), Utah (Barney and Frischknecht 1974), Nevada (Tausch and Tueller 1977) and Oregon (Bates *et al*. 2000). Increasing understory diversity and abundance has become a goal for many land managers concerned with forage for wildlife, livestock, erosion, and overall ecosystem health. Techniques for increasing understory diversity and abundance have included thinning, slash additions to bare soil, prescribed burning, and seeding. These techniques will be discussed below.

Slash Additions to Bare Soil

Since the market for juniper and pinyon wood is limited, most trees cut during thinning projects are left on site. Juniper slash may take centuries to decompose (Jack Metzger, personal communication). Land managers must decide what to do with slash created by thinning, since most game species and livestock will not use areas with heavy slash accumulation. When the slash is left on the ground, it can create favorable microsites for understory establishment by positively affecting soil erosion, water infiltration, soil respiration and accumulation of soil nutrients (Tongway and Ludwig 1996). Stoddard (2005) found that slash amendments to the soil significantly increased residual woody and litter debris, reduced soil movement, increased arbuscular mycorrhizal fungi and microbial carbon levels, and increased graminoid abundance after two years in degraded pinyon-juniper woodlands in northern Arizona. Scattered slash has been shown to increase understory abundance in other studies as well (Chong 1994, Jacobs and Gatewood 1999, Monsen and Stevens 1999). Some land managers pile juniper slash in gullies or form windrows at strategic places to deter erosion, retain water, and capture snow (Hessing and Johnson 1982, Judy Prosser personal communication).

A few studies have addressed the effects of different slash arrangements on ecosystem responses. Brockway et al. (2002) tested three slash arrangements (removal, clustering and scattering) followed by prescribed fire as techniques for restoring grassland savannas from degraded woodlands in central New Mexico. Over two years, they found understory biomass increased 200% for all harvest treatments, but understory response did not significantly differ among the various slash arrangements. Wood and Javed (2001) conducted a study testing hydrologic and vegetal responses to fuelwood harvest and slash disposal or removal over ten years. Treatments included: (1) control plots, (2) plots clearcut and slash completely removed, (3) plots clearcut with slash uniformly scattered and burned that same year, (4) plots clearcut with slash uniformly scattered and burned two years later. They found that yearly grass and forb production increased with all treatments compared to the controls by the tenth year of the study. They also recorded the highest levels of mean annual runoff and mean sediment concentration in the plots that were burned immediately after thinning (Wood and Javed 2001). Jacobs and Gatewood (1999) found overstory reduction and slash mulching treatments increased total herbaceous cover two to sevenfold over the control plots after three years. Jacobs and Gatewood (1999) did not combination of thinning and slash removal, therefore the effects of overstory reduction can not be separated from the effects of slash on bare soil. All of these studies have used slash additions to bare soil and witnessed increases in understory abundance, but only Stoddard (2005) separated the effects to thinning from slash arrangement.

Burning in Pinyon-Juniper Woodlands

The use of prescribed fire has had limited application in pinyon-juniper woodlands because of the difficulty of prescribed burning and debatable historic fire regimes (Baker and Shinneman 2004). Pinyon-juniper woodlands are often difficult to broadcast burn because of rugged terrain and inconsistent fuels (Aro 1971). In many areas, only extremely dry and windy conditions will carry a fire through the canopy, resulting in a high-severity, stand-replacing fire (Arnold *et al.* 1964, Dwyer and Pieper 1967). Some land managers have used prescribed fire followed by seeding to convert woodlands to grasslands, thus improving their rangeland for livestock. Jacobs and Gatewood (2002) used prescribed fire to maintain the mechanically created savanna structure by killing tree seedlings, but warn that excessive fuel loadings or less than optimal burning conditions can damage grass and forb communities. Prescribed fire has also been used to consume slash created by thinning. Researchers have seen drastic increases in understory abundance when burning was done several years after a thinning, giving the understory a chance to grow back (Wood and Javed 2001, Jacobs and Gatewood 2002). Both overstory and understory responses of pinyon-juniper woodlands to prescribed fire depend on stand structure, weather conditions, fuel availability and fuel conditions.

Seeding in Pinyon-Juniper Woodlands

Seed germination of understory species in pinyon-juniper woodlands is highly dependent on precipitation. Water availability is commonly thought to be the ultimate limiting resource for seedling establishment in pinyon-juniper woodlands (Archer and Pyke 1991). Seeding is also affected by animal predation (Archer and Pyke 1991), the availability of favorable microsites (Harper *et al.* 1965), seedbed preparation (Struth and Dahl 1974), and weed control (Herbel *et al*. 1974). Slash additions and minor soil disturbances can create favorable microsites for seed establishment (Stoddard 2005). Seeding after wildfires is a common practice in the USDA Forest Service, and has had mixed results in the pinyon-juniper woodlands of Coconino County in northern Arizona (Katherine Sanchez-Meador, personal communication). Most of the above mentioned literature pertaining to seeding in pinyon-juniper woodlands refers to seeding with crested wheat-grass and other non-native grasses to increase forage for livestock after total tree removal. Few studies have been conducted using native seeds for the purpose of increasing understory biodiversity. Stoddard (2005) showed seeding with a native seed mixture effectively increased graminoid cover in degraded pinyon-juniper woodlands in northern Arizona.

Justification for Research

Since pinyon-juniper woodlands are so vast and relatively understudied compared to other forested ecosystems in North America, there are many research opportunities that could help guide land management decisions. As described above, little is known about a variety of silvicultural techniques besides total tree removal or existing understory dynamics in pinyon-juniper woodlands. The objective of this study was to determine the effect of different treatments on understory species richness and abundance. The treatments consisted of overstory thinning, different arrangements of slash, and burning and seeding in different combinations. Our specific research questions were: (1) Does burning and or seeding after thinning influence resulting understory richness and abundance? (2) Does slash arrangement influence resulting understory richness and abundance? We hypothesized that broadcasting slash, followed by seeding would lead to the greatest understory response and that burning would decrease both abundance and diversity. To address these questions and hypotheses we measured changes in understory species richness and abundance in treatments including variations in thinning, fuel creation and consumption, maximum soil temperature reached during the prescribed burn, and understory vegetation responses. This study will help land managers implement multi-aged thinning prescriptions and understand the interactions of slash arrangements and treatments on resulting understory richness and abundance.

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Chapter 2

Effects of thinning, burning, seeding and various slash arrangements on understory communities in pinyon-juniper woodlands of northern Arizona, USA.

ABSTRACT

Pinyon-Juniper woodlands represent a dominant ecosystem in the American Southwest and have been increasing in density and range. Land managers are concerned about the resulting effects on wildlife habitat, forage production for livestock, and wildfire risk. In many places, the only treatment has been total tree removal. This study presents an alternative to wholesale tree removal, by using historic reference conditions to determine tree densities and using the resulting slash to try and increase understory diversity and abundance. We thinned twenty-three hectares of *Juniperus osteosperma* (Torr.) Little and *Juniperus monosperma* (Engelm.) Sarg. to simulate 1860 (pre-livestock grazing) age structure and density, over three sites. Each site was comprised of either limestone, sandstone or basalt parent soil materials. For each site there was a control plot and three slash treatments. Slash was either piled, broadcasted, or clustered. The control plots were not thinned. Each of these slash arrangements received one of four treatments: 1) prescribed fire, 2) seeding, 3) prescribed fire and seeding, 4) no treatment. Understory plant species richness and abundance was measured before thinning in June of 2005 and then again in June of 2006, after the slash arrangements and treatments were implemented. In 2005, we identified 115 plant species in the understory over all three sites. January to June of 2006 was the driest period in the last 30 years and species richness decreased by an average of 40% from the previous year in control plots. We found variable understory responses to the slash arrangements, burning and seeding. Plant species abundance was generally low and not influenced by slash arrangement,

burning, or seeding at any of the three sites. Plant species richness was significantly different due to slash arrangement at the basalt site, where broadcasting the slash produced the greatest richness. Plant richness was not affected by slash arrangement at the limestone site or at the sandstone site. Burning and or seeding did not affect species richness at any of the sites. This study demonstrates that extensive ecosystem manipulation (thinning, slash arrangements, burning, and seeding) in the pinyon-juniper woodlands of northern Arizona does not affect understory richness or abundance the first year after treatment.

INTRODUCTION

Pinyon-juniper woodlands occupy close to 30 million hectares in the western United States and are some of the largest ecosystems in the American Southwest (West 1999). Pinyon-juniper woodlands are usually found from elevations of 1,370 to 2,290 m where precipitation averages 25-40 cm a year (Gottfried and Swetnam 1995). Pinyon-juniper woodlands across the West are quite variable, depending on the overstory structure and composition, understory structure and composition, location, management history, and site potential. Pinyon-juniper woodlands are the most xeric forest type in the United States and often form the lower tree line between forests and desert grasslands.

Many studies have documented the expansion and contraction of pinyon-juniper woodlands over thousands of years, due to long term changes in climate (Van Devender *et al*. 1984, Mehringer and Wigand 1990, Gottfried *et al.,* 1995, Woolfenden 2003). In the last 150 years there has been expansion and densification in many pinyon-juniper areas (Cottam and Stewart 1940, Johnsen 1962, Burkhardt and Tisdale 1969, Blackburn and Tueller 1970, Tausch *et al.* 1981, Landis and Bailey 2005). This period coincides with Euro-American settlement in many areas, leaving scientists to untangle the effects of livestock grazing, climatic changes and fire suppression on current pinyon-juniper woodlands structure and function (Romme *et al.* 2003).

The current expansion and densification of pinyon-juniper woodlands is generally considered an undesirable trend for land managers. Land managers may thin or remove pinyon-juniper woodlands for a variety of reasons including: wildlife habitat improvements, watershed issues, increased forage for livestock, and fuels mitigation. Most managers remove all pinyon and juniper trees by chaining, or remove the majority of trees with a hydro-axe or masticator (Campbell 1999). Few studies have used historic reference conditions to guide thinning in pinyon-juniper woodlands (Jacobs and Gatewood 1999, Huffman *et al.* 2006).

The inverse relationship between overstory cover and understory cover in pinyon-juniper woodlands has been documented throughout the years (Parker 1945, Pieper 1990, Erramouspe 1994, Tausch and West 1995, White *et al.* 1997). Increasing understory diversity and abundance has become a goal for many land managers. Techniques for increasing understory health have included thinning, slash additions to bare soil, prescribed burning, and seeding (Jacobs and Gatewood 1999, Wood and Javed 2001, Brockway *et al*. 2002, Stoddard 2006).

Leaving the slash created by thinning on the ground may create favorable microsites for understory establishment. Stoddard (2006) found that slash amendments to the soil significantly increased residual woody and litter debris, reduced soil movement, increased arbuscular mycorrhizal fungi and microbial carbon levels, and that seeding increased graminoid abundance after two years in degraded pinyon-juniper woodlands in northern Arizona. Brockway *et al*.(2002) found that plant species richness and diversity increased most on sites where slash was either completely removed or scattered to serve as mulch and that understory biomass increased for all harvest treatments. Jacobs and Gatewood (1999) found that overstory reduction and slash mulching treatment produced two to sevenfold increases in herbaceous cover relative to the controls, three years after treatment. Neither study proved that slash additions to bare soil alone, without the confounding factors of thinning, increased understory diversity and cover.

The use of prescribed fire has had limited applications in pinyon-juniper woodlands, because of the difficulty of burning (Aro 1971) and the debatable historic fire regime (Baker and Shinneman 2004). In many areas, only extremely dry and windy conditions will carry a fire through the canopy, resulting in a high severity, stand replacing fire (Arnold *et al.* 1964, Dwyer and Pieper 1967). Prescribed fire success depends on stand structure, weather conditions, fuel availability and fuel conditions (Bruner and Klebenow 1979). Some land managers have used prescribed fire followed by seeding to convert woodlands to grasslands, thus improving their rangeland for livestock. Jacobs and Gatewood (1999) used prescribed fire to maintain the mechanically created savanna structure by killing tree seedlings, but warn that excessive fuel loadings or less than optimal burning conditions can damage grass and forb communities. Prescribed fire has also been used to consume the slash created by thinning. Researchers have seen increases in understory abundance when the burning was done several years after the thinning, giving the understory a chance to grow back (Jacobs and Gatewood 1999, Wood and Javed 2001).

The success or failure of seeding in pinyon-juniper woodlands is also highly dependent on the precipitation. Water availability is critical for seedling establishment in arid ecosystems (Griffiths 1907, Judd and Judd 1976). Seeding is also affected by animal predation (Archer and Pyke 1991) and the availability of favorable microsites (Harper *et al.* 1965). Slash additions and minor soil disturbances can create favorable microsites for seed establishment (Stoddard 2006). Seeding after wildfires is a common practice in the US Forest Service, and has been shown to effectively increase graminoid cover in degraded pinyon-juniper woodlands in northern Arizona (Stoddard 2006).

The objective of this study was to determine the effect of different silvicultural treatments on understory richness and abundance. The treatments consisted of overstory thinning, different arrangements of slash, and burning and seeding in different combinations. Our specific research questions were: (1) Does burning and/or seeding after thinning influence resulting understory richness and abundance? (2) Does slash arrangement influence resulting understory richness and abundance? To answer these questions we measured changes in forest structure from thinning, fuel creation and consumption, maximum soil temperature reached during the prescribed burn, and understory vegetation responses. We hypothesized that broadcasting slash, followed by seeding would lead to the greatest understory abundance and richness and that burning would decrease both abundance and richness. This study will help land managers implement multi-aged thinning prescriptions and understand the interactions of slash arrangements, burning, and seeding on resulting understory richness and abundance.

METHODS

Study Area

This study was conducted in 2005 and 2006 on Anderson Mesa, located 150 km southeast of Flagstaff, Arizona (Fig. 1). The climate of Anderson Mesa is semi-arid, receiving a mean precipitation of 470 mm per year. About half of this precipitation falls in the summer monsoon months of July and August as rain, and the other half as snow in January, February, and March. The average high temperature in July is 29° C and the average low temperature in January is -9° C (Western Regional Climate Center 2006). Historically, there are few average years due to dramatic climatic fluctuations from year to year. Since there are no weather stations remotely close to our research sites, climate data was calculated by averaging the 3 closest weather stations: Happy Jack, Fort Valley and Winslow (Landis 2005, Western Regional Climate Center 2006).

Three sites with different parental substrates were selected, due to their known historic forest structures (Landis and Bailey 2005) (Fig. 1). These sites were named after their parental soil material and are called the limestone site, the sandstone site, and the basalt site. Descriptions of each site are found in Table 1. In northern Arizona, pinyon-juniper woodlands transition into semi-arid grasslands at the lowest end of their elevational range and into ponderosa pine forests at the highest end of their elevational range. All three sites were in the middle of the local pinyon-juniper elevational gradient.

Juniperus osteosperma (Torr.) Little and *Juniperus momosperma* (Engelm.) Sarg. dominate the overstory and *Bouteloua gracilis* (Willd. ex Kunth) Lag. ex and *Gutierrezia sarothrae* (Pursh) Britt. & Rusby dominate the understory plant community at all sites. Other common, yet less abundant grasses and forbs include *Elymus elymoides* (Raf.) Swezey, *Chaetopappa ericoides* (Torr.) Nesom, *Opuntia sp*., *Descurainia sp.*, *Sphaeralcea parvifolia* A. Nels., *Lappula occidentalis* (S. Wats.) Greene, *Lupinus kingii* S. Wats., *Lesquerella intermedia* (S. Wats.) Heller, and *Arabis fendleri* Greene.

The limestone and sandstone sites have both had limited fall and spring livestock grazing since the 1950's. The basalt site has not been grazing from the 1920 to the present (Jack Metzger, personal communication). Other important grazers in the area include elk, mule deer and pronghorn antelope. All three sites have had very little modern human influence and have not been used as firewood gathering areas. The fire history of the area is unknown, although local anecdotal observations indicate that fires were limited to small (less than 1 ha), infrequent, high-severity fires (Maria Irwin, personal observation).

Experimental Design

We created a split-plot design with one of four slash arrangements applied to the subplots and one of four treatments applied to the whole-plots (Fig. 2). At each site we created four 160 x 160 m units. Each unit was divided into four 80 x 80 m whole plots. We randomly chose a treatment for each whole plot. There were four treatment options: burn, burn and seed, seed, or no treatment. The whole plots were divided into four 40 x 40 m subplots. Each subplot was randomly assigned one of four slash arrangements: pile, cluster, broadcast or no thinning. Therefore, each unit was composed of 16 subplots, and each subplot was a different slash arrangement and treatment combination (Table 2). We implemented thinning, slash arrangements and treatments in three of the four units at each site. The fourth unit was marked but never thinned due to time constraints. Thus, the 16 plots within the fourth unit served as another control at each site to measure temporal variability in understory vegetation. Henceforth the plots will be referred to as the control plots.

Vegetation Surveys

A pre-treatment vegetation survey was conducted using a modification of the Modified-Whittaker plot (Korb *In Press*) in June of 2005. A voucher specimen of each unknown species was collected and identified at the Deaver Herbarium at Northern Arizona University. We drew out a 50 m tape at a 45° angle from the southwest corner of each subplot, creating a 50 m line transect. Four 1-m^2 frames (0.5 x 2 m) were placed along alternating sides the line transect. Every 14 meters the frame was placed with the 2 meter side parallel to the line, starting at 0-2 m on the right side of the line. The second frame was placed at 16-18 m on the left side of the line. The third frame was placed at 32-34 m on the right side of the line. The fourth frame was placed at 48-50 m on the left side of the line. In each frame, we visually estimated the aerial percent cover (abundance) of each plant species, bare soil, rock, coarse woody debris, litter, and moss. We averaged the cover estimates in these four frames to get a plant species abundance for each subplot. To measure species richness in each subplot, we recorded all the species found within a five meter belt on either side of the line. Together the four 1-m^2 frames and the 500 m^2 belt transect provided us a measurement of plant richness and abundance in each subplot.

Post-treatment vegetation response was measured in June of 2006. This provided a measure of the first year understory response to our experiment. The control plots in the fourth unit allowed us to independently measure inter-annual variability between 2005 and 2006.

Thinning and Slash Arrangements

Thinning was conducted in the summer of 2005, following a custom BDQ prescription for each site (Landis and Bailey 2005). BDQ thinning prescriptions are a silvicultural approach for controlling uneven-aged forest structure by setting targets of desired numbers of trees in each diameter class (Smith *et al.* 1977). B stands for basal area in m^2/ha, D stands for maximum diameter measured at root collar in cm and Q stands for the q-ratio (Nyland 1996). This method seeks to balance standing tree density with expectations for growth and mortality up to some maximum diameter (Bailey and Covington 2002). At the limestone site the BDQ prescription was 30-100-1.4 (30 m^2/ha was the target basal area, 100 centimeters diameter at root collar was the maximum diameter this prescription included, and 1.4 was the slope of the q-ratio line). At the sandstone site the BDQ prescription was 20-100-1.25. At the basalt site, the BDQ prescription was 10-100-1.5. These prescriptions did not include *P. edulis*, which composed 1-10% of the woodland. The living *P. edulis* trees were not cut because of the recent drought and bark beetle related dieback (Breshears *et al.* 2005) since this prescription had been created. We also excluded *J. osteosperma and J. monosperma* trees over 100cm diameter at root collar (drc) because of their old-growth habit, potentially very old age and inherent value to the ecosystem. We found an average of 10 trees per hectare >100 cm drc.

We marked the prescription on a subplot level to keep slash levels as consistent as possible. When there were not enough trees in the subplot we marked the prescription on the unit level. We painted the trees we wanted to leave and marked the trees in a clumpy arrangement (3 trees or more together) when possible to mimic 1860 spacing patterns (Landis and Bailey 2005). All the thinning was done by hand with chainsaws. After each subplot was cut, we tallied the root collar diameter of all the stumps. This allowed us to calculate forest density and diameter distribution at each plot before and after thinning.

We arranged the slash as we were thinning the subplots. There were four possible slash arrangements: pile, cluster, broadcast, and no thinning (Fig. 3). We piled the slash for the pile arrangement. We felled the tree at the base and then left the limbs intact for the cluster arrangement. For the broadcast arrangement, we cut the slash into approximately one meter sections and then scattered it around the subplot. The no thinning plots acted as a control. We employed six to eight sawyers for 5 months and thinned and arranged the slash on 23.1 total hectares.

Fire Measurements and the Prescribed Burn

We measured surface fuel loading on each cluster, broadcast, and no thinning sup-plot using planar intercept transects (Brown 1974) after the thinning. From the center of each subplot, we drew a 15.24 m tape out towards a randomly chosen azimuth. We repeated this transect four times, and averaged the resulting fuel values per subplot. We estimated the volume of our pile subplots according to Hardy (1996). We remeasured fuels after the prescribed burn to estimate fuel consumption.

We placed 3 pyrometers at each subplot to measure maximum surface temperature reached during the prescribed burn. The pyrometers were composed of a "L" shaped strip (25.4 mm x 152.4 mm on the soil surface, 25.4mm x 76.2 mm below the ground) of thin sheet metal. This strip was painted with 11 temperature-sensitive paints that detect temperatures ranging from 79°C to 760°C (Table 6) (Tempilaq° G Temperature Indicating Liquids, Omega Engineering, Stamford, Conn.). After the paint had dried, a second strip of sheet metal was attached to the top of the pyrometer with two paperclips, to assure that scorch would not interfere with reading the paint changes (Fig. 4). These pyrometers measured maximum soil temperature during the prescribed burn. Pyrometers were also influenced by the duration of temperature, providing a somewhat integrated measure of intensity (Odin and Davis 2000, Schwilk 2003). Each subplot was visually stratified into areas of high, medium, and low slash accumulations. One pyrometer was randomly placed in each level of slash loading. After the prescribed burn, the pyrometers were collected with a metal detector and surface temperatures were recorded.

We used prescribed fire in the designated burn units in early November of 2005. Even under windy conditions (gusts >24 km/hour) we had a very difficult time getting the fire to carry because of lack of continuous surface fuels. The average wind speed was 8.8 km/hour. Most of the slash was lit piece by piece with a drip torch. Atmospheric temperatures ranged from 10°C to 18.3°C and relative humidity ranged from 29-59%.

Seeding

We hand-seeded a custom native seed mix after the prescribed burn, in November of 2005. We applied the seed mix directly to the ground in the whole-plots designated to be seeded. Our seed mixture was composed of three shrubs, one forb and six grasses (Table 3). All species in the seed mix were found on the sites in the 2005 vegetation survey. The seed and seeding rates were provided by Granite Seed in Lehi, Utah (www.GrantieSeed.com).

To measure seed predation, we measured seedling emergence of pairs of protected and unprotected seeds. At every subplot in the limestone site and the sandstone site that was seeded, we placed 2 g of seed under a small cage (154.2 mm x 154.2 mm x 25.4 mm) made of hardware cloth. The cage was positioned flush to the ground and held in place by an aluminum tent stake. The cage was randomly placed within the region of the subplot that was not covered by slash. Then 152 mm to the north of the cage, we placed 2 grams of seed mixture on the ground in the same sized area as the cage.

Data Analysis

Since each of the three sites had different thinning prescriptions, they were treated as independent experiments and were analyzed separately. We used a split-plot design analysis of variance to test the influence of slash arrangements, treatments, and their interactions on understory richness and abundance. When significant differences were found, we used Tukey-Kramer HSD to test differences among means. We compared the differences in abundance and richness between years by in the control plots of the fourth unit at each site using paired t-tests. Analyses were conducted using the statistical package JMP version 6 (SAS Institute, Inc. 2004). All significances were found at the α=0.05 level.

PC-ORD software (MjM Software, Gleneden Beach, OR, U.S.A.) was used to determine variation in plant community assemblages (using only herbaceous species abundance values) between slash arrangement, treatments and their interactions at each site using nonmetric multidimensional scaling (NMDS). Plant community data were revitalized to the maximum and the species that were only found on 5% of the plots or fewer were eliminated, to omit noise caused by very rare speices. NMDS autopilot mode was used to determine the appropriate dimensionality in the analysis (Table 4).

RESULTS

Thinning

We were able to meet our target number of trees in each diameter class. The resulting forest structures are depicted in Figure 5 and summarized in Table 5. We cut the most trees in all diameter classes at the basalt site, because it had changed the most since 1860.

Fuels

Each of the four slash arrangements created a different fuel structure on the ground before and after the prescribed burn. The most consumption was seen in the pile arrangement, then the broadcast, then the cluster arrangement, and lastly in the no thinning subplots (Table 6).

Pyrometer Readings

The pyrometer readings showed that the pile slash arrangement burned nearly 50% hotter than cluster and broadcast slash arrangements. There was little difference between the maximum temperatures reached in the broadcast and the cluster slash arrangements. The plots that were not thinned reported the lowest maximum temperature readings (Fig. 6).

Understory Vegetation

In the relatively wet year of 2005, we identified 115 species in the pinyon-juniper woodland understory over all three sites (Appendix A). The basalt site had the greatest richness and abundance of the three sites (Fig. 7). We calculated species evenness using

Simpson's and Shannon's indices and found species evenness generally increased with species richness at each site (Table 7). Non-native species were found on 6% of the plots at the limestone site, 24% of the plots at the sandstone site and 4% of the plots at the basalt site (Table 8).

Understory richness was not influenced by slash arrangement or treatment at the limestone site (Table 9a). Understory species richness was influenced by slash arrangement at the basalt site (Fig. 8) with the broadcast arrangement plots yielding the greatest richness (Fig. 9). Species evenness patterns did not mimic total species richness trends amongst slash arrangements at the basalt site (Table 10). At the sandstone site, we found a significant difference in richness due to the slash arrangement by treatment interaction, but the three interaction terms with the greatest richness values included the no thinning and no treatment combination (Table 11). Understory abundance measures did not differ by slash arrangements or treatments, at any of the three sites (Table 9 b).

Herbaceous community analysis using NMDS did not show significant differences in community assemblages due to slash arrangement, treatment, or their interaction at the limestone site (Fig. 10) or the sandstone site (Fig. 11) (Table 12). At the basalt site we found that the proportion of randomized runs with stress < or = observed stress was large, with p-values >0.05. Therefore a useful NMDS ordination could not be found for understory community analysis the basalt site.

We compared understory plant richness and abundance for 2005 vs. 2006 in the 16 control plots in the control units at each site. We found that species richness significantly decreased at all three sites (p=0.001 for the limestone site, p=0.001 for the sandstone site, and p=0.001 for the basalt site) (Fig. 12a). Plant richness decreased an average of 40% over the three sites with corresponding decreases in Simpson's and Shannon's Diversity indices (Table 13). Plant abundance was not significantly different between years at the limestone site (p=0.670) or at the sandstone site (p=0.199). Plant abundance was significantly reduced from 2005 to 2006 at the basalt site (p=0.024) (Fig. 12b). Non-native species occurrence decreased in the belt transect measurements from 2005 to 2006 at all sites (Table 8).

Seeding

In June of 2006 we surveyed the seed cages and exposed seed plots and found no seedling emergence in either of the plots, at any of the three sites. We found bare seeds lying on top of the soil inside of the cages. In the exposed plots, the seeds were no longer visible. Therefore, no analysis was done on the seed cage experiment.

DISCUSSION

Although our experiment was not set up to test for the effect of moisture, we believe plant responses to our slash arrangements, burning and seeding treatments were muted by the severe drought of the preceding winter and spring. Our vegetation surveys were conducted in June, which is traditionally the peak of the understory plant abundance and richness at our research sites (Jack Metzger, personal communication). January to May of 2006 was the driest winter and spring in the last 33 years (Western Regional Climate Center). This same period in 2005 was relatively wet (85th percentile), compared to the average precipitation year (Fig. 13). Pre-treatment vegetation measurements were conducted in a relatively wet period and post-treatment vegetation measurements were conducted in a very dry period. The seasonality of precipitation is very important in semiarid ecosystems (Schwinninng *et al.* 2005).

We documented drastic decreases in plant richness from 2005 to 2006 in the control plots (41% at the limestone site, 33% at the sandstone site, and 46% at the basalt site). Abundance levels did not significantly change in two of our three sites, probably because *Bouteloua gracilis* accounted for a very high percent of total plant abundance at each site (90% at the limestone site, 63% at the sandstone site, and 67% at the basalt site) (Fig. 12). The above ground tufts of this hardy perennial grass persisted throughout the dry winter and spring of 2006, accounting for the majority of the abundance measurements.

Despite the dry growing conditions, we did see a significant plant richness response to the various slash arrangement at one of the three sites. At the basalt site broadcasting the slash resulted in the highest richness, followed by the cluster, then the pile and lastly the no thinning (Fig. 9). The more spread out the slash was, the greater the resulting richness in the plant community. Our findings on the basalt site support the idea that slash additions to bare soil can create favorable microsites for understory establishment (Jacobs and Gatewood 1999, Stoddard 2006).

We cannot explain why slash arrangement did not significantly influence resulting understory richness at the limestone and sandstone sites (Fig. 8). The basalt site was 153 m higher than the other two sites and thus probably received more moisture. Also, the basalt site had the greatest overstory reduction (Table 5). Perhaps the difference in understory response was due to soil type, or some combination of the above factors. O'Rourke and Ogden (1969) found that certain soil characteristics such as high calcium carbonate levels, high pH, and low phosphorous, were associated with no increase in perennial grass production four to five years after pinyon-juniper control in north-central Arizona.

Burning did not influence understory richness or abundance at any of the sites, after one year. This result was counterintuitive given plants were consumed during the prescribed burn in the fall and the following spring was very dry. Other studies have burned slash created by thinning in pinyon-juniper woodlands and recorded an immediate decrease in plant abundance, followed by an increase each year since the burn (Wood and Javed 2001, Jacobs and Gatewood 2002).

Burning heavy loads of juniper slash creates very hot soil temperatures and may have negative impacts on future understory regeneration (Jacobs and Gatewood 2002). Our study showed that the maximum surface temperature exceed 700°C under slash piles. The broadcast and the cluster slash arrangements also recorded high soil temperatures during the burn. Soil heating can cause mortality to soil organisms, plant roots, alteration of physical soil properties, changes in nutrient cycling patterns and nutrient volatilization (Roberts 1965, Neary *et al*. 1999). Haskins and Gehring (2004) found that burning slash piles as a management tool in pinyon-juniper woodlands reduces native species richness increases non-native species compared to surrounding unburned plant communities. We did not see this in our first year vegetation response (Table 8), but will continue to look for differences in the burned and unburned plant communities in the future.

Since seedling emergence often depends on soil water availability (Harper 1977, Chambers 2000) we attribute the total lack of germination in seeding cages to dry growing season of 2006. Seeding success in other studies had been mixed. In 2006, Stoddard found seeding increased biodiversity in degraded pinyon-juniper woodlands in northern Arizona after the first two years of seeding. Judd and Judd (1976) examined plant survival and found that none of the seeded species were present 30 years after seeding in pinyon-juniper woodlands of the Tonto National Forest in Arizona.

More time monitoring these sites is needed to untangle the effects of slash arrangements and treatments on understory response in pinyon-juniper woodlands. Future studies on pinyon-juniper understory communities could be designed to control for moisture, reduce the numbers of influencing factors in the experimental design, and be remeasured to follow vegetation changes over many years and climatic patterns.

Management Recommendations

Using an 1860 thinning prescription, as opposed to total tree removal, assures that structure of the pinyon-juniper woodland is maintained within the historical range of variability (Landis and Bailey 2005). Thinning represents a compromise between total tree removal which would maximize forage production and no management action (Fairchild 1999). This study examines the effects of multi-aged thinning in pinyon-juniper woodlands and provides land managers with expected fuel loadings by initial woodland structure, slash arrangement type and thinning prescription.

Broadcasting the slash created by thinning increased initial understory diversity on the basalt derived soil site, despite the dry year. Burning slash did not affect initial grass and forb abundance and diversity, although it did produce exceedingly hot soil temperatures. Land managers must weigh the tradeoffs of burning slash for wildlife and livestock mobility benefits, with the potential negative effects mentioned above. Hand seeding was not found to be effective.

Variation in precipitation is the norm in the Southwest. Therefore, understanding temporal and spatial variability in the pinyon-juniper woodland understory plant community is vital to interpreting the influence of management actions. Global climate change is expected to affect ecosystems worldwide (Vitouskek 1994) by raising temperatures and changing precipitation patterns (IPPC 2001). Given the central role that precipitation plays in semiarid ecosystems, changing precipitation regimes and inter-annual variability may have a stronger affect on pinyon-juniper understory biodiversity and abundance than treatments enacted by land managers.

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Table 1. Site descriptions and soil characteristics of each of the three pinyon-juniper woodland research sites in northern Arizona.

	Limestone Site	Sandstone Site	Basalt Site
UTM Coordinates	481669E 3860185N (NAD27)	482106E 3859037N (NAD27)	484702 E 38517171 N (NAD27)
Elevation	1920m	1920m	2,073m
Maximum slope	<8%	2-15%	<8%
Land ownership	Arizona State Trust Land	Arizona State Trust Land	Private Land
Parent soil material	limestone	sandstone	basalt
Soil series	Deama gravely loam	Rune silty clay loam	Springerville very stony clay
Soil Order	Mollisols	Mollisols	Vertisol
Available water	Very low	High	Medium
Hazard of erosion	Slight to moderate	Moderate	Slight
Permeability	Moderate	Slow	Very slow

Taylor, 1983. Available water: capacity of the soil to hold water to be used by plants. Hazard of erosion: the probality of accelerated erosion after soils have been exposed. Permeabillity: quality of soil that allows water to move downward through the soil column.

Table 2. Each plot was assigned one of these sixteen possible slash arrangements and treatment combinations. Each combination was replicated three times per site (once at the limestone site, once at the sandstone site, and once at the basalt site). The no thinning and the no treatment are controls.

	subplot	*whole plot*	Response Variables	
Combination	*Slash Arrangment*	*Treatment*	*Richness*	*Abundance*
1	Pile	Burned	$x_{r,\, n = 3}$	$x_{a,\, n = 3}$
2	Pile	Seeded	$x_{r,\, n = 3}$	$x_{a,\, n = 3}$
3	Pile	Burned & Seeded	$x_{r,\, n = 3}$	$x_{a,\, n = 3}$
4	Pile	No Treatment	$x_{r,\, n = 3}$	$x_{a,\, n = 3}$
5	Broadcast	Burned	$x_{r,\, n = 3}$	$x_{a,\, n = 3}$
6	Broadcast	Seeded	$x_{r,\, n = 3}$	$x_{a,\, n = 3}$
7	Broadcast	Burned & Seeded	$x_{r,\, n = 3}$	$x_{a,\, n = 3}$
8	Broadcast	No Treatment	$x_{r,\, n = 3}$	$x_{a,\, n = 3}$
9	Cluster	Burned	$x_{r,\, n = 3}$	$x_{a,\, n = 3}$
10	Cluster	Seeded	$x_{r,\, n = 3}$	$x_{a,\, n = 3}$
11	Cluster	Burned & Seeded	$x_{r,\, n = 3}$	$x_{a,\, n = 3}$
12	Cluster	No Treatment	$x_{r,\, n = 3}$	$x_{a,\, n = 3}$
13	No Thinning	Burned	$x_{r,\, n = 3}$	$x_{a,\, n = 3}$
14	No Thinning	Seeded	$x_{r,\, n = 3}$	$x_{a,\, n = 3}$
15	No Thinning	Burned & Seeded	$x_{r,\, n = 3}$	$x_{a,\, n = 3}$
16	No Thinning	No Treatment	$x_{r,\, n = 3}$	$x_{a,\, n = 3}$

"x_r" represent the mean richness (n = 3) and "xa" mean abundance (n = 3)

Table 3. Plant species used for seeding and application rates of each species. This custom seed mixture was hand broadcast onto the seeding plots in November of 2005.

scientific name	**variety**	**common name**	**life form**	**kg/ha**
Artemisia tridentata	Wyomingensis	Wyoming Big Sage	shrub	0.1
Krascheninnikovia lanata		winterfat	shrub	1.1
Purshia tridentata		antelope bitterbrush	evergreen shrub	1.1
Linum lewisii		blue flax	perennial wildflower	6.7
Achnatherum hymenoides	Rimrock or Nez Par	Indian ricegrass	C3 bunchgrass	13.5
Aristida purpurea		purple three-awn	C4 bunchgrass	6.7
Muhlenbergia wrightii	El Vado	spike muhly	C4 bunchgrass	3.4
Pleuraphis jamesii	Viva florets or Viva Caryopsis	galleta grass	C4 bunchgrass/sodformer	7.8
Elymus elymoides	San Hallow	bottlebrush squirrel tail	C3 bunchgrass	13.5
Elymus trachycaulus	San Luis	slender wheat grass	C3 bunchgrass	9

Table 4. NMDS Autopilot Parameters

Parameter	Medium*
Maximum number of iterations	200
Instability criterion	0.001
Starting number of axes	4
Number of real runs	15
Number of randomized runs	30

*thoroughness setting

Table 5. Summary of the changes in forest structure before and after implementing the BDQ thinning prescription at each of the three research sites in the pinyon-juniper woodlands of northern Arizona. BDQ is expresses as m^2 of basal area, maximum diameter at root collar in cm, and the q-ratio.

		Trees per Hectare			Basal Area
Site	BDQ	pre-thinning	post-thinning	% reduction	% reduction
Limestone	30-100-1.4	531	284	53	28
Sandstone	20-100-1.25	212	156	26	42
Basalt	10-100-1.5	441	138	69	61

Table 6. Fuel loadings (Mg/ha) before and after the prescribed burn, by slash arrangement and site in the pinyon-juniper woodlands of northern Arizona. “na” stands for not applicable.

4a. Limestone Site	Pile		Cluster		Broadcast		No Thinning	
Fuel classes	before	after	before	after	before	after	before	after
1-HR	na	na	0.99	0.10	0.58	0.17	0.13	0.06
10-HR	na	na	2.95	0.36	2.41	1.78	0.39	0.25
100-HR	na	na	5.93	0.42	7.62	3.39	0.85	0.00
1000-HR sound	na	na	4.94	0.00	0.44	0.00	0.39	0.00
1000-HR rotten	na	na	22.79	1.95	12.08	2.77	0.00	1.02
total Mg/ha	29.39	2.94	37.60	2.82	23.14	8.10	1.75	1.33

4b. Sanstone Site	Pile		Cluster		Broadcast		No Thinning	
Fuel classes	before	after	before	after	before	after	before	after
1-HR	na	na	0.28	0.08	0.72	0.17	0.09	0.14
10-HR	na	na	1.60	0.67	4.37	1.28	0.60	0.67
100-HR	na	na	1.48	3.81	8.05	4.02	0.21	0.42
1000-HR sound	na	na	0.50	0.56	4.62	0.00	0.38	0.00
1000-HR rotten	na	na	4.81	3.92	11.90	2.66	1.84	6.15
total Mg/ha	24.84	2.49	8.68	9.04	29.66	8.13	3.12	7.38

4c. Basalt Site	Pile		Cluster		Broadcast		No Thinning	
Fuel classes	before	after	before	after	before	after	before	after
1-HR	na	na	0.61	0.15	0.67	0.27	0.10	0.23
10-HR	na	na	2.98	1.03	3.73	1.53	0.75	1.10
100-HR	na	na	9.32	1.48	5.93	1.91	1.69	1.27
1000-HR sound	na	na	0.99	0.00	6.20	0.00	0.00	0.00
1000-HR rotten	na	na	8.87	13.02	9.93	1.47	3.35	0.00
total Mg/ha	31.63	3.16	22.76	15.69	26.46	5.17	5.89	2.60

Table 7. Pre-existing differences in species evenness indices between the three sites in 2005 before the experiment began in the pinyon-juniper woodlands of northern Arizona. Data are expressed as means (n = 64) +/- SE.

	Limestone	Sandstone	Basalt
Simpson (D-1) index	0.45 (0.22)	0.60 (0.21)	0.62 (0.15)
Shannon H index	0.99 (0.49)	1.30 (0.50)	1.44 (0.39)

Table 8. Non-native species occurrence decreased the first year after treatments in the pinyon-juniper woodlands of northern Arizona. Data are the number of times that the non-native species appeared in the belt transect of a plot, out of the 64 possible plots. L stands for the limestone site, S stands for the sandstone site, and B stands for the basalt site.

				2005			2006	
Family	***Scientific Name***	**Common Name**	**L**	**S**	**B**	**L**	**S**	**B**
Chenopodiaceae	*Chenopodium album*	lambsquarters	11	51	10	0	12	0
Chenopodiaceae	*Salsola tragus*	russian thistle	3	23	0	6	23	0
Poaceae	*Bromus tectorum*	cheat grass	2	8	7	0	0	0
Geraniaceae	*Erodium cicutarium*	redstem stork's bill	1	13	1	0	0	0
Brassicaceae	*Sisymbrium altissimum*	tall tumblemustard	2	12	0	0	0	0
Asteraceae	*Tragopogon dubius*	yellow salsify	8	2	4	0	0	0
Asteraceae	*Lactuca sp.*	wild lettuce	3	8	1	0	0	0
Poaceae	*Bromus rubens*	red brome	0	4	0	0	0	0
Percentage of plots that contained non-native species			5.86	23.63	4.49	1.17	6.84	0.00

Table 9. P-value results for split-plot analysis of variance testing a) richness b) abundance differences due to the influences of treatment (burning, seeding, burning and seeding, or neither), slash arrangement (pile, cluster, broadcast, or no thinning) and their interaction on first year understory response in the pinyon-juniper woodlands of northern Arizona.

9 a. ***Richness*** p-values for split-plot ANOVA			
Factor	Limestone	Sandstone	Basalt
1 treatment	ns	ns	ns
2 slash arrangement	ns	ns	0.0004
3 slash arrangement x treatment	ns	0.0026	ns
9 b. ***Abundance*** p-values for split-plot ANOVA			
Factor	Limestone	Sandstone	Basalt
1 treatment	ns	ns	ns
2 slash arrangement	ns	ns	ns
3 slash arrangement x treatment	ns	ns	ns

n=3 for both tests, "ns" stand for non-significant p-values, all significances were determined at the α=0.05 level.

Table 10. Slash arrangement affects on resulting species evenness indices at the Basalt Site in 2006 in the pinyon-juniper woodlands of northern Arizona. Data are expressed as means (n = 12) +/- SE.

Diversity Index	Pile	Cluster	Broadcast	No Thinning
Simpson D	0.33 (0.06)	0.46 (0.23)	0.42 (0.25)	0.49 (0.23)
Shannon H	0.68 (0.13)	0.96 (0.52)	0.88 (0.52)	0.98 (045)

Table 11. Results of the Tukey's HSD test which was used to group means of the interaction factor at the sandstone site in the pinyon-juniper woodlands of northern Arizona. Richness means indexed by different letters are significantly different at the $p \leq 0.05$ level. The group of means with the highest richness (A's) included the no thinning and no treatment interaction.

Slash arrangement by treatment interaction term	Grouping		Mean
Broadcast x seed	A		18.66
Cluster x burn	A		18.00
No thinning x no treatment	A		17.04
Cluster x seed	A	B	16.66
Pile x seed	A	B	16.66
Burn x no treatment	A	B	16.66
No treatment x burn	A	B	16.33
Pile x burn and seed	A	B	16.00
Cluster x no thinning	A	B	15.90
Broadcast x burn and seed	A	B	15.66
Pile x burn	A	B	14.66
Pile by no thinning	A	B	14.00
Cluster x burn and seed	A	B	13.33
Broadcast x burn	A	B	13.00
No thinning x burn and seed	A	B	12.33
No thinning x seed		B	10.66

Table 12. Key to the Legends in the NMDS ordinations in Figures 15 and 16*

a) Slash arrangement	
1	pile
2	cluster
3	broadcast
4	no thinning
b) Treatments	
5	burn
6	seed
7	burn and seed
8	no treatment
c) Slash arrangement and treatment interaction	
15	pile x burn
16	pile x seed
17	pile x burn and seed
18	pile x no treatment
25	cluster x burn
26	cluster x seed
27	cluster x burn and seed
28	cluster x no treatment
35	no thinning x burn
36	no thinning x seed
37	no thinning x burn and seed
38	no thinning x no treatment

*PC ORD insists that the second matrix values be numbers and not words, which is why this "Key to the Legends" is required.

Table 13. Decrease in plant richness and corresponding diversity indices from the relatively wet year 2005 to the relatively dry year 2006 in the control plots in the pinyon-juniper woodlands of northern Arizona.

	Richness			Simpson's D Index		Shannon's H Index	
Site	2005	2006	% decrease	2005	2006	2005	2006
Limestone	18.94	11.19	41	0.32	0.20	0.70	0.39
Sandstone	26.31	17.50	33	0.50	0.36	1.05	0.70
Basalt	26.06	14.13	46	0.66	0.46	1.50	0.86

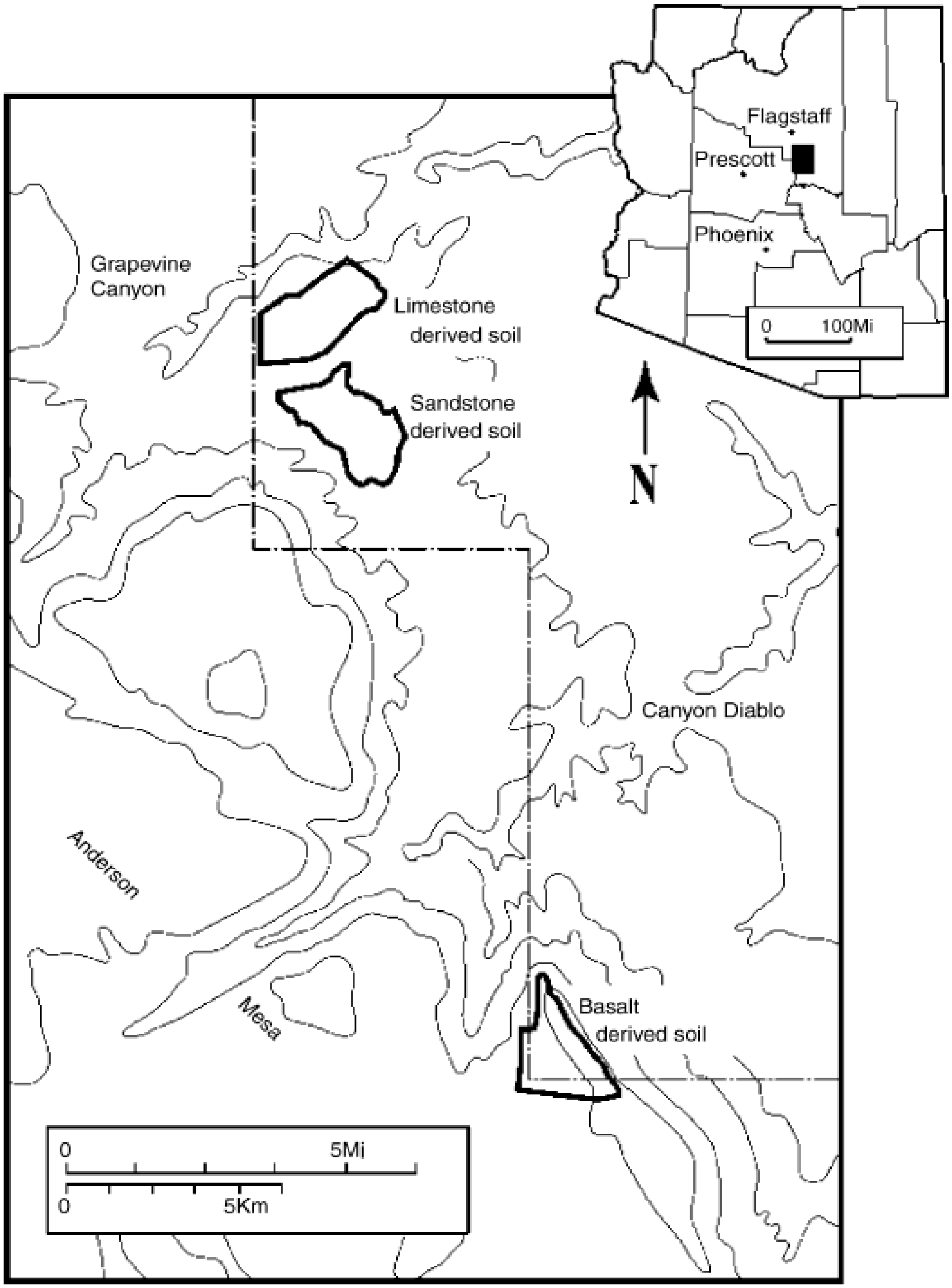


Figure 1. Map of the 3 study sites, 150 km southeast of Flagstaff, AZ, USA.

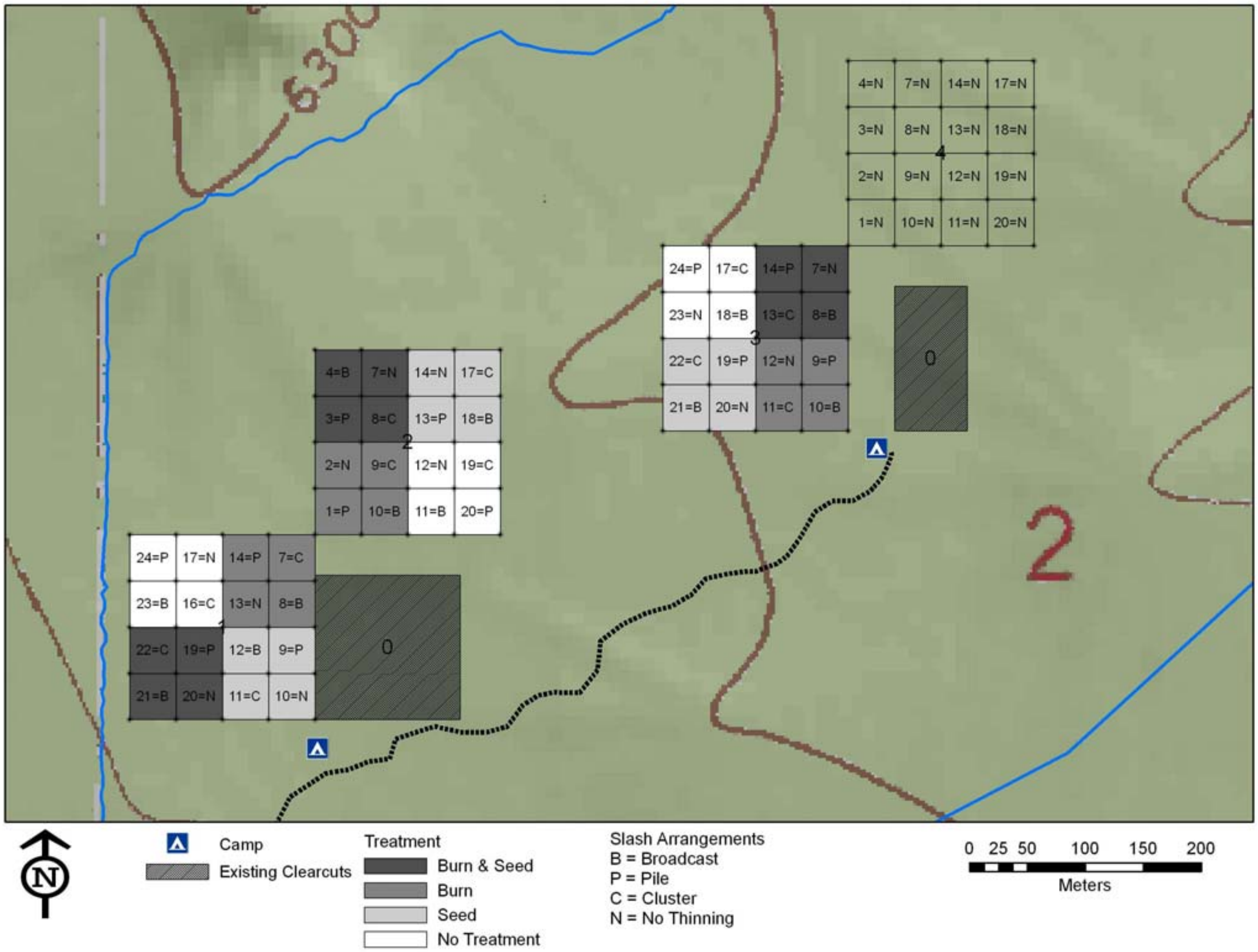
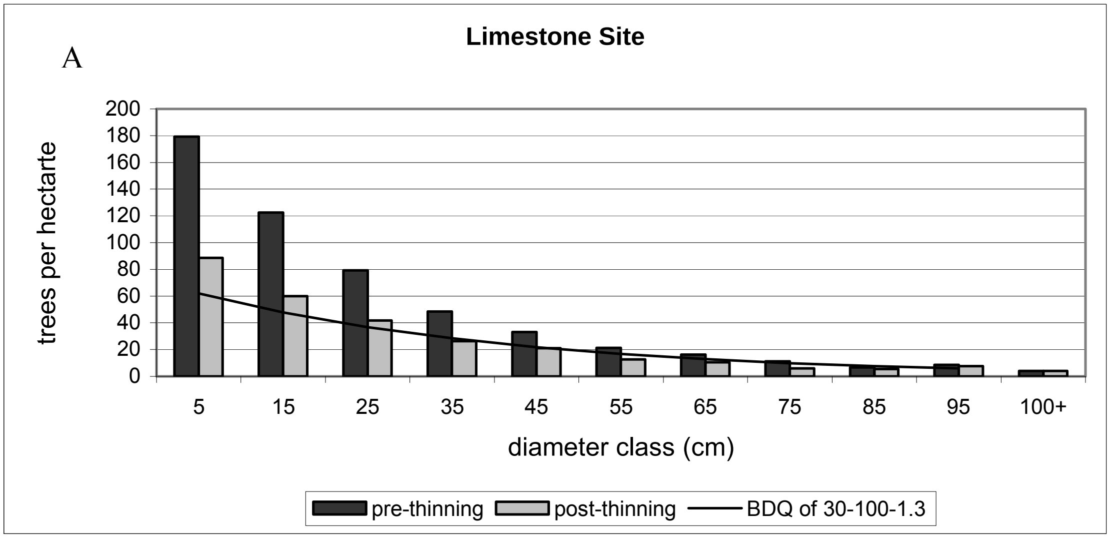


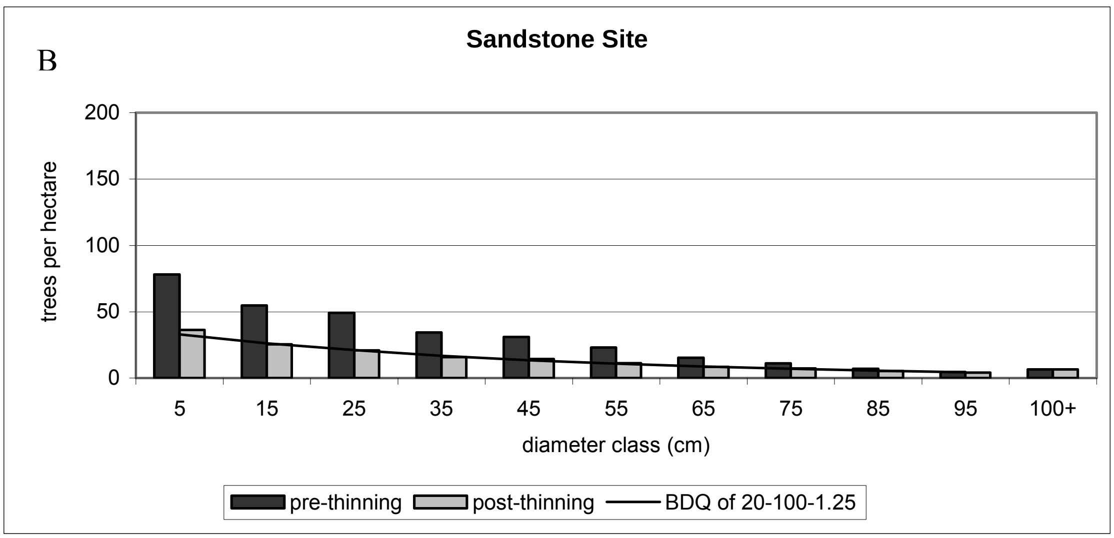
Figure 2. This split-plot experimental design was replicated at the limestone site, the sandstone site, and the basalt site in the pinyon-juniper woodlands of northern Arizona. This experimental design was used to test the interaction of slash arrangements, burning, and seeding on understory response. The letters indicate the slash arrangement, the grey shade indicates the treatment, and the numbers are a plot naming system. The "0" areas were clearcuts created by Landis and Bailey (2005) to recreate 1860 forest structure.

Figure 3. Four slash arrangements, clockwise from the upper left: pile, cluster, broadcast, and no thinning plots.

Figure 4. Pyrometer created with heat sensitive paint. The paint strips were arranged by temperature with the highest temperature closest to the bend in the metal. The pyrometer was covered with the strip of metal shown in the picture, attached with two small paperclips, and then pushed flush into the ground before the prescribed burn.

C°	color
760	dark orange
621	lightest green
538	peach
427	light green
343	light orange
288	pearly white
253	yellow
218	true blue
184	white
177	light blue
79	metallic blue


A
Limestone Site
trees per hectarte
200
180
160
140
120
100
80
60
40
20
0
5
15
25
35
45
55
65
75
85
95
100+
diameter class (cm)
pre-thinning
post-thinning
BDQ of 30-100-1.3


B
Sandstone Site
trees per hectare
200
150
100
50
0
5
15
25
35
45
55
65
75
85
95
100+
diameter class (cm)
pre-thinning
post-thinning
BDQ of 20-100-1.25

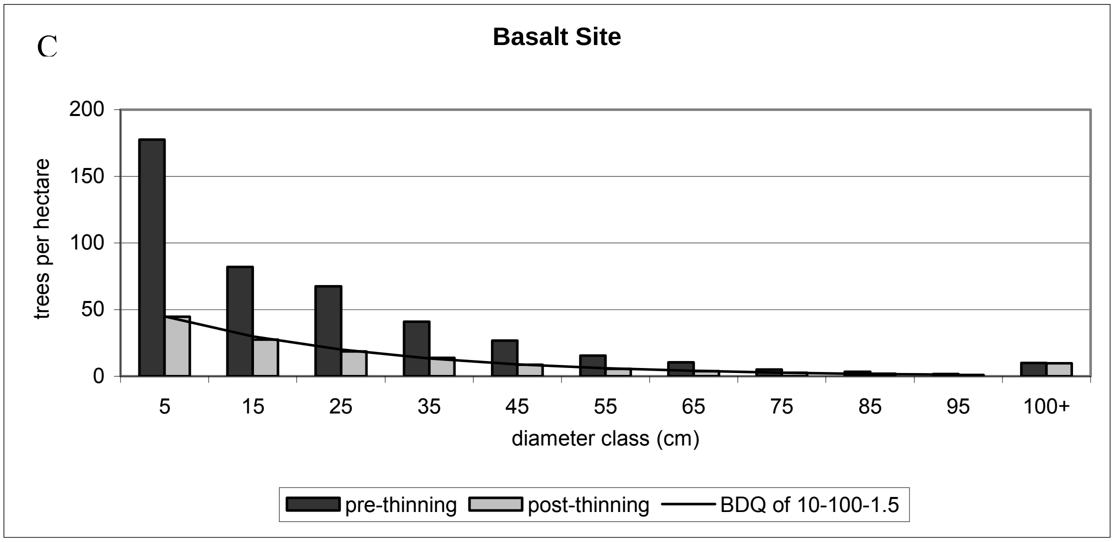


Figure 5. Stand structure before and after thinning in the pinyon-juniper woodlands of northern Arizona the limestone site (5A), the sandstone site (5B), and the basalt site (5C). An 1860 BDQ thinning prescription was implemented at each site in 2005.

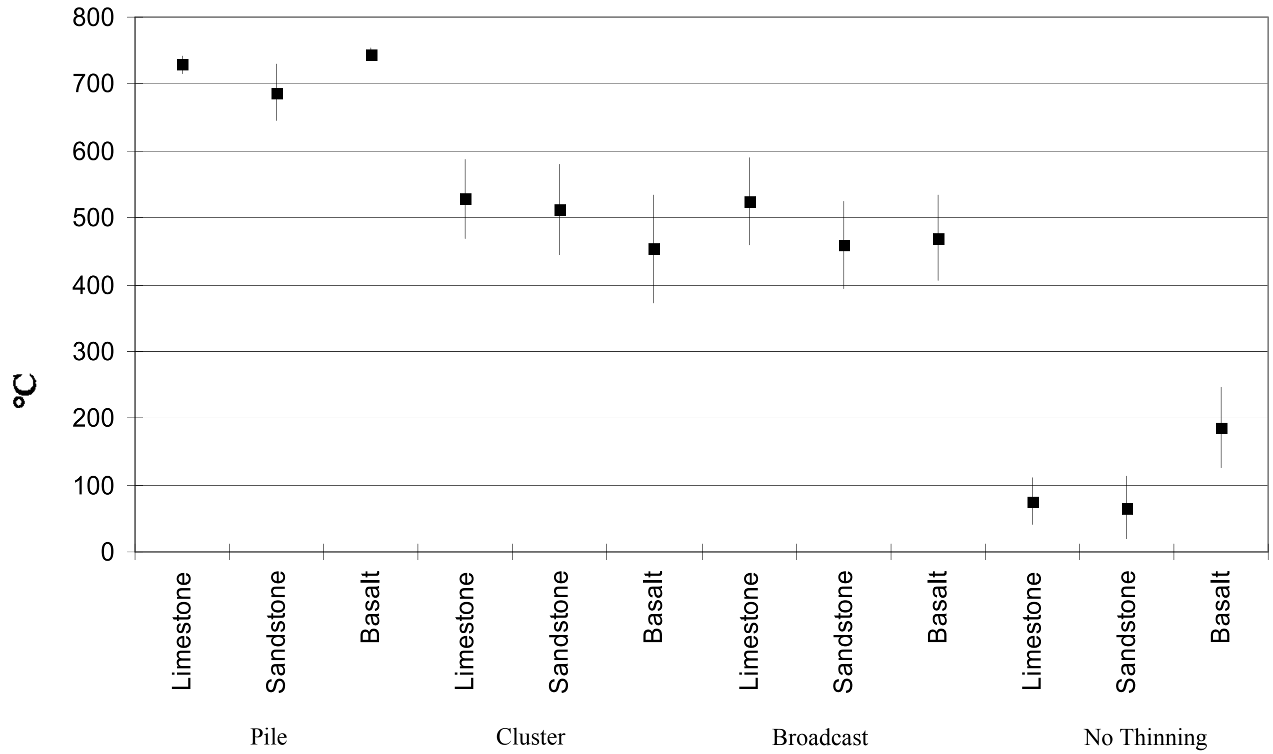


Figure 6. Pyrometer readings for each slash arrangement, by site, in the pinyon-juniper woodlands of northern Arizona. Data are expressed as means (n = 18) +/- SE.

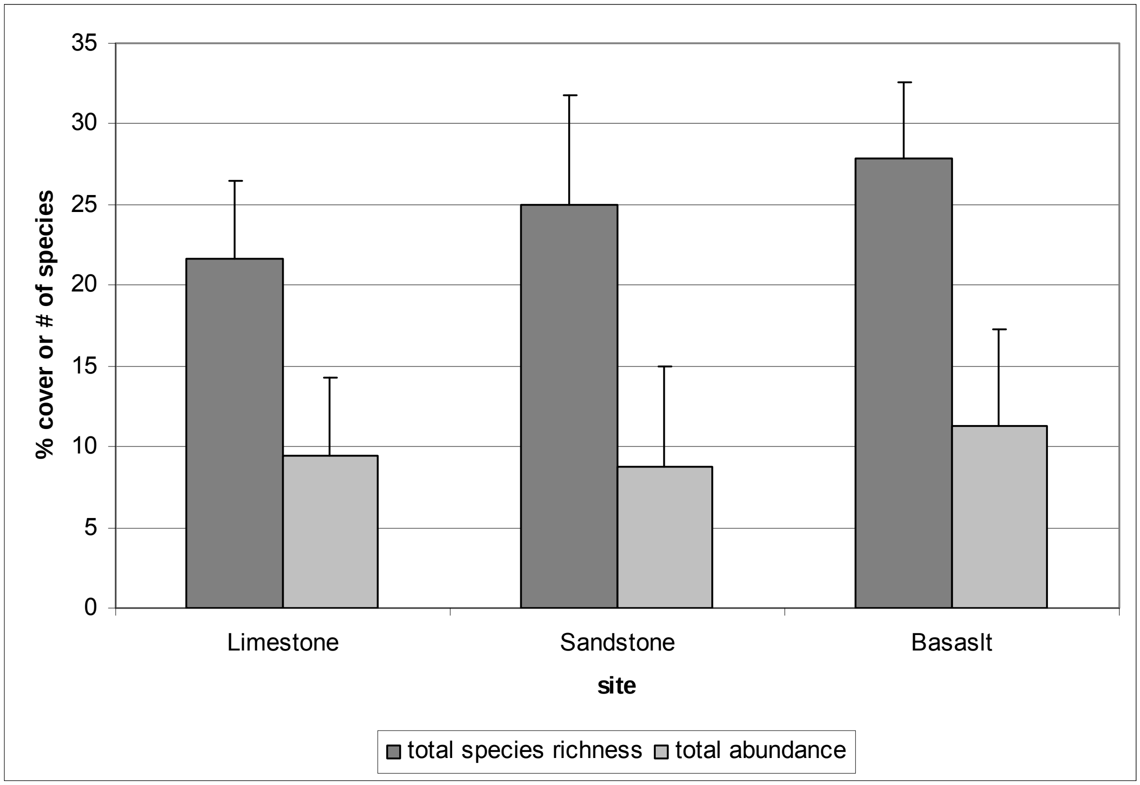
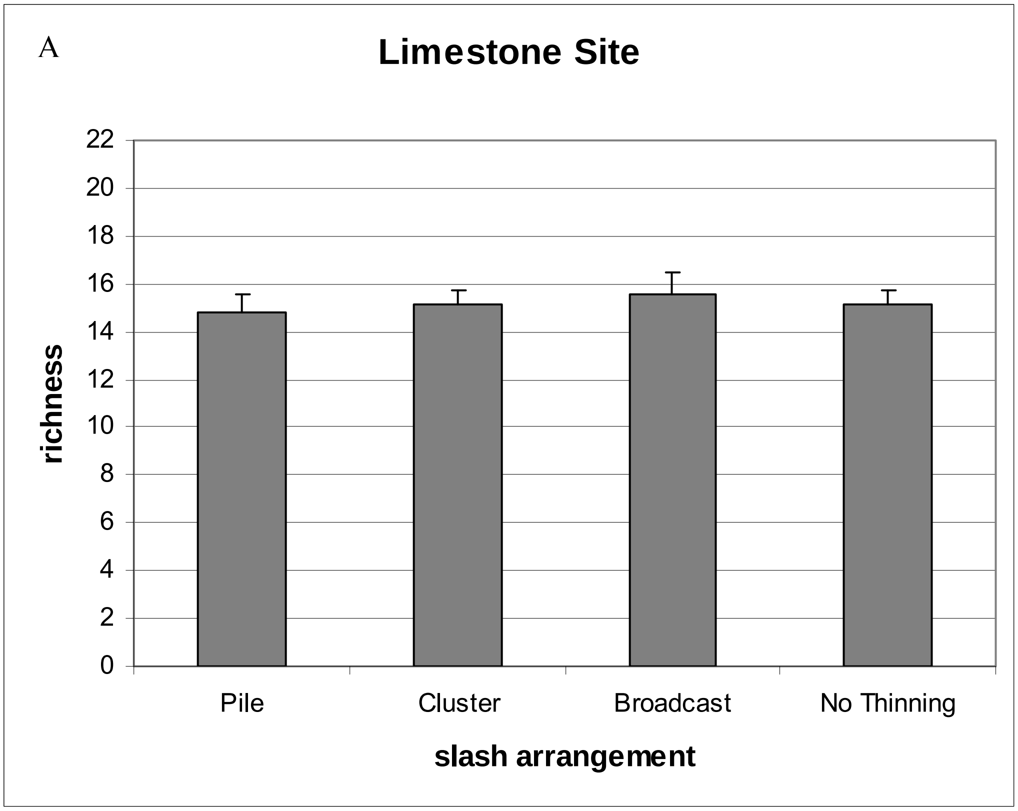
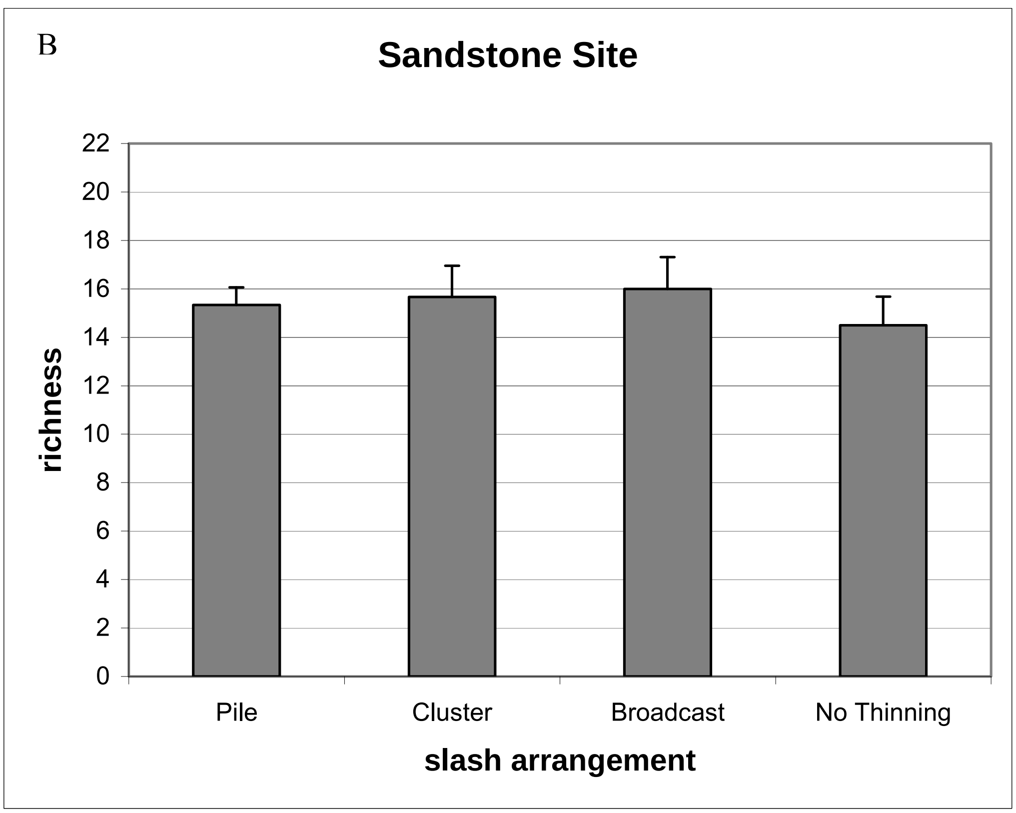


Figure 7. Background differences in understory richness and abundance between the three research sites, in 2005, in the pinyon-juniper woodlands of northern Arizona. The basalt site had the greatest richness and abundance of all three stands. Data are expressed as means (n = 64) +/- SE.


A
Limestone Site
richness
22
20
18
16
14
12
10
8
6
4
2
0
Pile
Cluster
Broadcast
No Thinning
slash arrangement


B
Sandstone Site
richness
22
20
18
16
14
12
10
8
6
4
2
0
Pile
Cluster
Broadcast
No Thinning
slash arrangement

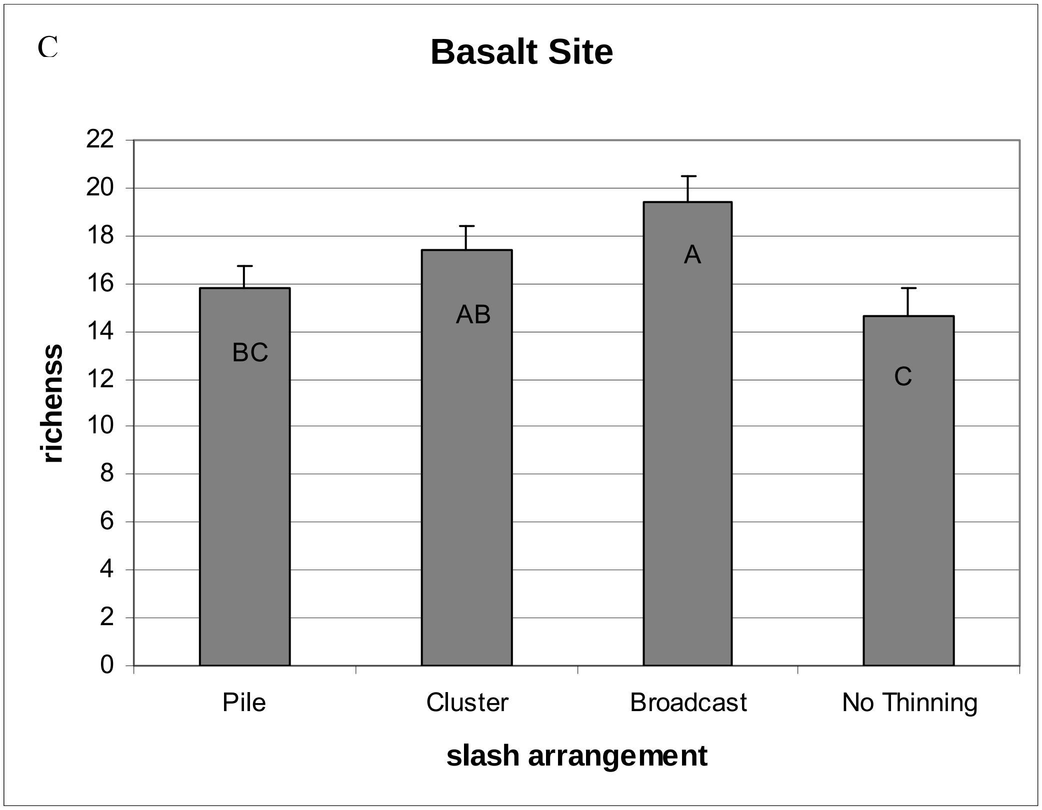


Figure 8. The A) limestone site, B) the sandstone site, C) the basalt site richness responses to different slash arrangements. The basalt site was the only site that showed slash arrangement to significantly influence resulting understory richness in the pinyon-juniper woodlands of northern Arizona. Data are expressed as means (n = 12) +/- SE. Values indexed by different letters are significantly different at $p \leq 0.05$ as determined by Tukey's HSD test between different slash arrangements.

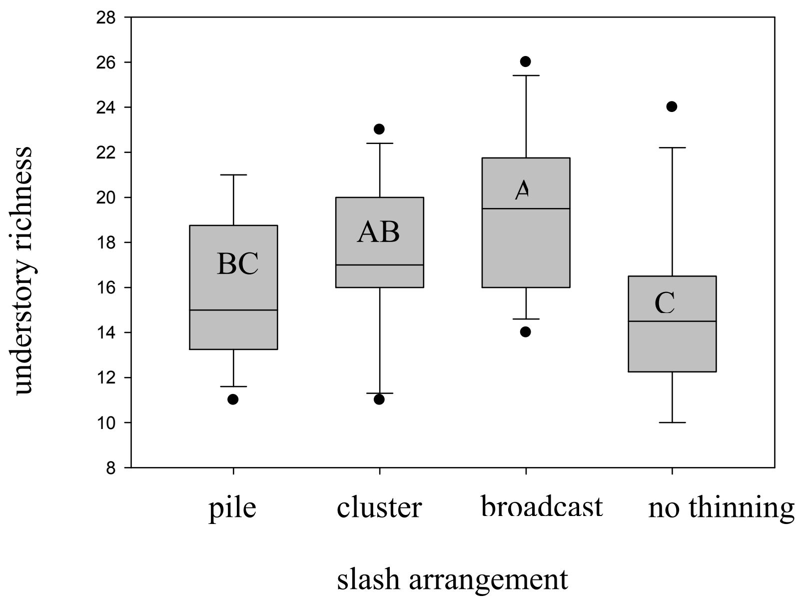
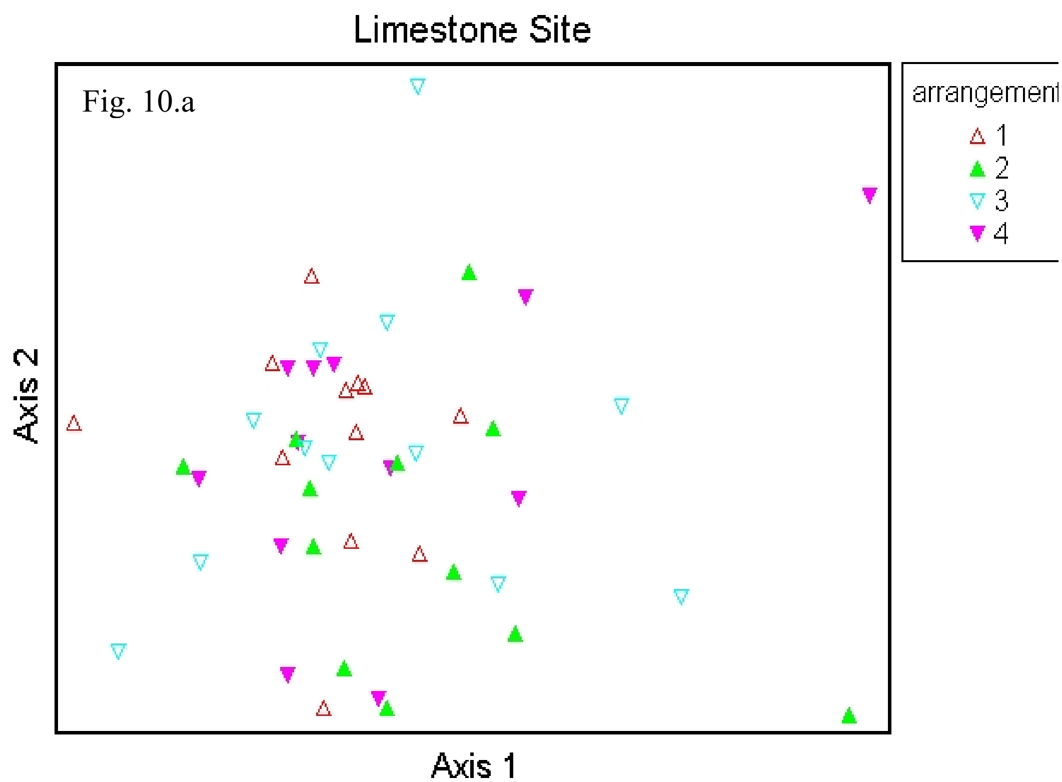
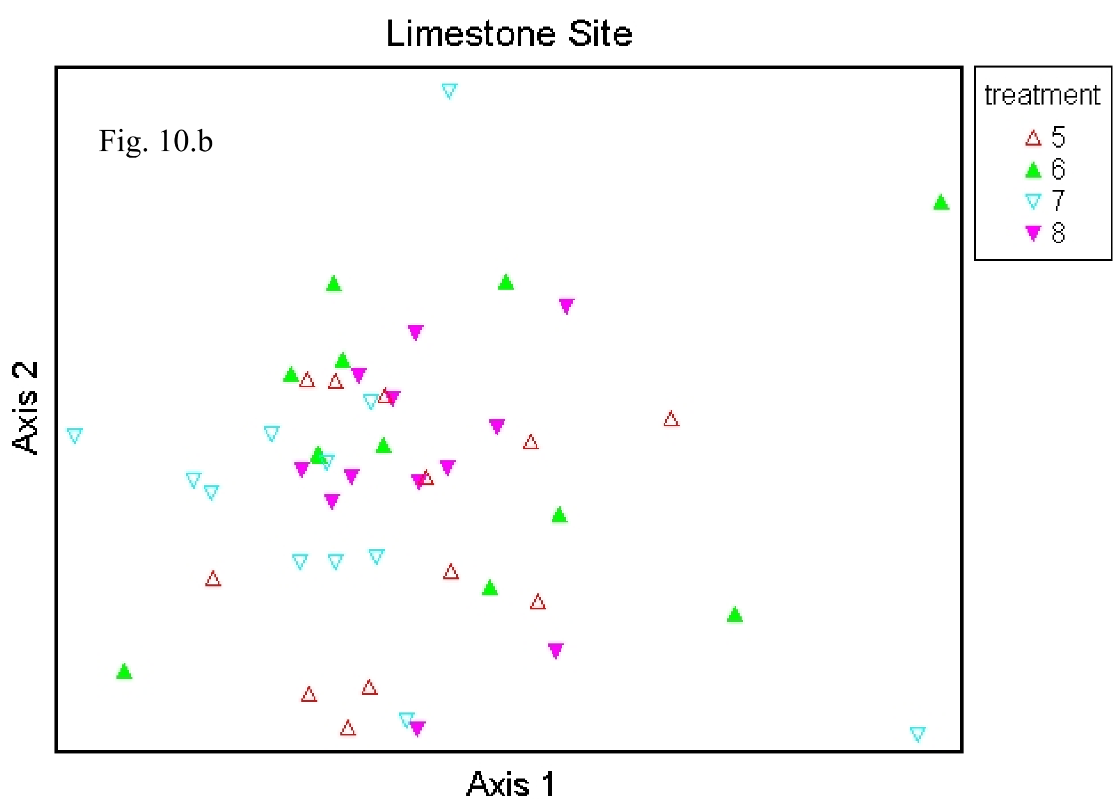


Figure 9. The more spread out the slash was, the greater resulting understory richness response at the basalt site in 2006 in the pinyon-juniper woodlands of northern Arizona. Data are expressed as means (n = 12) +/- SE. Values indexed by different letters are significantly different at $p \leq 0.05$ as determined by Tukey's HSD test between different slash arrangements. The box displays the upper 75th percentile of the data to the lower 25th percentile of the data, with a line going across the box marking the median in the data set. Error bars display the standard error and the dots show outliers.


Limestone Site
Fig. 10.a
arrangement
1
2
3
4
Axis 2
Axis 1


Limestone Site
Fig. 10.b
treatment
5
6
7
8
Axis 2
Axis 1

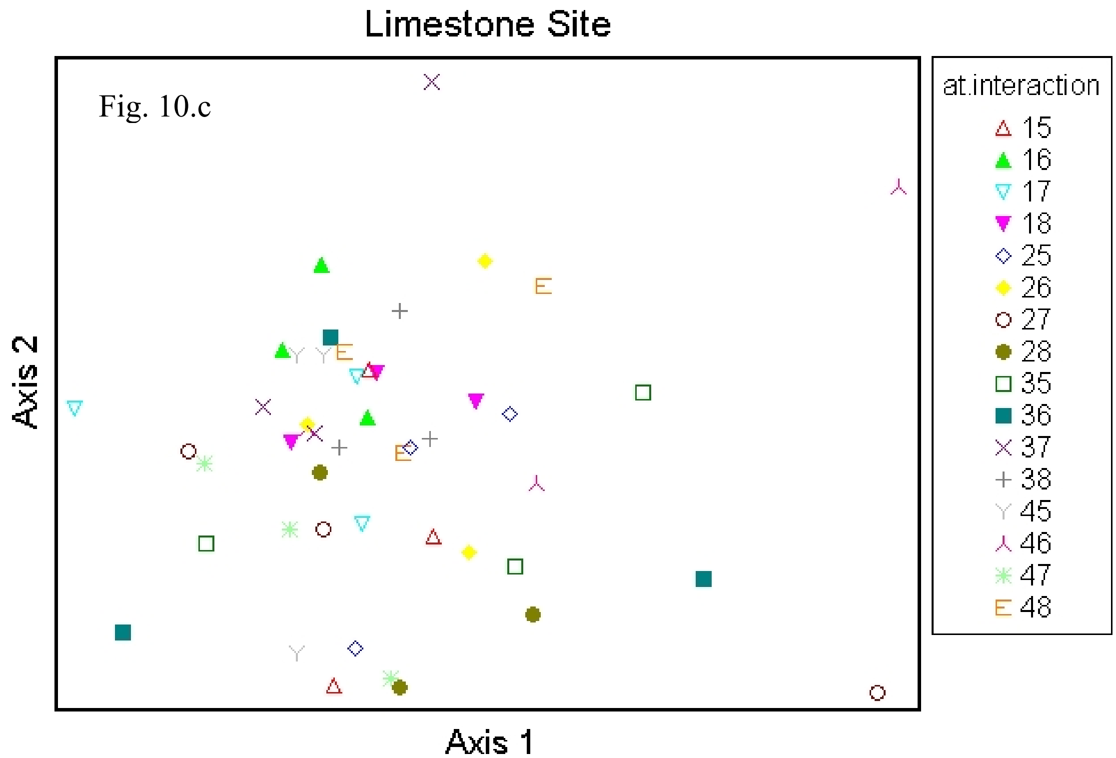
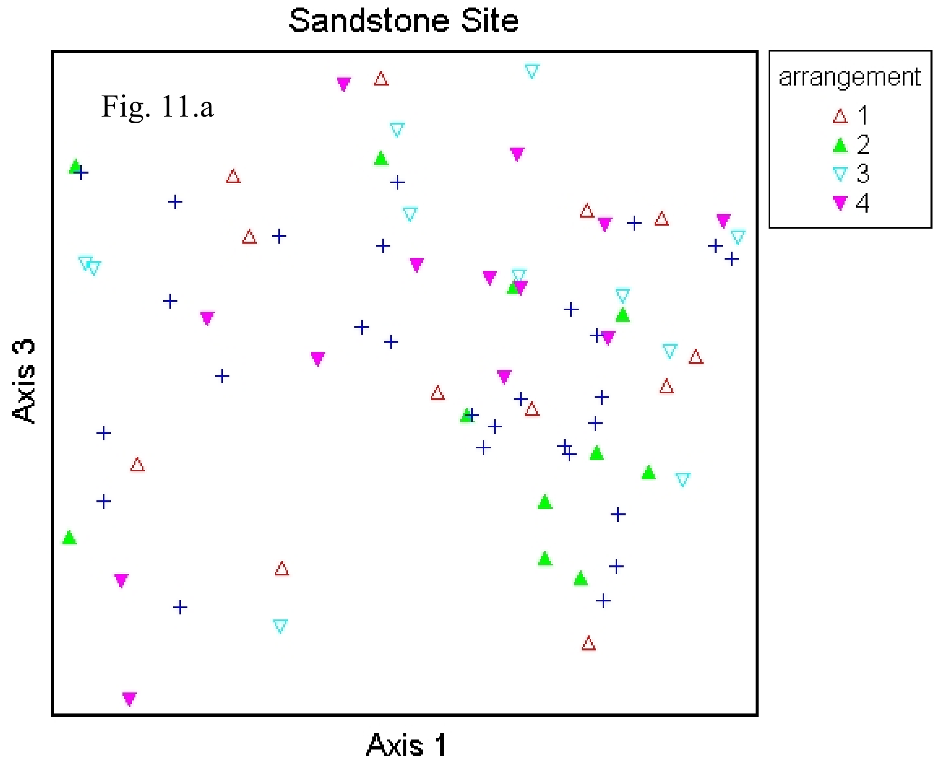
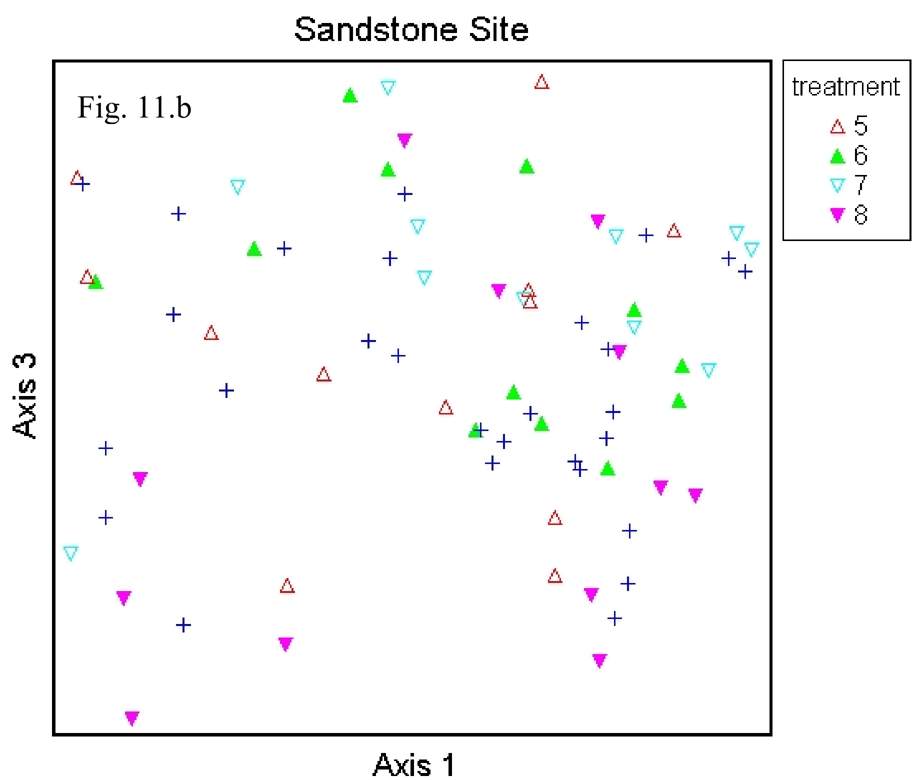


Figure 10. Ordination of the abundance plant community data at the limestone site in 2006, determined with nonmetric multidimensional scaling (NMDS) for a) slash arrangements, b) treatments, and c) slash arrangement and treatment interactions. Distance groupings of plant communities were not found due to a) slash arrangements, b) treatments, or c) slash arrangement and treatment interactions.

Each symbol represents a unique plant community for a specific plot at the limestone site (Table 12). Plant communities that are more similar are found closer together, and plant communities that are more dissimilar are further apart. Plant community data were revitalized to the maximum before analysis to omit noise created by very rare species (occurred on <5% of the plots) and NMDS autopilot mode was used to select the appropriate dimensionality in the final analysis.

NMDS result	Limestone Site
final stress for 3-dimensional solution	19.6006
final instability	0.0004
number of iterations	200
p-value	0.0392


Sandstone Site
Fig. 11.a
arrangement
1
2
3
4
Axis 3
Axis 1


Sandstone Site
Fig. 11.b
treatment
5
6
7
8
Axis 3
Axis 1

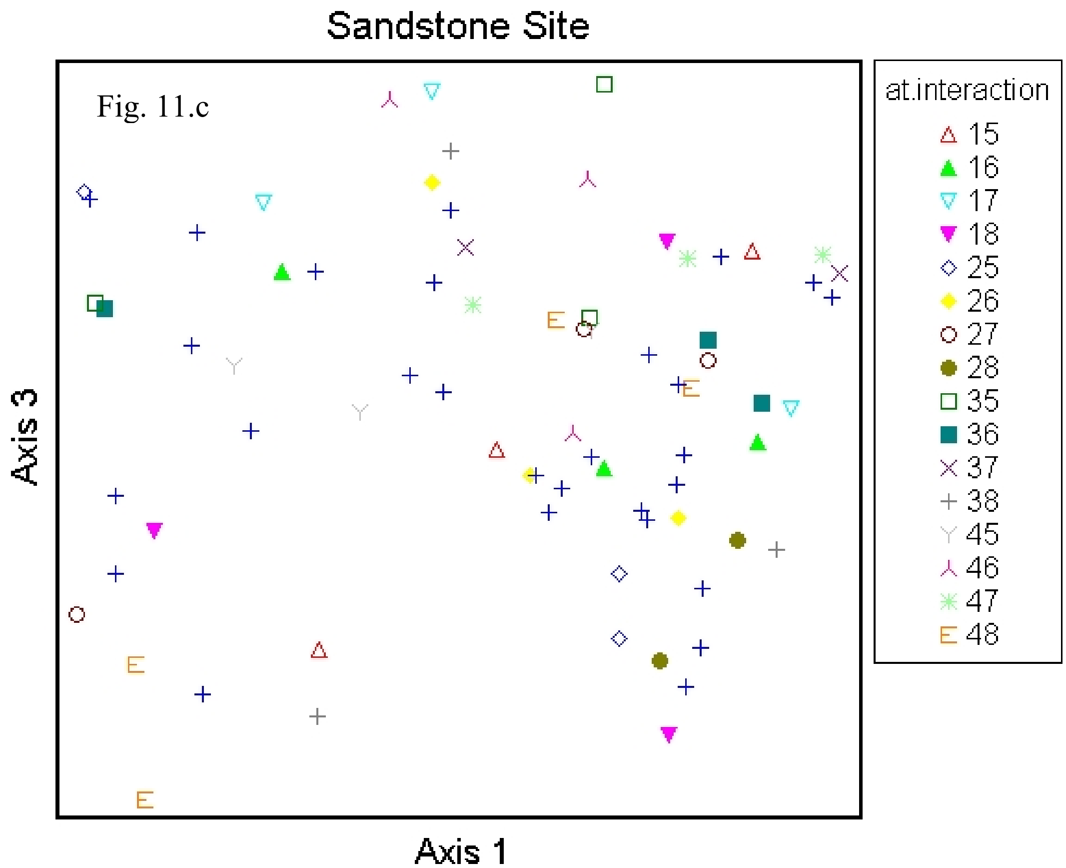


Figure 11. Ordination of the abundance plant community data at the sandstone site in 2006, determined with nonmetric multidimensional scaling (NMDS) for a) slash arrangements, b) treatments, and c) slash arrangement and treatment interactions. Distance groupings of plant communities were not found due to a) slash arrangements, b) treatments, or c) slash arrangement and treatment interactions.

Each symbol represents a unique plant community for a specific plot at the sandstone site (Table 12). Plant communities that are more similar are found closer together, and plant communities that are more dissimilar are further apart. Plant community data were revitalized to the maximum before analysis to omit noise created by very rare species (occurred on <5% of the plots) and NMDS autopilot mode was used to select the appropriate dimensionality in the final analysis.

NMDS result	Sandstone Site
final stress for 3-dimensional solution	19.01615
final instability	0.00033
number of iterations	200
p-value	0.0196

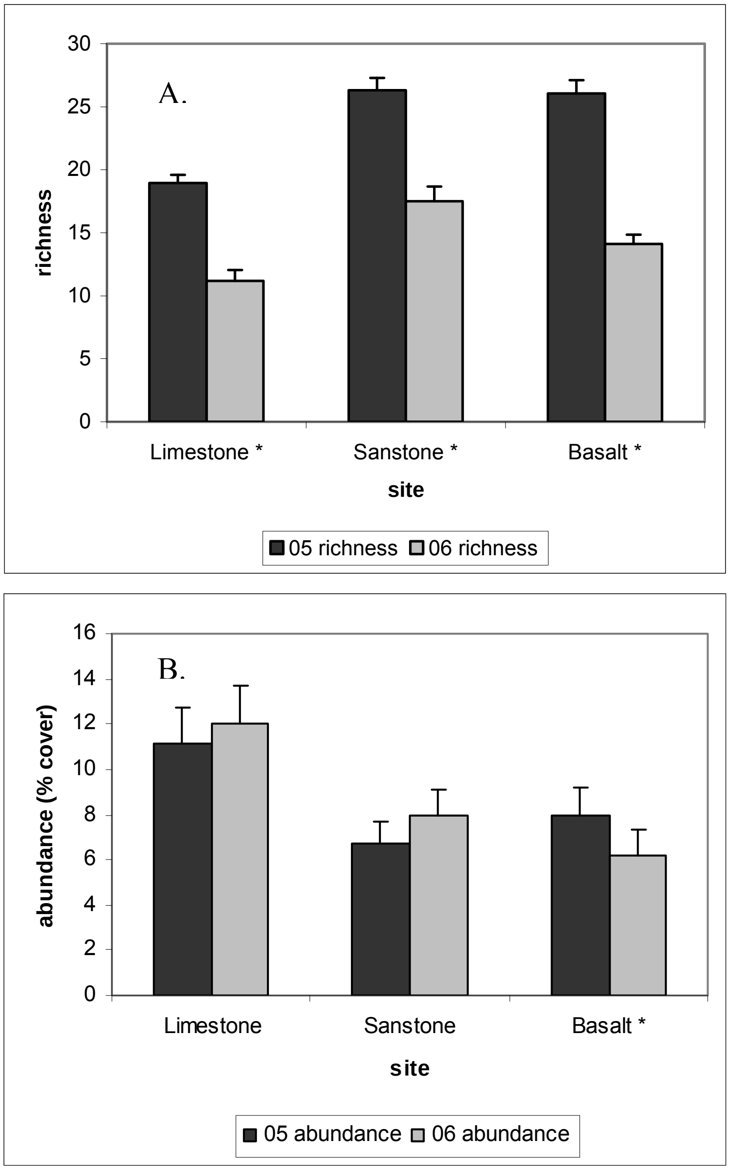


Figure 12. Differences in understory plant A) richness and B) abundance between the wet year of 2005 and the dry year of 2006 in the control plots at each site in the pinyon-juniper woodlands of northern Arizona. An asterisk after site names indicate significant differences in the understory at the α=0.05 level. Data are expressed as means (n = 16) +/- SE. Species richness decreased 40% at the limestone site, 33% at the sandstone site, and 45% at the basalt site from 2005 to 2006 in the control plots.

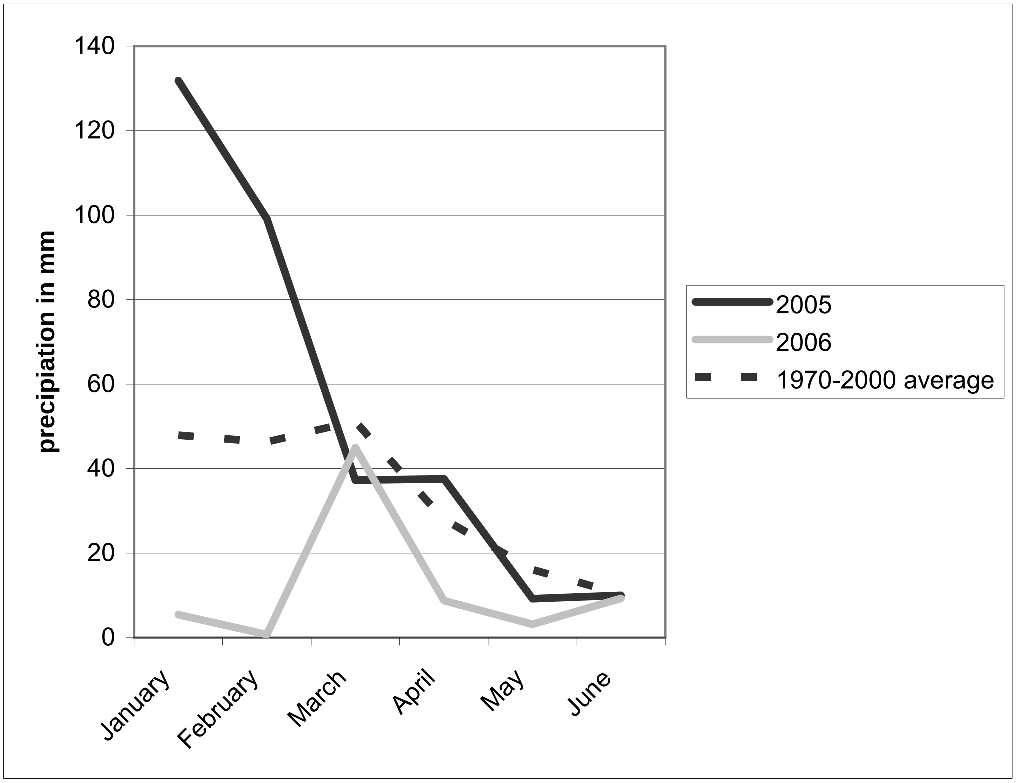


Figure 13. 2006 was the driest January-May period in the last 33 years, whereas this period in 2005 was wetter than 85% of the last 33 years. Since there are no weather stations close to our research sites in the pinyon-juniper woodlands of northern Arizona, we averaged the closest weather stations (Happy Jack, Fort Valley and Winslow) going back as far as possible, which was only 33 years. This data excludes 2001, 2002, 2003, and 2004 because of unreliable weather records from one of the weather stations. Precipitation data was gathered from the Western Regional Climate Center (http://www.wrcc.dri.edu).

Appendix A

Appendix A lists the 115 understory species found, from most common to least common occurrence, in the pinyon-juniper woodlands of northern Arizona.

Percentage of the time that a species was found on the (L) limestone site, (S) sandstone site, (B) basalt site								
			2005			2006		
Family	**Scientific Name**	**Common Name**	**L**	**S**	**B**	**L**	**S**	**B**
Poaceae	Bouteloua gracilis	blue gramma	100	88	100	100	89	97
Asteraceae	Gutierrezia sarothrae	broom snakeweed	97	95	94	100	100	81
Poaceae	Elymus elymoides	squirrel-tail	97	98	100	69	92	91
Cactaceae	Opuntia sp.	prickly pear	56	59	97	48	48	100
Asteraceae	Chaetopappa ericoides	rose heath	92	92	31	88	78	25
Euphorbiaceae	Chamaesyce sp.	sandmat	100	80	61	73	58	20
Brassicaceae	Descurainia sp.	tansymustard	100	100	52	8	27	0
Brassicaceae	Lesquerella intermedia	mid bladderpod	89	58	14	69	47	11
Malavaceae	Sphaeralcea parvifolia	sore eye, mallow	47	88	11	33	88	13
Polygonaceae	Eriogonum jamesii	James' buckwheat	86	44	2	92	38	2
Poaceae	Pleuraphis jamesii	James' galleta	41	67	11	22	77	11
Scrophhulariaceae	Penstemon thompsoniae	Thompson's beardstongue	75	48	3	55	39	6
Cactaceae	Opuntia whipplei	rat-tail cholla	6	38	77	3	23	70
Poaceae	Poa fendleriana	muttongrass	13	19	94	5	9	66
Poaceae	Piptatherum micranthum	smilograss	17	8	78	20	9	67
Oleaceae	Menodora scabra	rough menodora	3	36	66	5	33	56
Brassicaceae	Arabis fendleri	rockcress	33	38	94	0	8	25
Ephedraceae	Ephedra sp.	mormon tea	59	38	0	50	47	0
Asteraceae	Hymenopappus filifolius	fineleaf hymnopappus	17	17	83	16	9	48
Polygonaceae	Eriogonum unbellatum	sulphur wildbuckwheat	0	2	98	0	0	91
Asteraceae	Heliomeris longifloria	showy goldeneye	5	47	84	0	20	33
Scrophhulariaceae	Penstemon linarioides	toadflax penstemon	0	16	98	0	0	75
Polygonaceae	Eriogonum ericifolium	Yavapai County buckwheat	52	55	25	23	17	11
Berberidaceae	Mahonia fremontii	fremont's mahonia	41	19	23	39	28	25

Percentage of the time that a species was found on the (L) limestone site, (S) sandstone site, (B) basalt site

			2005			2006		
Family	**Scientific Name**	**Common Name**	**L**	**S**	**B**	**L**	**S**	**B**
Boraginaceae	Cryptantha cinerea	James' crypthana	67	23	0	56	27	0
Fabaceae	Lupine kingii	King's lupine	17	52	100	0	0	2
Boraginaceae	Lappula occidentalis	stickseed	30	89	31	0	16	0
Cactaceae	Escobaria vivipara	spinystar	5	5	72	2	0	75
Brassicaceae	Tetraneuris acaulis	four nerve daisy	53	28	5	28	20	0
Asteraceae	Townsendia incana	townsend daisy	70	27	0	22	14	0
Chenopodiaceae	Chenopodium album*	lambsquarters*	17	80	16	0	19	0
Scrophhulariaceae	Penstemon ophianthus	James' beardstongue	33	3	25	34	16	13
Poaceae	Aristida purpurea	purple three-awn	42	6	33	27	2	13
Asteraceae	Tetradymia canescens	spineless horsebrush	0	6	0	31	50	30
Polygonaceae	Eriogonum alatum	winged buckwheat	45	9	9	33	8	5
Rosaceae	Purshia mexicana	Mexican cliffrose	28	19	11	23	14	11
Brassicaceae	Draba cuneifolia	wedgeleaf whitlowgrass	34	66	3	0	2	2
Asteraceae	Erigeron divergens	spreaading fleabane	2	5	72	0	5	22
Poaceae	Muhlenbergia wrightii	spike muly	9	0	23	8	6	53
Polygonaceae	Polygonum douglasii	Douglas' knotweed	0	0	97	0	0	0
Asteraceae	Erigeron flagellaris	trailing fleabane	6	0	84	0	0	6
Fabaceae	Astragalus humistratus	groundcover milkvetch	30	2	19	16	13	17
Poaceae	Achnatherum hymenoides	indian ricegrass	3	53	0	3	27	2
Cactaceae	Echinocereus coccineus	scarlet hedgehog	0	22	25	3	20	17
Agavaceae	Yucca baccata	banana yucca	8	0	16	19	28	16
Apiaceae	Lomatium foeniculaceum	biscuitroot	0	3	80	0	0	3
Chenopodiaceae	Salsola tragus*	russian thistle*	5	36	0	9	36	0
Linaceae	Linum aristatum	bristle flax	33	0	28	5	0	16
Nyctaginaceae	Mirabilis multiflora	Colorado four'o'clock	19	42	11	0	8	2
Brassicaceae	Lepidium densiflorum	common pepperweed	34	39	3	0	0	0
Polemoniaceae	Gilia opthalmoides	eyed gilia	20	44	3	0	2	0
Orobanchaceae	Orobanche fasciculata	ghost plant	0	2	56	0	0	0
Fabaceae	Desmanthus cooleyi	Cooley's bundleflower	0	0	39	0	0	16

Percentage of the time that a species was found on the (L) limestone site, (S) sandstone site, (B) basalt site

Family	Scientific Name	Common Name	2005			2006		
			L	S	B	L	S	B
Polemoniaceae	Phlox longifolia	longleaf phlox	5	25	13	3	3	6
Loasaceae	Mentzelia montana	variegated-bract blazingstar	8	39	8	0	0	0
Liliaceae	Calochortus ambiguus	doubting Mariposa-lily	2	11	41	0	0	0
Polygonaceae	Eriogonum racemosum	redroot buckwheat	0	0	28	0	0	25
Polemoniaceae	Phlox gracilis	slender phlox	0	0	45	0	0	0
Asteraceae	Packera neomexicana	New Mexico groundsel	2	0	39	0	0	3
Asteraceae	Malacothrix torreyi	Torrey's desertdandelion	6	36	2	0	0	0
Polygonaceae	Eriogonum divaricatum	divergent buckwheat	0	20	0	0	22	0
Asteraceae	Machaeranthera grindelioides	rayless tansyaster	0	22	0	0	19	0
Poaceae	Elymus trachycaulus	slender wheatgrass	0	19	0	0	14	8
Poaceae	Koeleria macrantha	prairie Junegrass	0	0	33	0	0	6
Agavaceae	Yucca angustissima	narrowleaf yucca	9	13	0	6	9	0
Solanaceae	Chamaesaracha coronopus	greenleaf five eyes	5	23	0	0	5	0
Lamiaceae	Marrubium vulgare*	horehound*	11	8	3	2	9	0
Agavaceae	Yucca sp.	yucca sp.	13	19	2	0	0	0
Chenopodiaceae	Krascheninnikovia lanata	winterfat	0	9	5	0	17	0
Chenopodiaceae	Atriplex canescens	4-winged saltbrush	0	16	0	0	14	0
Fabaceae	Astragalus mollissimus	wolly locoweed	0	0	23	0	0	6
Poaceae	Bromus tectorum*	cheat grass*	3	13	11	0	0	0
Polygonaceae	Eriogonum deflexum	flatcrown buckwheat	3	23	0	0	0	0
Asteraceae	Hymenoxys richardsonii	pingue rubberweed	6	2	2	6	0	9
Geraniaceae	Erodium cicutarium*	redstem stork's bill*	2	20	2	0	0	0
Chenopodiaceae	Lycium pallidum	Desert-thorn	0	11	5	0	5	2
Nyctaginaceae	Mirabilis linearis	narrowleaf four'o'clock	3	14	5	0	0	0
Brassicaceae	Sisymbrium altissimum*	tall tumblemustard*	3	19	0	0	0	0
Asteraceae	Tragopogon dubius*	yellow salsify*	13	3	6	0	0	0
Poaceae	Hesperostipa comata	needle and thread grass	9	8	0	2	0	0
Asteraceae	Lactuca sp.*	wild lettuce*	5	13	2	0	0	0
Asteraceae	Bahia dissecta	ragleaf bahia	2	0	11	2	0	3

Percentage of the time that a species was found on the (L) limestone site, (S) sandstone site, (B) basalt site

			2005			2006		
Family	**Scientific Name**	**Common Name**	**L**	**S**	**B**	**L**	**S**	**B**
Anacardiaceae	Rhus trilobata	squaw bush	6	0	3	5	0	3
Asteraceae	Zinnia grandiflora	Rocky mountain zinnia	8	0	3	3	2	0
Asteraceae	Artemisia ludoviciana	white sagebrush	0	2	11	0	0	0
Fabaceae	Psoralidium tenuiflorum	slimflower scurfpea	0	0	9	0	0	2
Scrophhulariaceae	Castilleja integra	wholeleaf indian paintbrush	0	2	8	0	0	0
Asteraceae	Krigia biflora	two-flower dwarf-dandelion	0	0	8	0	0	0
Asteraceae	Cirsium wheeleri	Wheeler's thistle	3	2	3	0	0	0
Asteraceae	Artemisia tridentata	big sagebrush	0	5	0	0	2	0
Fagaceae	Quercus gambelii	Gambel oak	3	3	0	0	0	0
Lamiaceae	Salvia reflexa	lance-leaf sage	0	2	0	0	5	0
Asteraceae	Hymenopappus mexicanus	Mexican woollywhite	0	0	0	0	0	6
Poaceae	Bromus rubens*	red brome*	0	6	0	0	0	0
Scrophhulariaceae	Penstemon barbatus	beardlip penstemon	0	0	0	0	5	0
Rosaceae	Chamaebatiaria millefolium	fernbrush	2	0	0	3	0	0
Asteraceae	Artemisia frigida	fringed sagewort	2	0	0	2	0	2
Orobanchaceae	Orobanche ludoviciana	Lousiana broomrape	3	0	2	0	0	0
Asteraceae	Erigeron concinnus	Navajo fleabane	0	0	0	5	0	0
Cactaceae	Opuntia fragilis	brittle pricklypear	0	0	2	0	0	2
Poaceae	Bromus japonicus*	Japanese brome	0	3	0	0	0	0
Brassicaceae	Streptanthella longirostris	longbeak streptanthella	0	3	0	0	0	0
Cactaceae	Echinocereus fendleri	pinkflower hedgehog cactus	0	0	3	0	0	0
Asteraceae	Ericameria nauseosa	rubber rabbitbrush	0	0	0	0	3	0
Asclepiadaceae	Asclepias asperula	spider milkweed	2	0	2	0	0	0
Grossulariaceae	Ribes cereum	wax currant	0	0	2	0	0	2
Asclepiadaceae	Asclepias subverticillata	whorled milkweed	0	0	0	0	2	2
Onagraceae	Oenothera flava	yellow evening-primrose	2	0	2	0	0	0
Lamiaceae	Dracocephalum parviflorum	American dragonhead	0	2	0	0	0	0
Verbenaceae	Verbascum thapsus*	common mullen*	2	0	0	0	0	0
Asteraceae	Verbesina encelioides	golden crownbeard	0	2	0	0	0	0

Percentage of the time that a species was found on the (L) limestone site, (S) sandstone site, (B) basalt site

			2005			2006		
Family	**Scientific Name**	**Common Name**	**L**	**S**	**B**	**L**	**S**	**B**
Asteraceae	Psilostrophe sparsiflora	greenstem paperflower	0	2	0	0	0	0
Chenopodiaceae	Chenopodium leptophyllum	narrowleaf goosefoot	2	0	0	0	0	0
Linaceae	Linum lewisii	prairie flax	0	0	2	0	0	0
Asteraceae	Ericameria nauseosa	rubber rabbitbrush	0	0	0	2	0	0

N=115 total species found, * indicates a non-native species

CHAPTER 3

The Clearcut Case Study

INTRODUCTION

The inverse relationship between overstory tree and understory plant cover in pinyon-juniper woodlands has been well documented (Parker 1945, Pieper 1990, Tausch and West 1995, White *et al.* 1997). On Anderson Mesa, in northern Arizona, many hectares of pinyon and juniper trees have been cut down or chained to create a more abundant understory plant community for livestock and wildlife (Jack Metzger, personal communication). We wanted to see if the understory in clearcut areas near this thesis project (chapter 2) responded with greater richness and abundance than the understory in the surrounding uncut woodlands.

In 2002 Landis and Bailey (2005) created two clearcut areas at each of the three research sites (Fig. 1 and Fig. 2) used in the thesis experiment. One was 125 x 125 m and the other was 125 m x 62.5 m. Each tree was stem mapped and a cross section of the base of the tree was removed for the dendrochronology study (Landis and Bailey 2005). The rest of the tree was cut into meter sections and left in the newly created clearcut area. In the fall of 2004 we removed all of the wood greater than 7 cm in diameter from the clearcuts, to simulate firewood harvesting.

We used these clearcut areas as a case study to examine three year vegetation response to clearcutting. We hypothesized that the understory in the clearcut areas would have greater richness and abundance than the understory in the surrounding uncut woodlands. We also hypothesized that burning would reduce plant richness and abundance one year after the burn.

METHODS

In 2005, we created twelve 40 x 40 m plots inside the clearcut areas at each of the three sites (9 plots in the 125 x 125 m clearcut and 3 plots within the 62.5 x 125 m clearcut). In June of 2005 we measured the understory vegetation, using the same modified modified Whittaker technique as we did in the thesis experiment (chapter 2). We wanted to see if the plots in the clearcut areas had higher understory richness and abundance than the plots we established in the surrounding woodlands (Fig. 2). The plots in the surrounding uncut woodlands were in three groups of 16 plots each. Each of these groupings was called a unit. There were 12 plots in the clearcut areas, which will henceforth be referred to as the clearcut or "CC" unit. We compared the means of the clearcut units to the means units in the uncut woodlands. We calculated the mean and confidence interval for each of the 4 units and the clearcut unit.

In the fall of 2005 we burned 4 of the 12 plots within each clearcut unit at each site. In the summer of 2006 we sampled the post-treatment vegetation response and used a t-test for unequal sample sized to compare the burned and unburned plots within each clearcut unit.

RESULTS

Contrary to our expectations, the clearcut units did not always have the highest richness and abundance compared to the other units in 2005 (Table 1). At the limestone site, the clearcuts had the highest richness and abundance values (Fig. 3 and 4). At the sandstone site, the clearcut unit did not have the highest richness (Fig. 3). The clearcut unit did have the greatest abundance, but not much more than unit 3 (Fig. 4). At the basalt site, the clearcut unit had the greatest richness, but not the greatest abundance (Fig. 3 and 4). These results are summarized in Table 1 and p-values are given in Table 2.

When we compared the burned and unburned plots within the clearcut units, we found burning did not alter plant richness (Fig. 5), but abundance was greater in unburned plots at all sites (Table 2 and Fig. 6). Burning reduced plant abundance by 66% at the limestone site, 57% at the sandstone site, and 31% at the basalt site.

DISCUSSION

This case study suggests that cutting down every tree and leaving the small diameter slash for mulch still does not guarantee greater understory richness and abundance after three years, across three soil types. This was surprising because the vegetation in the clearcuts looked plentiful compared to the vegetation in the surrounding woodlands. Our results are contrary to other research projects that have found removing the trees and leaving the debris to serve as mulch increases the understory cover in pinyon-juniper woodlands (Albert *et al.* 2004, Jacobs and Gatewood 1999, Brockway *et al*. 2002).

Since all three sites were clearcut at the same time, shared the same management history and received above average precipitation during the 2005 growing season, we assume that the differences in vegetation response to clearcutting were due to soil type. The understory at the limestone site responded to the clearcutting with much higher richness and abundance than the vegetation in surrounding uncut woodlands (Fig. 3 and 4). The other two sites did not show that clearcutting increases understory richness or abundance (Fig. 3 and 4). O'Rourke and Ogden (1969) found that certain soil characteristics such as high calcium carbonate levels, high pH, and low phosphorous, were associated with no increase in perennial grass production four to five years after pinyon-juniper elimination in north-central Arizona. Although we did not measure these soil parameters, we also found soil to influence understory response to tree removal (Chapter 2).

We saw that burning decreased understory abundance, but did not affect richness (Chapter 2). Dwyer and Pieper (1969) found that forage production was significantly reduced the first year following a wildfire, but recovered by the end of the season. They also found that species composition of herbaceous vegetation was not significantly affected by the wildfire. Our prescribed fire after clearcutting burned relatively heavy fuels compared to a wildfire in an uncut area. Haskins and Gehring (2004) found that burning slash piles as a management tool in pinyon-juniper woodlands reduces native species richness increases non-native species compared to surrounding unburned plant communities.

Comparing the Thesis and the Clearcut study results

When trying to interpret the thesis study (chapter 2) in light of the clearcut case study (chapter 3), it is important to remember that the clearcut case study was not replicated. However, the vegetation from the clearcut case study had two years to respond and was measured in the wet year of 2005. The thesis study only had one year to respond and was measured in the very dry year of 2006, but was replicated. Also, the clearcut case study has the advantage of being very simple. It only had one thinning prescription and slash arrangement, and was replicated over three soil types. Interpreting the thesis study in light of the clearcut case study does not simplify anything, but brings up some interesting questions, described below.

Tree Removal

The clearcut case study suggests the understory plant community growing on the limestone soil is more responsive to tree removal than the other research sites. However, this soil type was the least responsive to different slash arrangements, burning and seeding in the larger thesis experiment (chapter 2). This discrepancy might be a result of the lack of replication in the clearcut study.

Burning

The clearcut case study showed that burning reduces understory abundance by about half the first year after the burn, given three years for the understory to respond between thinning and burning. Burning was not found to reduce abundance in the larger thesis experiment. This discrepancy may be due to the higher fuel loadings in the clearcut areas or the lack of replication in the clearcut case study.

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Table 1. The understory in the clearcut units did not show consistently greater richness and abundance than the uncut surrounding units at all sites, even in the relatively wet year of 2005.

Site	richness	abundance
Limestone	yes	yes
Sandstone	no	no
Basalt	yes	no

Table 2. P-values for a one-tailed t-test for unequal variances (N=12), comparing burned and unburned plots within the clearcuts in 2006.

Site	richness	abundance
Limestone	0.0565	0.0185
Sandstone	0.02688	0.0165
Basalt	0.6693	0.0117

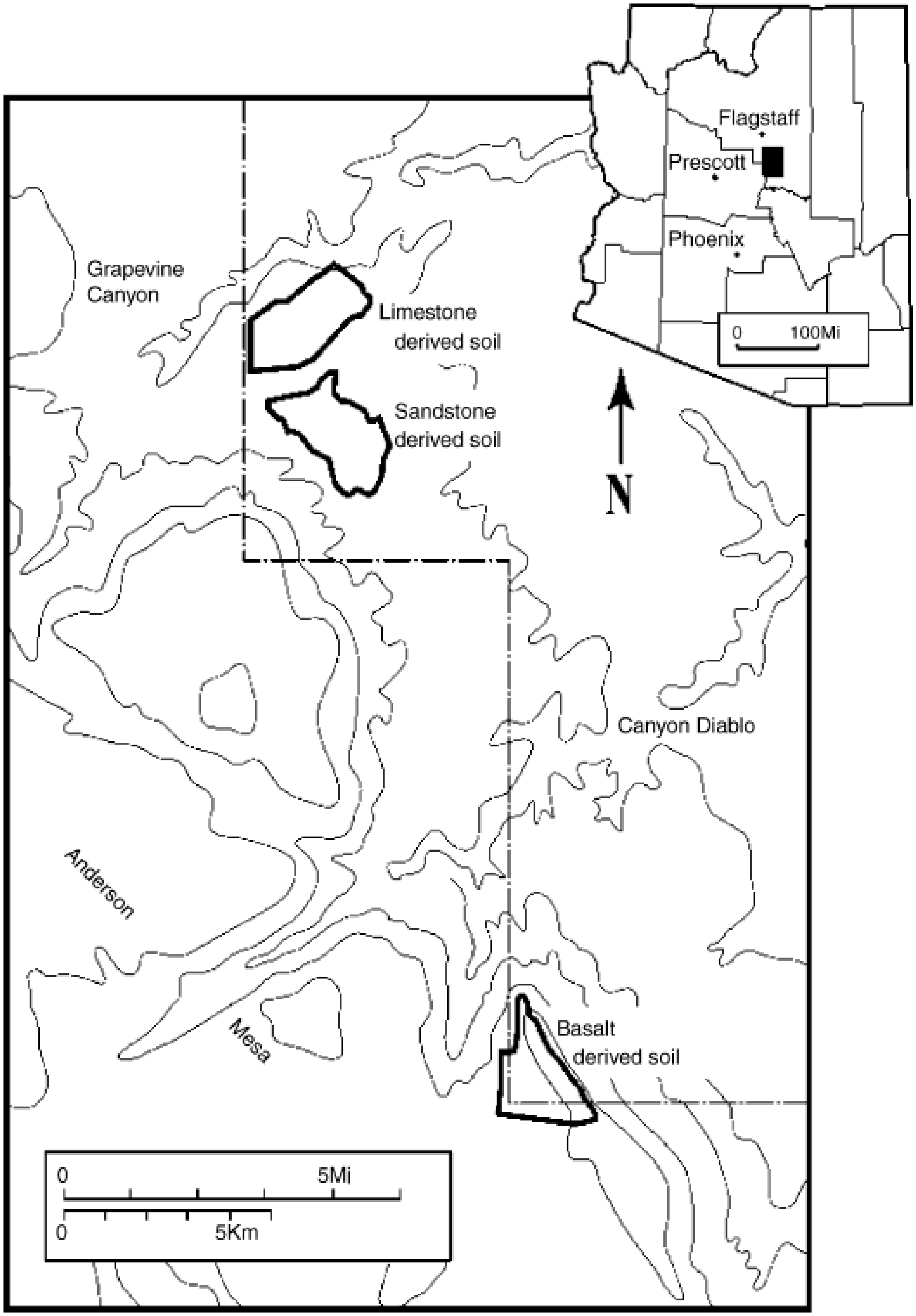


Figure 1. Map of the 3 study sites, 150 km southeast of Flagstaff, AZ

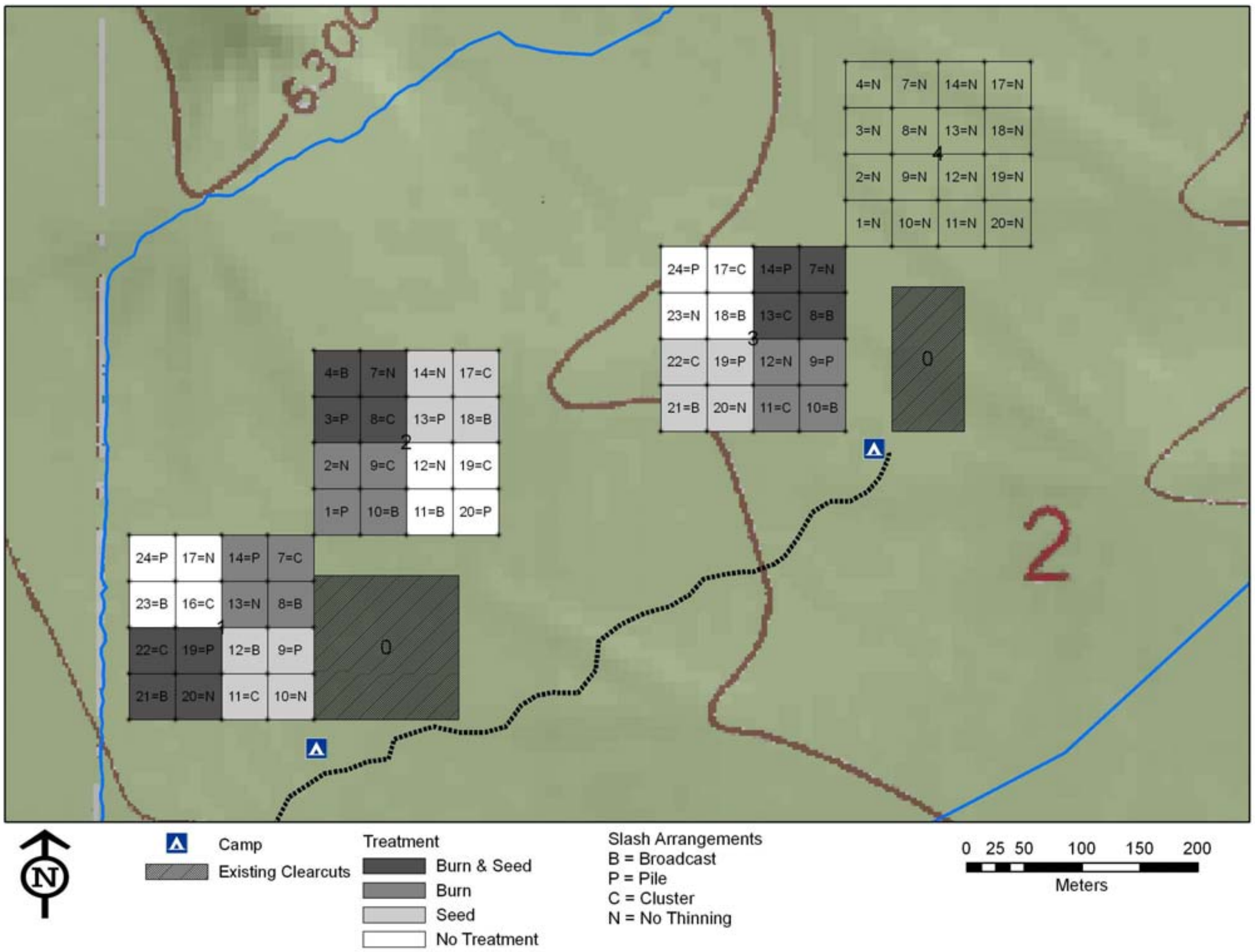


Figure 2. Research design of the thesis experiment (chapter 2). The units labeled 1, 2, 3, and 4 were used for the thesis experiment. The units labeled 0 are clearcut areas, created by Landis and Bailey (2005) and are the subject of this clearcut case study (chapter 3). This experimental design was replicated at the limestone site, the sandstone site, and the basalt site. p. 100

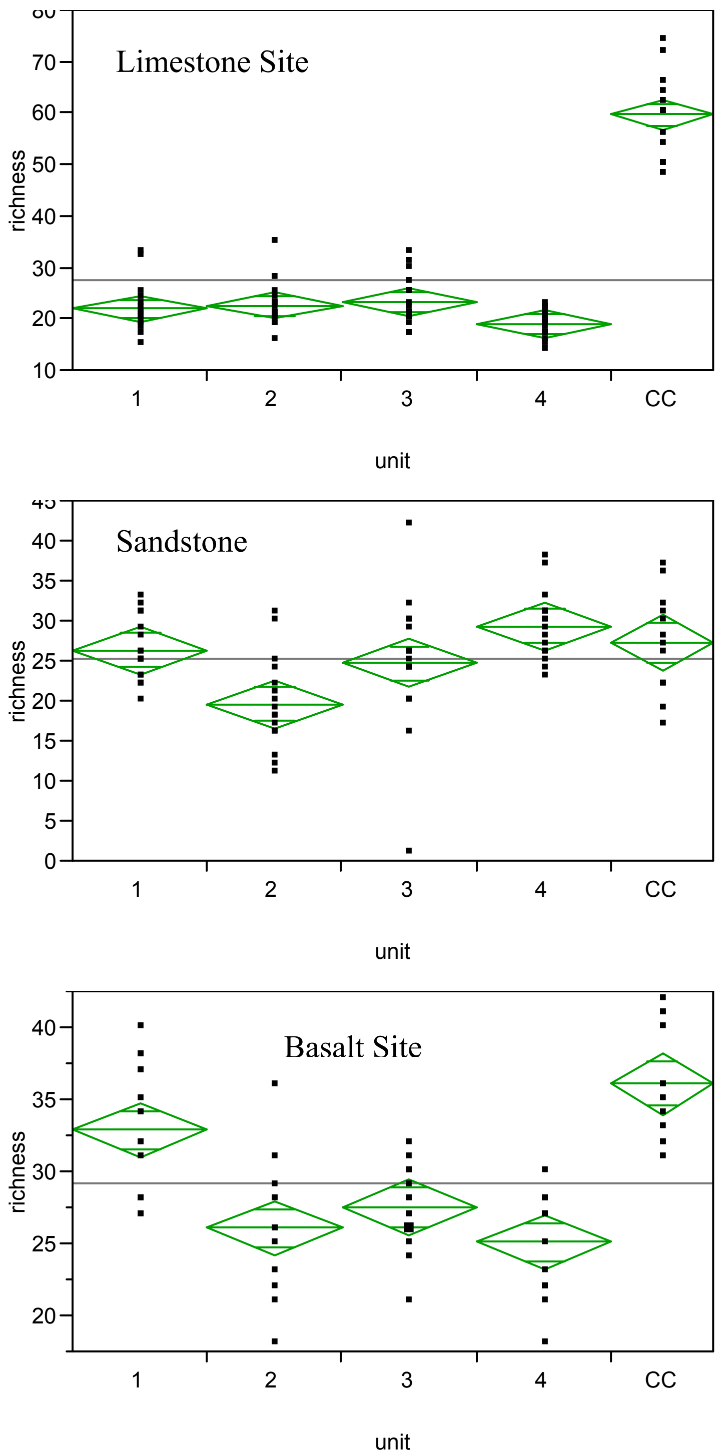


Figure 3. In 2005, we measured the vegetation in areas that were clearcut in 2002. We compared the mean richness of these clearcut areas (CC) to the four surrounding uncut units (1,2,3,4). The limestone site was the only site where the clearcut unit had higher mean richness values than the surrounding uncut units. Data are presented in dots with means diamonds, which illustrate the unit mean and 95% confidence interval. The line across each diamond represents the group mean. The vertical span

of each diamond represents the 95% confidence interval for each group. Overlap marks are drawn (($\sqrt{2}$CI)/2) above and below the group mean. The horizontal extent of each group along the *x*-axis (the horizontal size of the diamond) is proportional to the sample size of each level of the *x* variable, which is why the CC unit has a narrower mean diamond (n=12) than the other units (n=16).

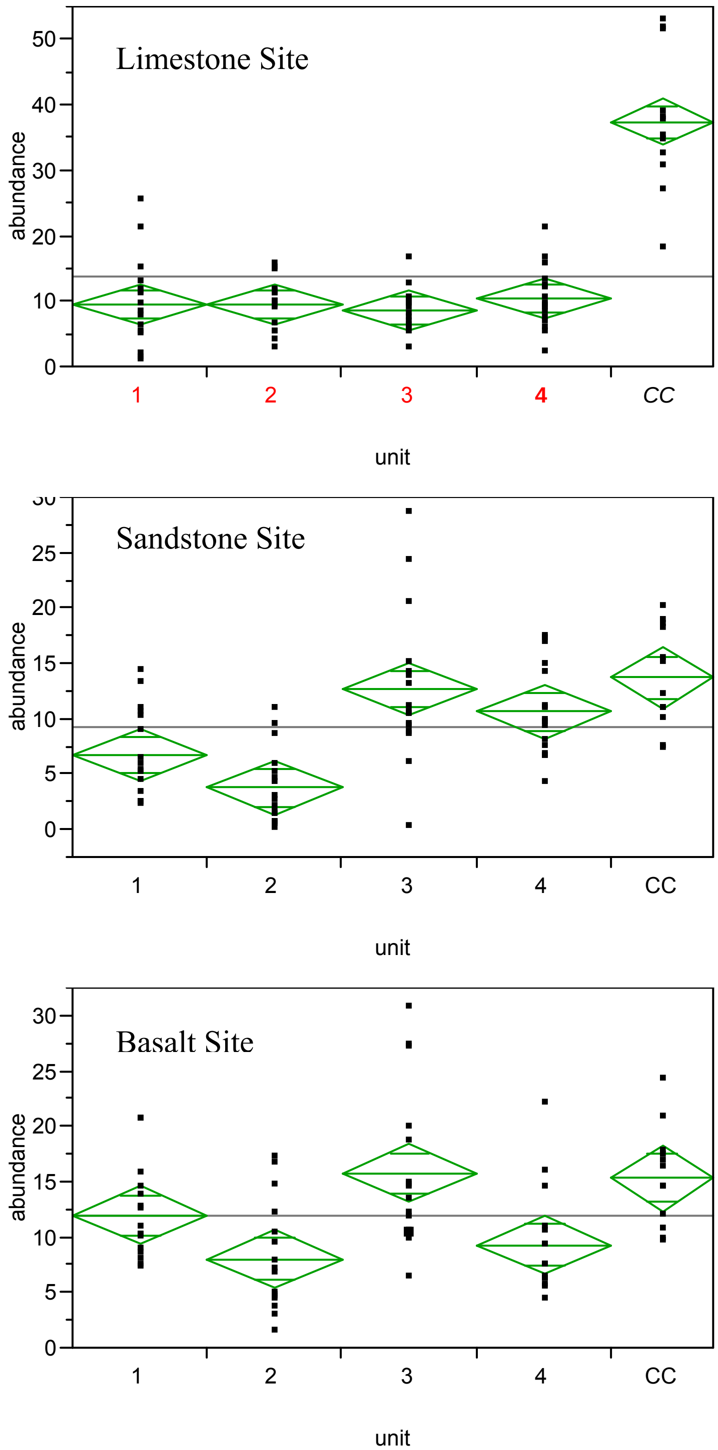
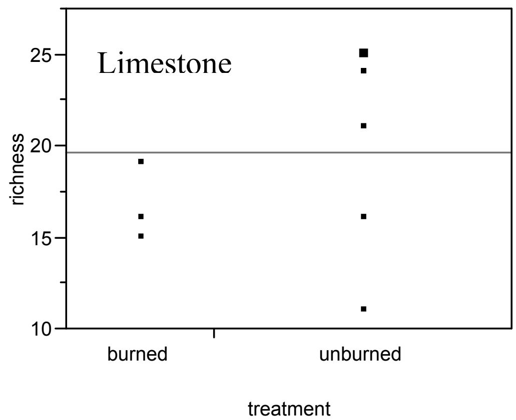
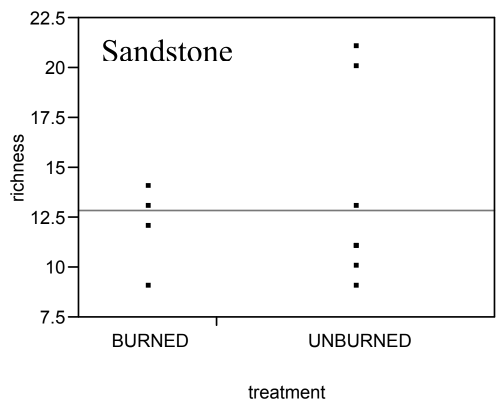


Figure 4. In 2005, we measured the vegetation in areas that were clearcut in 2002. We compared the mean abundance of these clearcut areas (CC) to the four surrounding uncut units (1,2,3,4). The limestone site was the only site where the clearcut unit had higher mean abundance values than the surrounding uncut units.

Data are presented in dots with means diamonds, which illustrate the unit mean and 95% confidence interval. The line across each diamond represents the group mean. The vertical span of each diamond represents the 95% confidence interval for each group. Overlap marks are drawn (($\sqrt{2}$CI)/2) above and below the group mean. The horizontal extent of each group along the *x*-axis (the horizontal size of the diamond) is proportional to the sample size of each level of the *x* variable, which is why the CC unit has a narrower mean diamond (n=12) than the other units (n=16).





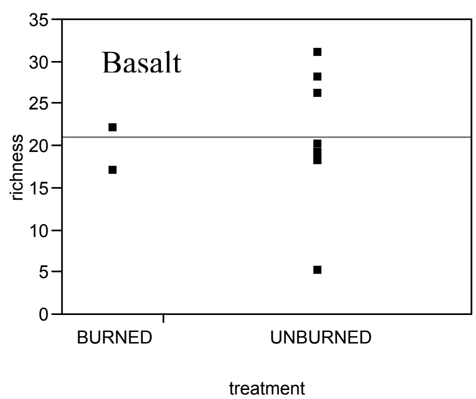


Figure 5. The differences in mean richness between the burned and unburned plots within the clearcut units were not significant for any of the three sites at the $\alpha = 0.05$ level. The data are presented in dots. n=3 for the burned plots and n= 12 for the unburned plots.

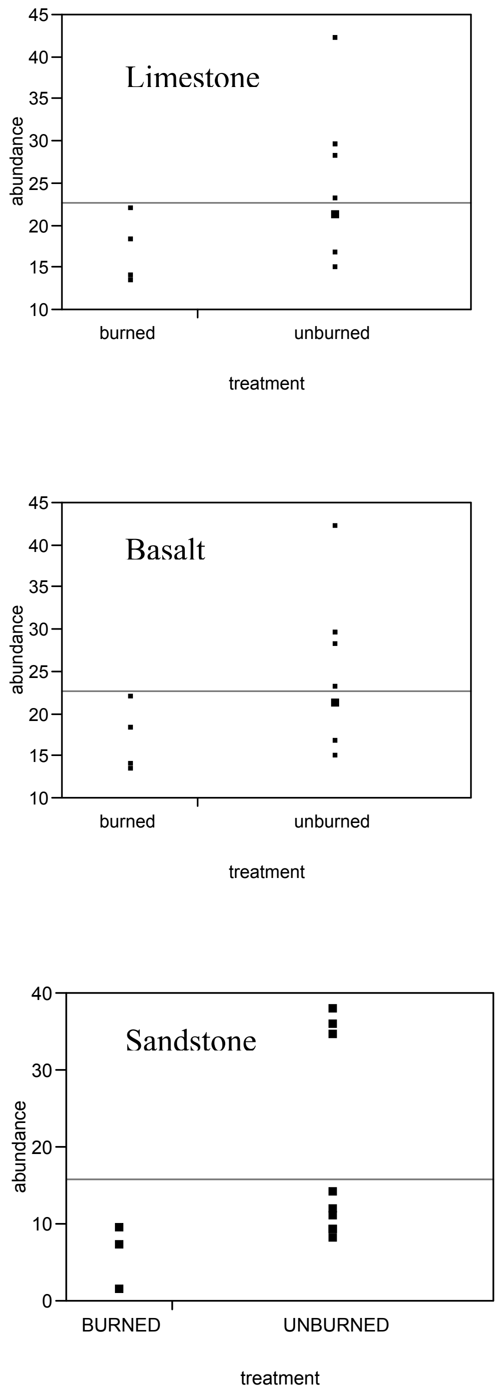


Figure 6. The unburned plots had significantly greater abundance than the burned plots at all sites, at the $\alpha = 0.05$ level. The data are presented in dots. n=3 for the burned plots and n= 12 for the unburned plots.

Chapter 4

Management Implications

Thesis summary

The objective of this study was to determine the effect of different silvicultural treatments on understory richness and abundance in the pinyon-juniper woodlands of northern Arizona. The treatments consisted of overstory thinning, different arrangements of slash, and burning and seeding in different combinations. Our specific research questions were: (1) Does burning and/or seeding after thinning influence resulting understory richness and abundance? (2) Does slash arrangement influence resulting understory richness and abundance? To answer these questions we measured changes in forest structure from thinning, fuel creation and consumption, maximum soil temperature reached during the prescribed burn, and understory vegetation responses.

In the dry growing season of 2006 we did not see any clear response trends in the understory community to thinning, slash arrangements, seeding or burning. We did find that understory plant richness responded to slash arrangement at the basalt site, but not at the limestone site or the sandstone site. At the basalt site, we found that slash arrangement did influence understory richness. Broadcasting the slash produced the greatest biodiversity in the understory plant community. Clustering the slash produced the second highest number or species, followed by the piling arrangement. The no thinning control plots showed the lowest levels of total species richness on the basalt site. These plots will be measured again in five and ten years to detect long term responses to our treatments.

Management Implications

We do not recommend thinning or seeding to increase understory richness or abundance, due to our mixed first year results. We expect the plant communities to change and grow over the years in response to our slash arrangements and treatments, and these trends will produce more meaningful management recommendations. We expect the plots that were broadcast, seeded, and not burned to show the highest understory responses, based on the results of previous studies (Chong 1994, Jacobs and Gatewood 1999, Brockway *et al.* 2002, Stoddard 2006).

We do not recommend burning in pinyon-juniper woodlands. Our clearcut study (chapter 3) showed burning can reduce plant abundance in half, the first year after the burn. Since overall plant cover is so low to begin with, this is a major concern for wildlife needs, understory recovery and possible erosion events. We also showed that the temperatures during a prescribed burn can be exceedingly hot, over 700°C. This severe soil heating may cause mortality to soil organisms, plant roots, alteration of physical soil properties, changes in nutrient cycling patterns and nutrient volatilization (Roberts W. B 1965, Neary *et al*. 1999). Also, burning piles of pinyon and juniper slash can result in plant communities that are persistently dominated by exotic species (Haskins and Gerhring 2004). Land managers must weigh the tradeoffs of burning slash for wildlife and livestock mobility benefits, with the potential negative effects mentioned above.

This study also shows the potential variability in the understory community between years. We found a drastic decrease in understory richness between 2005 and 2006 in our control plots. This study demonstrates the importance of understanding the range of variability in pre-existing understory conditions before judging the effect of management actions in pinyon-juniper woodlands.

Using a restoration thinning prescription assures that structure of the woodland is maintained within the historical range of variability, while allowing land managers to decrease tree density to accomplish their rangeland objectives. It represents a compromise between total tree removal and no management action, which have traditionally been the two alternatives for land managers in pinyon-juniper woodlands.

Thinning does not have to follow strict BDQ prescription guidelines to maintain multi-aged woodlands. Thinning prescriptions can be flexible based on the goals of the land manager. Diameter at root collar can be used as a rough surrogate for tree age and thus leaving a variety of three diameters behind creates an uneven-aged woodland structure. This technique is more ecologically sound than chaining or other methods of total tree removal because it does not change a historical woodland to a grassland.

Overall, this research implies that increasing understory community biodiversity and abundance in pinyon-juniper woodlands is difficult, especially in a dry year. More long term research on the effects of slash arrangements, burning and seeding needs to be conducted to help managers decide if active ecological manipulation is appropriate and effective in pinyon-juniper woodlands.

Future Research Needs

The Pinyon-Juniper Treatment Inventory Database of BLM Land on the Colorado Plateau (http://www.mpcer.nau.edu/pj/pjwood/) reports that over 700,000 acres of pinyon-juniper woodlands have been "treated" on the Colorado Plateau. This area encompasses 786 kinds of tree removal treatments. Given the uncertain ecological effects of these treatments, it would be very useful to conduct studies comparing these understory communities with each other and over time. Then we could further investigate the relationship between understory and overstory cover in pinyon-juniper woodlands. More botanical survey work is needed to understand the existing plant communities in pinyon-juniper woodlands, how they change over time, how soil type might influence vegetation response and how they change with various precipitation fluctuations.

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