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

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Grafical Abstract

Abstract: Pinyon-juniper woodlands are a dominant ecosystem in the American Southwest that have been increasing in density over the last century, generating concerns about the effects on wildlife habitat, livestock forage, and wildfire risk. We tested 16 treatment combinations designed to restore stands to historic conditions by examining the impact on understory plant richness and abundance. We thinned three sites comprised of different parent soil materials: limestone, sandstone, and basalt. Each site had four slash arrangements: piled, broadcast, clustered, or no thinning. Each of these arrangements received a different burning/seeding treatment: prescribed fire, seeding, prescribed fire and seeding, or none. This study corresponded with the driest period in the last 55 years, and plant species richness decreased by an average of 40% from the previous year in the control plots. Richness was significantly different due to slash arrangement at the basalt site only. Burning or seeding did not affect richness at any of the sites. Plant species abundance was generally low and not influenced by treatment or site. This study demonstrates that extensive ecosystem manipulation in the pinyon-juniper woodlands of northern Arizona did not affect understory richness or abundance the first year after treatment during a drought.

Keywords: *piñon, restoration, prescribed fire, understory response, silviculture*

Introduction

Pinyon-juniper woodlands occupy almost 30 million hectares in the western United States and are one of the largest ecosystems in the American Southwest.[1] Pinyon-juniper woodlands are usually found at elevations of 1,370 to 2,290 m, and are the most xeric forest type in the US with precipitation averaging 25-40 cm a year.[2] Many studies have documented the expansion and contraction of pinyon-juniper woodlands over thousands of years, due to long term changes in climate.[3,4,5] In the last 150 years many pinyon-juniper areas have expanded their geographic extent and/or increased in density.[6,7,8,9,10] This period coincides with Euro-American settlement in many areas, when livestock grazing, climatic changes, and fire suppression were introduced to pinyon-juniper forests.[11]

The current expansion and densification of pinyon-juniper woodlands is generally considered an undesirable trend for land managers, who thin or remove pinyon-juniper woodlands for wildlife habitat improvements, increased forage for livestock, and fuels mitigation. Many managers remove all pinyon and juniper trees by chaining (dragging a heavy chain between two bulldozers to knock over the trees) or mastication.[12] Few studies have used historic reference conditions to guide thinning in pinyon-juniper woodlands.[13, 14]

The inverse relationship between overstory and understory cover in pinyon-juniper woodlands has been documented.[15,16,17,18,19] 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.[13,20,21,22]

Leaving the slash created by thinning on the ground may create favorable microsites for understory establishment. Slash amendments to the soil significantly increased residual woody and litter debris, reduced soil movement, and increased arbuscular mycorrhizal fungi and microbial carbon levels.[22] Brockway *et al.* 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.[21] Jacobs and Gatewood determined that overstory reduction and slash mulching treatments produced two to sevenfold increases in herbaceous cover relative to controls.[13] It remains an open question whether slash additions to bare soil alone, without the confounding factors of thinning, increase understory diversity and cover.

The use of prescribed fire has had limited applications in pinyon-juniper woodlands because of the difficulty of burning [23] and uncertainty about the historic fire regimes.[24] In many areas, only extremely dry and windy conditions will carry a fire through the canopy, resulting in a high severity, stand replacing fire.[25,26] Prescribed fire success depends on stand structure, weather conditions, fuel availability, and fuel conditions.[27] Some land managers have used prescribed fire followed by seeding to convert woodlands to grasslands, thus improving their rangeland for livestock. Jacobs *et al.* 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.[13] Prescribed fire has also been used to consume the slash created by thinning. Understory abundance can increase when a site is burned several years after thinning.[13,20]

The success or failure of seeding in pinyon-juniper woodlands is highly dependent on precipitation. Water availability is critical for seedling establishment in arid ecosystems.[28,29] Seeding is also affected by animal predation[30] and the availability of favorable microsites.[31] Slash additions and minor soil disturbances can create favorable microsites for seed establishment.[22] Seeding after wildfires is a common practice for the US Forest Service, and has been shown to effectively increase graminoid cover in degraded pinyon-juniper woodlands in northern Arizona.[22]

The objective of this study was to determine the effect of different silvicultural treatments in a pinyon-juniper woodland 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 post-treatment changes in forest structure, 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. The results from this study will assist land managers designing thinning prescriptions and in understanding the interactions of slash arrangements, burning, and seeding on resulting understory richness and abundance.

Methods

Study Site

This study was conducted in 2005 and 2006 on Anderson Mesa, located 150 km southeast of Flagstaff, Arizona. The climate of Anderson Mesa is semi-arid, receiving a mean annual precipitation of 470 mm. About half of the precipitation falls in 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.[32] Historically, there are few average years due to dramatic climatic fluctuations from year to year. [32]

Because of the effect of soil parent material on the developmental dynamics of vegetation in this region we selected three sites with different parental substrates.[10] These sites also have well documented historic forest structures (see [10] for detailed site descriptions). These sites were named after their soil parent material: limestone, sandstone, and basalt. 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 had limited fall and spring livestock grazing since the 1950's. The basalt site has not been grazed from 1920 to the present (Jack Metzger, Flying M Ranch, personal communication). Other important grazers in the area include elk (*Cervus elaphus*), mule deer (*Odocoileus hemionus*), and pronghorn antelope (*Antilocarpa americana*). 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.

Experimental Design

We created a split-plot design with one of four slash arrangements applied to the subplots and one of four seed/burn methods applied to the whole-plots (Figure 1). At each site we created three 160 x 160 m units. Each unit was divided into four 80 x 80 m whole plots, and the whole plots were divided into four 40 x 40 m subplots. Each subplot was randomly assigned one of four slash arrangements: thin and pile, thin and cluster, thin and broadcast, or no thinning (control). Then, we randomly chose a burn/seed method for each whole plot. There were four options: burn, burn and seed, seed, or no burn/seed method (control). Therefore, each unit was composed of 16 subplots, and each subplot was a different slash arrangement and burn/seed method combination for a total of 16 treatments with three replications at each of the three sites.

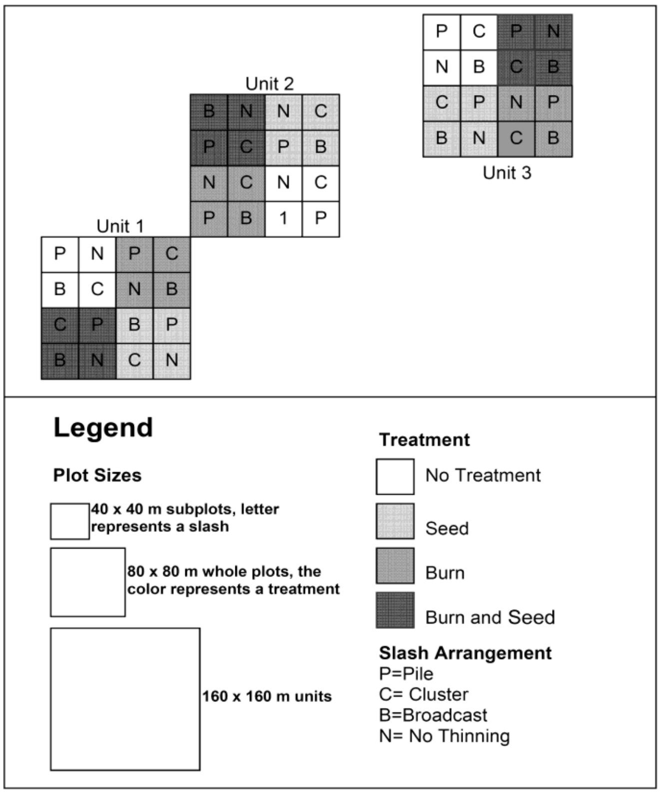

Figure 1. Split-plot experimental design replicated at each of the three sites.

Vegetation Surveys

A pre-treatment vegetation survey was conducted using a modification of the Modified-Whittaker plot in June of 2005. [33] We drew out a 50 m tape at a 45° angle from the southwest corner of each subplot, creating a 50 m line transect. A 1-m² frame (0.5 x 2 m) was placed along alternating sides of the transect at 14 meter intervals with a total of four samples per transect. 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 estimate 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. A voucher specimen of each unknown species was collected and identified at the Deaver Herbarium at Northern Arizona University. Post-treatment vegetation response was measured in the same way in June of 2006.

Thinning and Slash Arrangements

Thinning was conducted in the summer of 2005, following a BDQ prescription for each site that was based on the 1860 stand structure at each site.[10] B stands for basal area in m^2/ha, D stands for maximum diameter measured at root collar (DRC) in cm, and Q stands for the q-factor, a fixed ratio of trees in one diameter class to the next largest diameter class.[34] 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. [34] This method seeks to balance standing tree density with expectations for growth and mortality up to some maximum diameter.[35] These prescriptions did not consider *P. edulis*, which composed 1-10% of the woodland and much of which suffered from recent drought-induced mortality.

In applying the prescription, we attempted to retain trees in a clumpy arrangement (3 trees or more together) when possible to mimic 1860 spacing patterns.[10] All of the thinning was done by hand with chainsaws. After each subplot was cut, we tallied the root collar diameter of all the stumps. These data, coupled with pre-treatment inventory data, 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 (Figure 2). We piled the slash for the pile arrangement. We felled the trees 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 uniformly around the subplot. We left unthinned plots as controls.

Figure 2. Four slash arrangements, clockwise from the upper left: pile, cluster, no thinning, and broadcast.

Fire Measurements and the Prescribed Burn

We measured surface fuel loading on each pile, cluster, broadcast, and no thinning sup-plot using planar intercept transects after the thinning.[36] We estimated the volume of slash piles according to Hardy *et al.*[37]

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 difficult time getting the fire to carry because of a lack of continuous surface fuels. We placed 3 pyrometers at each subplot into areas of high, medium, and low slash accumulations. The pyrometers were composed of an "L" shaped strip of thin sheet metal, painted with 11 temperature-sensitive paints that detect temperatures ranging from 79°C to 760°C (Tempilaq° G Temperature Indicating Liquids, Omega Engineering, Stamford, Conn.). These pyrometers measured maximum soil temperature during the prescribed burn, and were also influenced by the duration of temperature, providing a somewhat integrated measure of intensity.[38,39] After the prescribed burn, we collected the pyrometers and recorded temperatures, and measured fuels to estimate fuel consumption.

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 (*Artemisia tridentate, Krascheninnikovia lanata, Purshia tridentate, Linum lewisii, Achnatherum hymenoides, Aristida purpurea, Muhlenbergia wrightii, Pleuraphis jamesii, Elymus elymoides*) and was applied at a rate of 62.9 kg/ha. 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.GraniteSeed.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 randomly placed within an area 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 thinning, slash arrangements, seed/burn methods, and their interactions on understory richness and abundance. We used Tukey-Kramer honestly significant difference tests (HSD) to test for differences among means. We compared the differences in abundance and richness between years in the control plots 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.

Results

Thinning

The prescriptions based on reference conditions resulted in basal area reductions across the three sites ranging from 28% to 61% (Table 1).

Table 1. Summary of the changes in forest structure after implementing the BDQ thinning prescription at each of three sites.

Site	BDQ[1]	Pre-thinning density (trees/ha)	Post-thinning density (trees/ha)	Density reduction (%)	Basal area 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

1 B = basal area (m^2 ha^{-1}), D = maximum diameter at root collar (cm), Q = ratio of trees in one diameter class to the next largest diameter class.

Prescribed Fire and 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. The pyrometer readings showed that the pile slash arrangement burned hotter than all of the other slash arrangements, between 680 and 750 °C. There was little difference between the maximum temperatures reached in the broadcast and the cluster slash arrangements; both ranged between 450 and 550 °C. The plots that were not thinned reported the lowest maximum temperature readings, between 50 and 200 °C.

Understory Vegetation

In 2005, we identified 115 species in the understory over all 3 sites. The basalt site had the greatest richness and abundance of the three sites. In 2006, we found 80 species over all 3 sites and few understory responses to treatments. Understory species richness was not influenced by thinning, slash arrangement, or burn/seed method at the limestone site (Table 2). At the basalt site, understory richness was influenced by thinning and slash arrangement, with the thinned plots and broadcast arrangement plots yielding the greatest richness (Figure 3). At the sandstone site, we found a significant difference in richness only due to the slash arrangement by seed/burn method interaction, but the three treatments with the greatest species richness included the control (no thinning and no burn/seed method combination). Understory abundance did not significantly differ by thinning, slash arrangements, or burn/seed method at any of the three sites (Table 2).

Table 2. P-values for split-plot ANOVA testing understory species richness differences due to the influences of thinning (thin vs no thin), slash arrangement (pile, cluster, broadcast, or no thinning), seed/burn method (burning, seeding, burning and seeding, or none), and the slash arrangement and seed/burn method interaction. All understory plant abundance results for the same variables were not significant (ns).

Variable	Limestone	Sandstone	Basalt
Thinning	ns	ns	0.02
Slash arrangement	ns	ns	0.0004
Seed/burn method	ns	ns	ns
Slash arrangement x thin/burn method	ns	0.003	ns

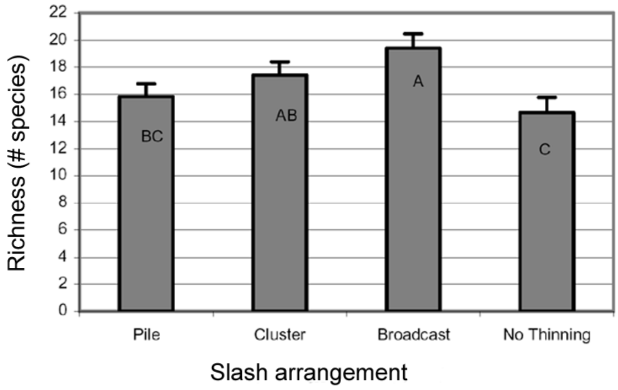

Figure 3. The basalt site understory species richness responses to different slash arrangements. Data are expressed as means (n = 12) +/- SE. Values indexed by different letters are significantly different at p ≤ 0.05 as determined by Tukey's HSD test.

We compared understory plant richness and abundance for 2005 vs. 2006 in the 3 control (no thinning and no burn/seed method) sub-plots 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) (Figure 4) by an average of 40%. Plant abundance was not significantly different between years at the limestone site (p=0.7) or at the sandstone site (p=0.2), but was significantly reduced at the basalt site (p=0.02).

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 either of the sites. We found bare seeds lying on top of the soil inside of the cages. In the exposed plots, the seeds were no longer present, either consumed by herbivores or blown away by wind. There was no germination and therefore, no analysis was performed on the seed cage experiment.

Discussion

Although our experiment was not designed to test for the effect of moisture, we believe plant responses to our thinning, slash arrangements, and burning and seeding treatments were muted by the severe drought of the preceding winter and spring. 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.[40] Our vegetation surveys were conducted in June, which is traditionally the peak of the understory plant abundance and richness at our research sites.[41] The growing season of 2005-2006 was the 3rd driest growing season ever recorded. January to May of 2006 was the driest winter and spring in the last 55 years (Western Regional Climate Center). This same period in 2005 was relatively wet (85th percentile), compared to the average precipitation year (Figure 5).

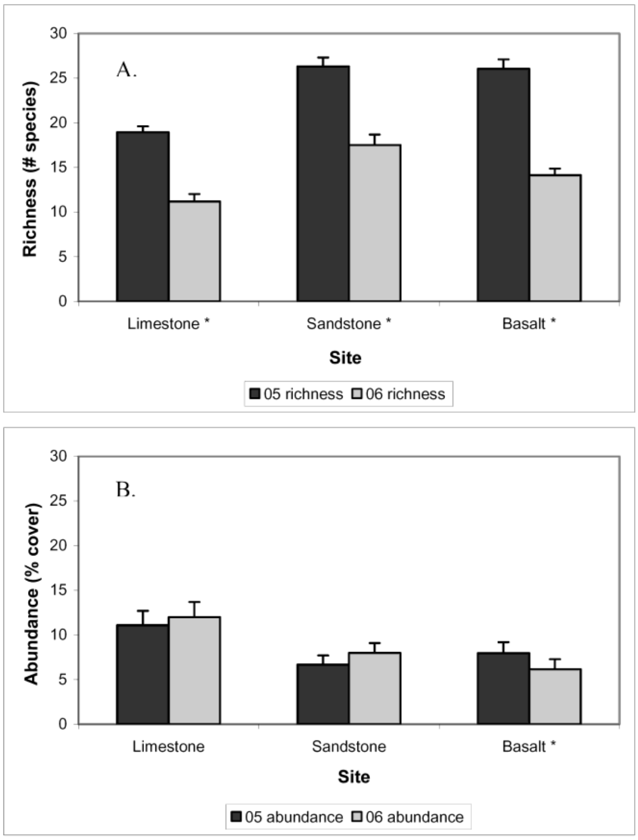

Figure 4. Differences in understory plant (A) richness and (B) abundance between 2005 and 2006 in the control plots at each site. An asterisk after site names indicate significant differences in the understory at the α=0.05 level. Data are expressed as means (n = 16) +/- SE. Species richness decreased 40% at the limestone site, 33% at the sandstone site, and 45% at the basalt site.

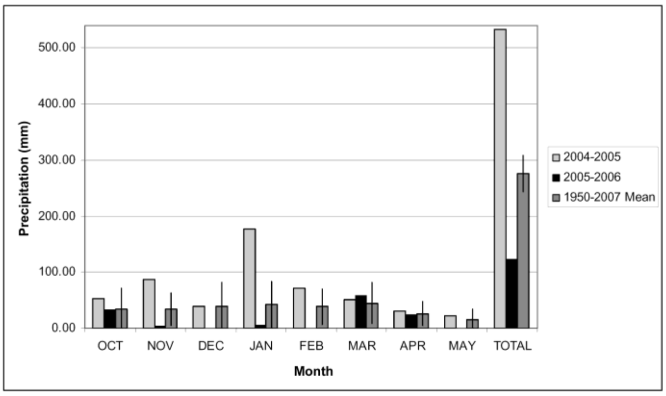

Figure 5. Precipitation data from 1951 to 2006. (Western Regional Climate Center (http://www.wrcc.dri.edu)). The lines on the bars represent one standard deviation above and below the mean for the 1951-2006 precipitation data.

We documented decreases in plant richness from 2005 to 2006 in the control plots; however, 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). 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 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 (Figure 3). In other words, the more dispersed 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.[10, 22]

Slash arrangement did not significantly influence resulting understory richness at the limestone and sandstone sites (Table 2). The basalt site may have had a greater response because of increased moisture, a great reduction in overstory, soil type, or a combination of factors. The basalt site was 153 m higher than the other two sites and thus probably received more moisture and had the greatest overstory reduction (Table 1). Additionally, certain soil characteristics such as high calcium carbonate levels, high pH, and low phosphorous have been associated with no increase in perennial grass production.[42]

Burning did not influence understory richness or abundance at any of the sites after one year. Other studies have burned slash created by thinning in pinyon-juniper woodlands and recorded an immediate decrease in plant abundance, followed by an increase in years following the burn.[20,43] Burning heavy loads of juniper slash creates very hot soil temperatures and may have negative impacts on future understory regeneration.[43] Our study showed that the maximum surface temperature exceeded 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.[44, 45]

Since seedling emergence often depends on soil water availability,[46,47] we attribute the total lack of germination in seeding cages to the dry growing season of 2006. Seeding success in other studies had been mixed. Stoddard (2006) found seeding increased biodiversity in degraded pinyon-juniper woodlands in northern Arizona after the first two years of seeding.[22] 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.[29]

A longer monitoring period is needed to determine the effects of 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.[10] Thinning represents a compromise between total tree removal which would maximize forage production and no management action.[48]

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[49] by raising temperatures and changing precipitation patterns.[50] Given the central role that precipitation plays in semiarid ecosystems, changing precipitation regimes and inter-annual variability may have a stronger effect on pinyon-juniper understory biodiversity and abundance than land management decisions.

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