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Restoring grassland savannas from degraded pinyon-juniper woodlands: effects of mechanical overstory reduction and slash treatment alternatives

Dale G. Brockway*†, Richard G. Gatewood‡ and Randi B. Paris§

† *Southern Research Station, USDA Forest Service, 520 Devall Drive, Auburn, AL 36849, USA*
‡ *Bandelier National Monument, USDI National Park Service, Los Alamos, NM 87544, USA*
§ *Trinity County Resource Conservation District, P.O. Box 1450, Weaverville, CA 96093, USA*

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Although the distribution and structure of pinyon-juniper woodlands in the southwestern United States are thought to be the result of historic fluctuations in regional climatic conditions, more recent increases in the areal extent, tree density, soil erosion rates and loss of understory plant diversity are attributed to heavy grazing by domestic livestock and interruption of the natural fire regime. Prior to 1850, many areas currently occupied by high-density pinyon-juniper woodlands, with their degraded soils and depauperate understories, were very likely savannas dominated by native grasses and forbs and containing sparse tree cover scattered across the landscape. The purpose of this study was to evaluate the effectiveness of mechanical overstory reduction and three slash treatment alternatives (removal, clustering and scattering) followed by prescribed fire as techniques for restoring grassland savannas from degraded woodlands. Plant cover, diversity, biomass and nutrient status, litter cover and soil chemistry and erosion rates were measured prior to and for two years following experimental treatment in a degraded pinyon-juniper woodland in central New Mexico. Treatment resulted in a significant increase in the cover of native grasses and, to a lesser degree, forbs and shrubs. Plant species richness and diversity increased most on sites where slash was either completely removed or scattered to serve as a mulch. Although no changes in soil chemistry or plant nutrient status were observed, understory biomass increased over 200% for all harvest treatments and was significantly greater than controls. While treatment increased litter cover and decreased soil exposure, this improvement did not significantly affect soil loss rates. Even though all slash treatment alternatives increased the cover and biomass of native grasses, scattering slash across the site to serve as a mulch appears most beneficial to improving plant species diversity and conserving site resources.
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Introduction

Pinyon-juniper woodlands currently occupy 3 million ha in the Southwest (USDA Forest Service, 1993) and 24 million ha throughout the western United States (West, 1984). However, controversy exists concerning whether the present extent and structure of this ecosystem are characteristic of its historical flux or whether the current occupancy and structure now exceed its range of natural variation (Gottfried *et al.*, 1995). Pinyon-juniper woodlands of relatively high-density are thought by some to represent a 'climax' state that is approaching an equilibrium with climatic conditions. Others, noting the loss of understory grasses and forbs and resulting soil erosion associated with high-density pinyon-juniper woodlands, see them as a retrogressive condition resulting from the interaction of a changing climate and

* Corresponding author. Email: dbrockway@fs.fed.us

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historical management practices. Much of what is now pinyon-juniper woodland may have once been mostly juniper savanna, dominated by grasses and forbs and containing perhaps no more than 10–15 trees/ha. Interruption of ecological processes, such as periodic fire, and implementation of management activities, such as heavy grazing, may have led to the existing condition of extensive high-density pinyon-juniper woodlands.

Studies of pollen, packrat middens, dry caves, lake sediments and archaeological sites have been useful in documenting the substantial expansion and contraction in the range of pinyon-juniper woodlands as climate has changed during the past several thousand years (Van Devender *et al.*, 1984; Mehringer and Wigand, 1990; Gottfried *et al.*, 1995). During periods of increased moisture (4000–1900 BP), juniper expanded down mountain slopes into more xeric communities (Wigand, 1987) and grass occupancy increased, resulting in periodic fires that maintained low-density open stands of pinyon and juniper trees in association with herbaceous understories (Miller and Wigand, 1994). As the climate became warmer and drier (1900–1000 BP), juniper occupancy declined and grass and forb levels persisted (Davis, 1982; Wigand, 1987; Wigand and Rose, 1990; Wigand and Nowak, 1992). Although pinyon pine expanded dramatically around 1000 BP, subsequent drought and fire (700–500 BP) led to a widespread decrease of pinyon and juniper (Wigand and Rose, 1990). Increased winter precipitation beginning in the 1500s initiated a re-expansion of juniper woodland, which with some fluctuation in the early 1800s, sharply increased in the 1900s (Mehringer and Wigand, 1990). Since Anglo-European settlement of the Southwest began around 1850, temperatures have increased and pinyon-juniper woodlands have initiated another expansion episode (Ghil and Vantgard, 1991). Variation in the regional climate has caused several local episodes of juniper expansion and contraction (Betancourt, 1987) and global climate change has been recently linked to extensive and rapid displacement of plant communities along the ecotone with encroaching juniper woodlands (Allen and Breshears, 1998). Cultural impacts of Native Americans and Spanish settlers from fuelwood harvesting and grazing were relatively small and dispersed, resulting in only minor declines in pinyon-juniper occupancy and slight increases in soil erosion rates. Major ecological changes occurred in the Southwest with arrival of Anglo-European settlers, their large herds of cattle and sheep and coincidental droughts in the late 1800s and mid-1900s (Gottfried *et al.*, 1995).

Prior to European settlement, fluctuations in the range of pinyon-juniper woodlands were largely a result of climatic change and disturbance, with periodic fire as an important disturbance agent (Leopold, 1924; Pieper, 1993; Betancourt, 1996). Much of this ecosystem was characterized by savanna-like vegetation, with high-density woodlands confined to rocky ridges, hillslopes and flats where fine fuels were insufficient to carry fire (O'Rourke and Ogden, 1969; West, 1984; Swetnam and Brown, 1992; Wood and Javed, 1992; Miller and Rose, 1995). However, during the past 150 years, juniper trees have increased both in distribution and density throughout their range (Parker, 1945; Johnsen, 1962; Tausch *et al.*, 1981; West, 1984; Erramouspe, 1994) and have aggressively invaded grasslands, meadows, sagebrush steppe, aspen and riparian communities (Parker, 1945; West, 1984; Eddleman, 1987; Miller and Rose, 1995). Pinyon-juniper woodland has expanded its range five-fold and increased its density 6–20 times (Cottam and Stewart, 1940), with densities now averaging 338 trees per ha (Miller and Rose, 1995). Most present day woodlands are <100 years old. Climate, grazing and fire are the major factors most often linked to expansion of pinyon-juniper woodlands (Miller and Wigand, 1994). Favourable climate during the late 1800s and early 1900s (Antevs, 1938; Graumlich, 1985), promoted vigorous juniper growth (Fritts and Xiangdig, 1986) and stimulated increases in grasses and forbs which increased the potential for fire. However, heavy grazing by domestic livestock reduced understory fuels and caused a decrease in fire frequency, facilitating expansion of pinyon-juniper woodland and increases in tree density (Johnsen, 1962; Burkhardt and Tisdale, 1976; Young and Evans, 1981; Evans, 1988). Pre-settlement fire frequencies ranged from 15 to 25 years (Agee, 1993), with junipers <50 years old easily killed by fire (Burkhardt and Tisdale, 1976). Periodic fire maintained trees and shrubs at relatively low densities and restricted woody plants to sites containing low levels of fuel (Miller and Wigand, 1994). However, removal of fine fuels by grazing as early as the mid-1800s and suppression of fire since the mid-1900s have been major factors in reducing fire frequency (Wright *et al.*, 1979; Savage and Swetnam, 1990). Livestock may have also contributed to juniper expansion through seed dissemination, reducing competition from preferred forage species and increasing safe sites for juniper seedling establishment. Reduced competition from herbaceous forage species has been implicated in predisposing plant communities to juniper invasion (Cottam

and Stewart, 1940). A combination of frequent fire and competition from cool-season grasses can effectively exclude juniper during the critical period of seedling establishment.

During the past 50 years in central New Mexico, climate has varied from very dry at mid- century, causing high juniper mortality, to very wet over the recent 20 years, favouring juniper expansion (Gottfried *et al.*, 1995; Betancourt, 1996). Increased levels of atmospheric CO_2 are also thought to have contributed to the expansion of pinyon-juniper woodlands in the Southwest (Johnson *et al.*, 1993; Polley *et al.*, 1993). Since cool-season C_3 plants respond more favourably to increased CO_2 concentrations than do warm-season C_4 species (Bazzaz *et al.*, 1985), higher CO_2 may increase growth of cool-season junipers at the expense of associated warm-season grasses (Miller and Wigand, 1994). Other southwestern woody plants, such as creosotebush (*Larrea tridentata*) and mesquite (*Prosopis glandulosa*), have also expanded their ranges and invaded native grasslands during the past century, indicating that expanded juniper occupancy may be only one component of a much broader ecological trend across the region (Buffington and Herbel, 1965; Grover and Musick, 1990; Schlesinger *et al.*, 1990; Virginia *et al.*, 1992). Yet considering the highly dynamic nature of semiarid grasslands and woodlands, it is quite likely that the theory of multiple stable states applies to these ecosystems (Friedel, 1988; Westoby *et al.*, 1989; Laycock, 1991). Unlike the earlier site potential concept (Dyksterhuis, 1949; Humphrey, 1949) that considers all range conditions with reference to a 'climax' condition, this more recent theory postulates the existence of numerous conditions in which a vegetation assemblage may persist for a prolonged time period (Friedel, 1991; George *et al.*, 1992; Tausch *et al.*, 1993). These states are separated from one another by thresholds that may be overcome by a single disturbance or sequence of multiple disturbance events that move a floristic assemblage in a non-linear fashion from one long-term stable state to another. Although, the current episode of juniper expansion into grasslands may simply be its re-establishment on sites previously occupied by woodland (Samuels and Betancourt, 1982; Dick-Peddie, 1993), many of these lands, because of human interference with natural processes, contain degraded pinyon-juniper woodlands that could benefit substantially from ecological restoration to grassland savannas.

In a pinyon-juniper woodland, containing a relatively dense overstory, depauperate herbaceous understory and eroded surface soils following a history of livestock grazing and fire suppression, the overstory was mechanically reduced to 15 trees/ha and three slash treatment alternatives were applied as a prelude to re-introducing fire in this ecosystem. In measuring the post-treatment changes in vascular plant cover, diversity, biomass, foliar nutrition, litter cover, soil chemistry and erosion, the objectives of this study were to (1) assess the effectiveness of mechanical overstory reduction as a method of decreasing competition between trees and desirable understory plant species, (2) evaluate the efficacy of slash treatment alternatives for stabilizing surface soils, conserving site nutrients and improving plant growth and diversity and (3) determine whether mechanical overstory reduction and slash treatment can serve as a viable procedure for restoring grassland savannas from degraded pinyon-juniper woodlands.

Methods

Study site

This experiment was conducted on the Mountainair Ranger District of the Cibola National Forest in Torrence County, central New Mexico. The study site is located near the Abo Unit of the Salinas Pueblo Mission National Monument (34° 30′ N, 106° 30′ W), adjacent to the Manzano Mountains and is typical of pinyon-juniper woodland in this region. The climate is semiarid and annual precipitation is highly variable, averaging 400 mm, with about 60% of this arriving as summer thundershowers (Bourlier *et al.*, 1970). Average monthly temperatures range from 8°C to 19°C for the April to September period and from −1°C to 10°C during October to March.

The study area is approximately 1950 m above sea level on a broad, north–south trending ridge adjoining the Manzano Mountains in the Basin and Range Province. The numerous ridges and canyons in this locale are drained toward the Rio Grande by a number of intermittently flowing and highly eroded arroyos. Surface slopes at the study site range from nearly level (0–2%) to moderately inclined (up to 9%). The surface geology is underlain by the Abo Formation which dates to the Lower Permian. This 275 m thick bedrock consists of red and reddish-brown crossbedded siltstone and medium to fine-grained sandstone overlying shale, siltstone, sandstone and conglomerate. Soils developed as mollisols in parent materials that are residuum weathered from fine-grained sandstone

and shale. The predominant soil is Encierro channery loam (Lithic Argiustoll, clayey, mixed, mesic), which is low in water holding capacity and has a medium to high runoff rate. Gravel and larger rock fragments occur over the surface and throughout the profile of this shallow soil, which ranges in thickness from 13 to 51 cm above bedrock (Bourlier *et al.*, 1970). Plant root development is correspondingly restricted.

Vegetation on this eroded, shallow range site consisted of a relatively dense overstory and sparse understory, which resulted in bare soil exposure approaching 70%. The overstory ranged from 2 to 3 m in height and was dominated by one-seed juniper (*Juniperus monosperma*), with lesser amounts of pinyon pine (*Pinus edulis*). Commonly observed shrubs included broom snakeweed (*Gutierrezia sarothrae*), skunkbush sumac (*Rhus trilobata*) and pricklypear cactus (*Opuntia* spp.). Blue grama (*Bouteloua gracilis*), black grama (*Bouteloua eripoda*), galleta (*Hilaria jamesii*), ring muhly (*Mulenbergia torreyi*), sideoats grama (*Bouteloua curtipendula*), purple threeawn (*Aristida purpurea*) and sand dropseed (*Sporobolus cryptandrus*) were among the prominent graminoids. Associated forbs included sagewort wormwood (*Artemesia campestris*), roseheath (*Chaetopappa ericoides*), catseye (*Cryptantha* spp.), fleabane (*Erigeron* spp.), spurge (*Euphorbia* spp.), pepperweed (*Lepidium* spp.), flax (*Linum* spp.) plains blackfoot (*Melampodium leucanthum*), woolly indianwheat (*Plantago purshii*), linear-leaved tansy mustard (*Sisymbrium linearifolium*), silverleaf nightshade (*Solanum eleagnifolium*), scarlet globemallow (*Sphraeralcea coccinea*) and dandelion (*Taraxacum officinale*).

Site history and experimental treatments

Although the study area had been grazed by domestic livestock for many decades, a seasonal grazing system was first implemented in 1969, which allowed 30 cattle to graze the site for 9 months each year. More recently, the grazing season was reduced to 7 months per year to avoid possible resource degradation resulting from heavy utilization. Because of deteriorating understory vegetation and soil conditions on the site, all grazing was suspended from 1995 until mid-1997. While cattle grazing contributed to the decrease in herbaceous plant cover, competition for limited site resources from a relatively dense juniper overstory was also thought to be a principal cause for decline in the understory plant community. Cultural treatments which cause large-scale soil disturbance, such as anchor chaining, have been proven effective in removing larger juniper trees (Miller and Wigand, 1994). However, such methods also stimulate regeneration of juniper seedlings and exacerbate soil loss, thereby defeating the primary objectives of grassland savanna restoration. Therefore, methods which reduce competition from woody overstory plants while protecting the soil surface are essential to achieving ecological restoration.

In April 1995, a randomized complete block experimental design was established on the study site. Four experimental treatments were replicated in four blocks distributed across the 16 ha study area. Each 1 ha (100 m × 100 m) block contained four 0·25 ha (50 m × 50 m) plots. Aside from the unharvested control plots, all treatments consisted of mechanical removal of the overstory juniper trees leaving a residual density of 15 trees/ha. This was accomplished in summer 1996 using chainsaws and the larger juniper stems were removed from the site for use as fuelwood. Treatment of residual slash consisted of (1) evenly scattering slash materials across the entire plot as a mulch to protect the soil surface and provide ameliorated microsites for understory plants, (2) leaving slash clustered around the base of each cut juniper tree, to simulate the typical result of a fuelwood harvest and (3) completely removing all slash from the plot, to discern whether slash management provides any additional benefits to soil or understory recovery over simply reducing direct competition from overstory junipers.

Measurements

In June 1995, plant cover, species diversity, litter cover, understory biomass, foliar nutritional status, soil chemical properties and erosion measurements were conducted on all plots to assess the pretreatment status of this ecosystem. Repeated post-treatment measurements were then completed during October 1996 and 1997 to ascertain the ecological changes resulting from fuelwood harvesting and slash treatment alternatives. Soil exposure, litter cover and total foliar cover of all plant species (vertical projection of canopy) was measured using the method of community structure analysis (Pase, 1981) along two 25 m transects (oriented east and west) within each plot. Identification and nomenclature for plant species were consistent with taxonomic authorities (Hitchcock, 1950; Humphrey, 1956; Hermann, 1966; Nickerson

et al., 1976; Weber, 1976; Kartesz *et al.*, 1994). Aboveground herbaceous understory biomass was quantified on three randomly selected 1 m^2 sampling subplots within each larger treatment plot. The standing biomass of understory plants was destructively sampled by clipping all understory herbaceous vegetation at the groundline and placing samples into paper bags. Soils were sampled to a depth of 15 cm, using a 5 cm diameter coring device, at 5 m intervals along two 25 m transects (oriented parallel to the plant transects) within each plot. Soil stability (loss or aggradation) was estimated through erosion bridge measurements (Shakesby, 1993), using four 2 m long erosion bridges installed in the interstitial spaces on each plot.

All herbaceous plant samples were dried to a constant mass in a force draft oven at 75°C for 48 hours and weighed. These data were then used to construct biomass estimates for understory vegetation relative to experimental treatment. These samples were subsequently ground in a Wiley mill using a 20 mesh screen and chemically analyzed to determine the concentrations of N, P, K, Ca, Mg, Na, Fe, Mn, Zn, Cu, B and Al present in the plant tissue. Data on the foliar cover of each species were summarized as estimates for each plot and analyzed by treatment and change through time. These cover data were used as importance values to compute several indices of alpha diversity, including species richness, species evenness and species diversity (Ludwig and Reynolds, 1988). Species richness is the total number of species present (N_0), evenness describes how abundance is distributed among species (modified Hill ratio, E_5), approaching one when all species are of equal abundance and declining toward zero when few species dominate, and species diversity mathematically combines species richness and evenness components into a single numeric value (Shannon index, H'). Soil samples were air dried, passed through a 2 mm sieve to remove coarse fragments and chemically analyzed to measure NO_3-N, NH_4-N, total N, P and K, exchangeable Ca, Mg and Na, SAR, electrical conductivity, pH and organic matter content. Soil erosion data for the 3-growing-season time period were summarized by plot and analyzed by treatment.

All data for dependent variables were summarized as estimates of the mean for each plot and these means were then used to estimate the mean and variance for each of the four treatments. For each dependent variable, a comparison of differences among experimental treatments and over the time sequence of repeated measurements was then undertaken. A repeated measures ANOVA, using initial conditions as covariates, was used to evaluate time and treatment effects and interactions. Treated responses were compared to the untreated response using orthogonal polynomials. Since pretreatment rates were not available, soil erosion was evaluated using an analysis of variance rather than the analysis of covariance. Statistical analysis of the time and treatment interaction for computed diversity indices was completed using the bootstrap technique PROC MULTTEST in SAS (Efron and Tibshirani, 1993; Westfall and Young, 1993; SAS Institute, 1996). Adjusted *P*-values, which maintain a constant Type I error across the full range of comparisons, were used to determine significant differences among means (10 000 bootstrap iterations were used). A probability level of 0·05 was used to discern significant differences.

Results

Foliar cover changes

The foliar cover of juniper was dramatically reduced in 1996 by mechanical treatment (Table 1). This fuelwood harvest, which left a residual overstory density of 15 trees/ha, decreased juniper cover by 94–97% with no evidence of recovery during subsequent growing seasons. Since juniper comprised a vast majority of the overstory, total tree cover was correspondingly reduced. However, no significant reductions were observed for pinyon pine. The effect of the overstory removal treatment on shrubs was to produce an increase in foliar cover through time on all harvested plots. This increase was largely the result of expanding coverage of the most prominent shrub, broom snakeweed, from approximately 1% to ≥3% cover. Overall woody plant cover on the control plots remained stable throughout this period.

Following overstory reduction, the foliar cover of graminoids on all harvested plots was significantly greater than on controls (Table 1). While grass cover on control plots expanded by about 150% in subsequent growing seasons, increases on the harvested plots were consistently greater, approaching 250%. Significant linear increases in graminoid cover occurred through time on all harvested plots; however, there were no significant differences among the methods of slash treatment. With increases in the cover of other grasses not significant, blue grama and black grama appear to be the principal graminoids responsible for the above

Table 1. Plant cover response to overstory thinning and slash treatments (% cover)

	Control	Slash removed	Slash clustered	Slash scattered	Adjusted mean[a]
Trees					
1995	24·5	17·5	16·6	25·5	
1996	18·3	0·8	0·1	1·5	5·1
1997	21·5	0·0	0·7	1·5	5·9
Adjusted mean[a]	19·6	0·8[b]	1·0[b]	0·7[b]	
One-seed juniper					
1995	22·0	16·5	16·1	25·5	
1996	18·3	0·8	0·0	1·5	5·1
1997	21·5	0·0	0·2	1·5	5·8
Adjusted mean	22·8	4·8[b]	5·7[b]	9·5[b]	
Pinyon pine					
1995	0·0	1·0	0·5	0·0	
1996	0·0	0·0	0·1	0·0	0·0
1997	0·0	0·0	0·5	0·0	0·1
Adjusted mean	0·2	0·4	0·2	0·2	
Shrubs					
1995	0·5	1·7	1·0	0·1	
1996	0·0	0·3	0·6	0·1	0·2[c]
1997	1·0	6·5	2·8	3·5	3·5[c]
Adjusted mean	15·3	2·6	17·4		
Broom snakeweed					
1995	0·0	1·7	1·0	0·1	
1996	0·0	0·3	0·6	0·1	0·2[c]
1997	0·5	6·5	2·8	3·5	3·3[c]
Adjusted mean	0·1	3·6	1·8	1·6	
Graminoids					
1995	7·9	12·2	13·0	8·9	
1996	9·7	27·4	16·6	11·7	16·3[c]
1997	20·2	38·0	35·0	30·6	30·9[c]
Adjusted mean	11·0	35·2[b]	29·6[b]	28·6[b]	
Blue grama					
1995	5·6	8·5	10·3	7·1	
1996	7·0	16·0	16·6	11·7	11·2[c]
1997	20·2	38·0	35·0	30·6	18·9[c]
Adjusted mean	14·4	18·0	11·9	15·8	
Black grama					
1995	1·2	1·4	0·7	1·0	
1996	2·0	3·9	1·6	2·0	2·4[c]
1997	7·0	3·9	4·8	5·2	5·2[c]
Adjusted mean	4·9	5·3	1·6[b]	3·4	
Galleta					
1995	0·3	0·2	0·8	0·1	
1996	0·3	1·7	1·0	0·8	0·9
1997	0·9	5·2	3·8	2·8	3·2
Adjusted mean	0·6	3·5	2·1	2·0	
Ring muhly					
1995	0·4	1·4	1·1	0·3	
1996	0·3	3·0	0·6	0·1	1·0
1997	0·5	4·2	2·0	0·5	1·8
Adjusted mean	1·1	2·6	0·8	1·0	
Forbs					
1995	1·4	0·4	0·5	0·9	
1996	2·1	2·4	1·0	2·1	1·9
1997	0·6	2·8	1·3	1·6	1·6
Adjusted mean	0·5	3·2[b]	1·5	1·7	

[a] Post-treatment mean adjusted by analysis of covariance.
[b] Significantly different from untreated control plots, $P \leq 0{\cdot}05$.
[c] Significant change through time following treatment, $P \leq 0{\cdot}05$.

result. But, because of the high variability in cover measurements for individual grass species, when adjusted for initial conditions, single species differences among treatments were generally not significant and thus largely time driven ($P<0{\cdot}05$). Only for the clustered slash treatment was black grama cover found to be significantly less than on other treatments. Following harvest, grasses expanded into newly available growing spaces which were formerly adjacent to and beneath the crowns of junipers. The smallest increase in grass cover was noted on control plots where the juniper overstory continued to dominate the plant community. Significant increases through time in the foliar cover of forbs were not observed, but significant differences among the methods of slash treatment were noted. Slash removal following fuelwood harvest resulted in a significant rise in forb cover. However, overall forb presence on the site remained very low at <3% cover.

Plant diversity dynamics

A total of 41 vascular plant species were found on the Abo study plots (Table 2). With very few tree species present in this plant community, one-seed juniper dominated the overstory prior to

Table 2. Plant species present on the Abo study site, Cibola NF

	Scientific name	Common name
Trees	*Juniperus monosperma*	one-seed juniper
	Pinus edulis	pinyon pine
Shrubs	*Gutierrezia sarothrae*	broom snakeweed
	Opuntia spp.	pricklypear cactus
	Rhus trilobata	skunkbush sumac
Graminoids	*Aristida purpurea*	purple threeawn
	Bouteloua curtipendula	sideoats grama
	Bouteloua eripoda	black grama
	Bouteloua gracilis	blue grama
	Deschampsia spp.	hairgrass
	Distichlis spicata	inland saltgrass
	Elymus elymoides	longleaf squirreltail
	Eragrostis cilianensis	stinking lovegrass
	Festuca octoflora	six-weeks fescue
	Hilaria jamesii	galleta
	Kolaria cristata	junegrass
	Lycurus phleoides	wolftail
	Muhlenbergia torreyi	ring muhly
	Oryzopsis micrantha	little ricegrass
	Panicum obtusum	vine mesquite
	Schedonnardus paniculatus	tumblegrass
	Sporobolus cryptandrus	sand dropseed
Forbs	*Artemesia campestris*	sagewort wormwood
	Chaetopappa ericoides	roseheath
	Chenopodium graveolens	ragleaf goosefoot
	Cryptantha spp.	catseye
	Erigeron spp.	fleabane
	Euphorbia fendleri	Fendler spurge
	Euphorbia spp.	spurge
	Lepidium spp.	pepperweed
	Linum spp.	flax
	Melampodium leucanthum	plains blackfoot
	Nama dichotomum	nama
	Physalis spp.	groundcherry
	Plantago purshii	woolly indianwheat
	Portulaca oleracea	pursley
	Sisymbrium linearifolium	linear-leaved tansy mustard
	Solanum eleagnifolium	silverleaf nightshade
	Sphraeralcea coccinea	scarlet globemallow
	Taraxacum officinale	dandelion
	Verbena spp.	verbena

Total plant species=41.

fuelwood harvest. Juniper remained the principal tree following treatment, but was now widely scattered at intervals approximating 20–30 m, simulating a grassland savanna condition. Very few shrubs were present on this site, with broom snakeweed being the only species having more than a trace occurrence. The variety of graminoids is evident; however, only a few such as blue grama, black grama, galleta and ring muhly appeared to be abundant. Sideoats grama, purple threeawn and sand dropseed were well represented on some portions of the site. Few forb species were present and, with none being prominent, they typically persisted at very low levels prior to and following treatment.

During the 1996 and 1997 growing seasons, species richness (N_0) was significantly greater than controls only on plots where slash had been completely removed following fuelwood harvest (Table 3). Although representing a 50% rise, the increase from 8 species before treatment to 12 species is indicative of the overall low richness in this plant community. During 1996, species richness also increased significantly on plots where slash was evenly scattered as a mulch; however, these values declined to near pre-treatment levels by 1997. Richness remained unaffected on plots where slash was clustered following harvest.

Fuelwood harvest and slash treatment alternatives caused no significant changes in plant species diversity relative to untreated control plots (Table 3). Diversity did progressively increase through time on all but the clustered-slash treatment, with increases becoming significant for the scattered-slash plots by 1996 and the control plots in 1997. The largest increase for the Shannon diversity index (H'), from 0·85 to 1·34, was observed on scattered-slash plots. Plant species evenness was unaffected by fuelwood harvest and slash treatment alternatives during this time.

Table 3. Plant species richness, diversity and evenness responses to overstory thinning and slash treatments

	Control	Slash removed	Slash clustered	Slash scattered
Number of species:				
1995	7·5	8·0	8·3	8·3
1996	10·0	12·3[ab]	8·3	10·8[b]
1997	7·5	10·8[a]	7·5	9·8
Shannon index:				
1995	0·97	1·24	1·16	0·85
1996	1·14	1·41	0·97	1·27[b]
1997	1·30[b]	1·46	1·14	1·34[b]
Modified hill ratio:				
1995	0·61	0·81	0·68	0·62
1996	0·65	0·63	0·67	0·72
1997	0·77	0·68	0·71	0·63

[a] Significantly different from untreated control plots, $P \leq 0{\cdot}05$.
[b] Significant change through time following treatment, $P \leq 0{\cdot}05$.

Understory biomass

The standing biomass of herbaceous understory plants increased progressively through time on all treatments (Table 4). While pretreatment values ranged from 320 to 429 kg/ha, post-treatment levels varied from 630 to 1034 kg/ha following the 1997 growing season. Although biomass on control plots increased by 70%, that on the scattered-slash plots rose by 132%, that on the slash-removed plots grew by 141% and that on the clustered-slash plots increased by 215% during this period. Herbaceous plant biomass on all fuelwood harvested plots was significantly greater than the biomass measured on unharvested controls.

Plant nutrients and soil chemistry

Nutrient concentrations in understory plant foliage were unaffected by fuelwood harvest and slash treatment alternatives (Table 5). Although levels of Fe were somewhat high, total N, Zn and B were generally low and P, K, Ca, Mg, Na, Mn, Cu and Al were quite variable, all values fell within the normal range for such plants. Experimental treatments also resulted in no significant changes in surface soil chemistry (Table 6). With concentrations of Ca high and values for NO_3-N, NH_4-N, Mg, Na and SAR relatively low, levels of total N, P, K, organic matter and pH were within the normal range for arid and semiarid soils.

Table 4. Understory herbaceous plant biomass response to overstory thinning and slash treatments (kg/ha)

	Control	Slash removed	Slash clustered	Slash scattered	Adjusted mean[a]
1995	369·5	429·0	320·5	385·5	
1996	338·3	558·0	503·5	449·8	462·4[c]
1997	629·8	1034·0	1009·5	895·3	892·1[c]
Adjusted mean[a]	482·3	809·4[b]	742·4[b]	674·9[b]	

[a] Post-treatment mean adjusted by analysis of covariance.
[b] Significantly different from untreated control plots, $P \leq 0{\cdot}05$.
[c] Significant change through time following treatment, $P \leq 0{\cdot}05$.

Table 5. Understory plant foliar nutrition response to overstory thinning and slash treatments (mg/kg)

	Control	Slash removed	Slash clustered	Slash scattered
N				
1995	6575	7550	7425	6300
1997	6575	6353	7240	7055
Adjusted mean[a]	6978	5741	6759	7744
P				
1995	500	575	500	450
1997	899	1050	1362	1071
Adjusted mean	847	1626	1310	599
K				
1995	2350	3575	3000	2575
1997	4609	4099	4211	4912
Adjusted mean	4929	3672	4134	5095
Ca				
1995	3225	4800	3400	4775
1997	2666	3303	2766	3069
Adjusted mean	2871	3117	2928	2889
Mg				
1995	1150	1500	1300	1425
1997	778	855	905	853
Adjusted mean	777	856	905	853
Na				
1995	125	225	175	175
1997	156	159	149	145
Adjusted mean	149	166	149	145
Fe				
1995	1100	1391	1466	1886
1997	856	718	636	681
Adjusted mean	1175	779	631	306
Mn				
1995	96	119	109	114
1997	49	55	57	57
Adjusted mean	55	50	57	55
Zn				
1995	32	33	29	28
1997	20	24	18	17
Adjusted mean	21	25	17	15
Cu				
1995	6	7	6	6
1997	14	28	15	15
Adjusted mean	13	65	9	9
B				
1995	12	17	14	14
1997	26	25	30	22
Adjusted mean	28	22	30	21
Al				
1995	228	310	316	406
1997	896	849	693	739
Adjusted mean	1289	874	690	324

[a] Post-treatment mean adjusted by analysis of covariance.
[b] Significantly different from untreated control plots, $P \leq 0{\cdot}05$.

Litter cover, soil exposure and erosion

Litter cover on fuelwood harvested plots was significantly increased over that on controls, with a rise during the 1996 year of treatment and a significant decline by the end of the following growing season (Table 7). The percentage of bare soil correspondingly decreased during this period, resulting in significantly less soil exposure on harvested plots than on control plots. Despite this decline in exposed soil, no significant differences in soil erosion rates were observed (Table 8). Although the mean soil loss during this period on harvested plots ranged from 1·2 to 3·5 mm and that on controls averaged 0·2 mm, the high variability among measurements rendered these differences nonsignificant.

Discussion

Effects on foliar cover

Fuelwood harvest, which left a residual density of 15 trees/ha in this pinyon-juniper woodland, dramatically reduced overstory cover from as high as 25% to <2%, creating a plant community structure similar to that of a savanna. The abrupt decrease in competition from the dominant overstory species on this shallow soil allowed grass to rapidly expand from as low as 9% cover to as high as 38% cover within two growing seasons. The inverse relationship that frequently exists between overstory cover and understory cover in pinyon-juniper woodlands has been long recognized (Parker, 1945; Pieper, 1993; Erramouspe, 1994; Tausch and West, 1995; White *et al.*, 1997), with groundcover in very dense stands being nearly absent (Tausch and Tueller, 1990). This interspecific competition effect appears greatest on sites with shallow soils (<60 cm), since juniper trees have widely spreading lateral root systems that are able to out-compete many herbaceous species for limited nutrient and water resources (Johnsen, 1962; Gottfried *et al.*, 1995; Wilcox *et al.*, 1996b). The dynamics of water availability is highly related to the pattern of vegetation in semiarid pinyon-juniper environments, with lower soil temperatures and rates of evaporation resulting in greater soil water content beneath tree canopies than in the interstitial spaces (Wilcox and Breshears, 1995; Breshears *et al.*, 1998). Horizontal variations in soil moisture across a site are as important in discerning plant-water relationships as those associated with depth in the soil

Table 6. Soil chemistry response to overstory thinning and slash treatments

	Control	Slash removed	Slash clustered	Slash scattered
NO_3-N (mg/kg)				
1995	3·9	3·8	3·8	4·3
1997	1·2	1·0	1·2	1·2
Adjusted mean[a]	1·2	1·0	1·2	1·2
NH_4-N (mg/kg)				
1995	0·3	0·2	0·2	0·2
1997	2·0	2·4	2·0	2·4
Adjusted mean	2·1	2·4	1·9	2·4
Total N (mg/kg)				
1995	1400	1278	1396	1337
1997	640	998	950	1143
Adjusted mean	411	653	802	1089
Total P (mg/kg)				
1995	295	309	289	300
1997	271	335	289	283
Adjusted mean	272	332	291	282
Total K (mg/kg)				
1995	1469	2357	1806	1316
1997	1555	1758	1874	1687
Adjusted mean	1705	1409	1835	1924
Exch. Ca (meq/100g)				
1995	49	53	50	53
1997	24	25	21	31
Adjusted mean	24	25	22	30
Exch. Mg (meq/100g)				
1995	1·4	1·5	1·5	1·4
1997	2·2	2·0	2·2	2·1
Adjusted mean	2·2	2·0	2·2	2·0
Exch. Na (meq/100g)				
1995	0·02	0·13	0·05	0·07
1997	0·04	0·04	0·04	0·05
Adjusted mean	0·05	0·02	0·04	0·05
SAR				
1995	0·01	0·07	0·03	0·04
1997	0·12	0·21	0·23	0·14
Adjusted mean	0·01	0·36	0·20	0·14
Elec. Cond. (dS/m)				
1995	0·60	0·67	0·63	0·67
1997	0·25	0·28	0·24	0·27
Adjusted mean	0·26	0·27	0·24	0·26
pH				
1995	7·43	7·35	7·37	7·40
1997	8·03	8·03	7·99	8·06
Adjusted mean	7·94	8·11	8·03	8·02
Organic Matter (%)				
1995	2·59	2·38	2·68	2·54
1997	1·53	1·35	1·72	1·71
Adjusted mean	1·58	1·17	1·87	1·70

[a] Post-treatment mean adjusted by analysis of covariance.
[b] Significantly different from untreated control plots, $P \leq 0{\cdot}05$.

profile (Breshears, 1993). Except for higher initial grass cover (10%) on our study area, pretreatment conditions were very similar to those described for drier pinyon-juniper sites: overstory cover 20–30%, understory cover <5% and exposed soil nearly 70% (Miller and Wigand, 1994).

Table 7. Litter cover and soil exposure response to overstory thinning and slash treatments (% cover or exposure)

	Control	Slash removed	Slash clustered	Slash scattered	Adjusted mean[a]
Litter					
1995	25·6	21·2	15·1	29·7	
1996	19·9	28·2	18·0	36·6	25·0[c]
1997	17·0	13·0	7·2	25·2	15·6[c]
Adjusted mean[a]	15·0	22·9[b]	21·3[b]	21·9[b]	
Soil					
1995	65·2	63·8	70·5	60·6	
1996	62·5	42·7	67·2	50·8	55·8[c]
1997	61·7	39·6	53·7	40·1	48·8[c]
Adjusted mean	61·9	42·3[b]	55·3[b]	49·6[b]	

[a] Post-treatment mean adjusted by analysis of covariance.
[b] Significantly different from untreated control plots, $P \leq 0{\cdot}05$.
[c] Significant change through time following treatment, $P \leq 0{\cdot}05$.

Table 8. Soil erosion response (mm) to overstory thinning and slash treatments (1995 to 1997)

	Control	Slash removed	Slash clustered	Slash scattered
Mean soil loss	0·2	3·5	1·5	1·2
Range	−2·1 to 3·0	−1·3 to 12·1	−1·2 to 5·8	−3·1 to 5·9

Juniper reduction in the overstory was also related to increases in the cover of shrubs, principally broom snakeweed, and forbs. Since these increases were small, it is unclear whether they were driven by relief from competition with juniper or resulted from soil disturbance related to fuelwood harvesting activities which created favourable microsites for their modest expansion. It appears as though slash removal following harvest was the only treatment that significantly benefitted forb cover during this period. Stirring of the soil surface was greater on these plots than on the other treatments where slash remained on-site. Except for steadily increasing its cover through time, broom snakeweed appears to follow a similar, though nonsignificant, pattern as that of forbs. As a well known 'increaser' on grazed range sites, the small increases in the cover of snakeweed were very likely facilitated by soil disturbance during wood harvesting. By contrast for graminoids, the significant differences between harvested plots and controls, the relatively similar response pattern to harvest and the absence of differences related to alternative slash treatments indicates that grass cover increases were primarily the result of release from overstory competition and perhaps only secondarily benefited by disturbance of surface soils during harvest. The progressive increase in grass cover across all plots through time, indicates that some benefit may have been provided by resting the site from grazing during this period.

Influence on diversity

Pinyon-juniper environments are frequently characterized by seasonal water deficits, low soil fertility, shallow rocky soils which limit available rooting space and low to moderate species diversity (Gottfried *et al.*, 1995). The 41 species overall and the fewer than one dozen species recorded on each plot are indicative of the low plant diversity on this study site. Plant species diversity is largely determined by interspecific competition interacting with site productivity, microsite heterogeneity and disturbance regimes (Tilman, 1982). Plant community structure of juniper-invaded grasslands typically shifts from being dispersed over the site to being highly aggregated (Carrara and Carroll, 1979) and plant species richness in such woodlands is known to decline as juniper dominance increases in the overstory (Koniak and Everett, 1982). Changes in plant community structure and decreases in understory species are greatest on sites having shallow soils (40–60 cm) and/or southerly aspects (Cottam and Stewart, 1940; Johnsen, 1962; Tress and Klopatek, 1987). Plant diversity dynamics on our study site reflected the shallow soils present (13–51 cm) and the resulting relatively more intense levels of interspecific competition.

Plant species richness generally increased during the 1996 growing season and then declined the following year to near pretreatment values. This rise was significant only on plots where slash was completely removed or scattered as a mulch and not at all evident where slash was left clustered around the base of harvested trees. Since species richness during both 1996 and 1997 was significantly greater than controls only on the plots where slash was completely removed following fuelwood harvest, it is quite likely that decreasing competition from overstory junipers did not by itself have a major impact upon plant species numbers during this period. Rather, disturbance of the soil during slash removal was also necessary to create microsites favourable for the establishment of additional species. Modest increases in the cover of forbs, broom snakeweed and some graminoids

appear to be associated with this general rise. The Shannon index indicates a general increase through time in species diversity for all treatments except where slash was left clustered. Only on the controls and on plots where slash was scattered as a mulch was this rise significant. While our experimental treatment may have had some beneficial effects upon diversity, more likely the complete rest from grazing during this period allowed plant diversity to modestly improve on this site. Diversity losses elsewhere have been attributed to excessive grazing (Milton *et al.*, 1994). Although fuelwood harvesting has dramatically reduced the juniper presence on this site, the lack of any significant response in species evenness indicates a general absence of change in the relative dominance and resource allocation among understory plant species.

In focusing on the vascular plants in this pinyon-juniper woodland, only low levels of diversity were recorded. However, substantially greater diversity exists in these ecosystems when soil biota in various microhabitats are considered (Dindal, 1990; Whitford, 1991). Cryptogamic crusts, which are composed of cyanobacteria, lichens, mosses, green algae and fungi, are also prominent features of pinyon-juniper woodlands (Belnap, 1990; West, 1990). In addition to stabilizing surface soils (Belnap and Gardner, 1993) and conserving site nutrients and water (Loftin and White, 1996), these biotic crusts also contribute to the diversity of these ecosystems. It is worth noting that these crusts are easily broken by the mechanical action of livestock hooves (Brown, 1994).

Herbaceous biomass

Herbaceous understory production is known to decline as crown cover increases in the overstory of pinyon-juniper woodlands (Arnold *et al.*, 1964). Indeed, more intense competition from the increasing presence of juniper in combination with excessive livestock grazing is widely thought to be responsible for the overall decline in herbaceous productivity on such rangelands (Milton *et al.*, 1994). Therefore, overstory reduction or removal is one possible means of increasing understory productivity (Gottfried and Severson, 1994). However, at least two-thirds of the overstory crown cover must be removed to achieve any substantial increase in the growth of understory plants (Fowler and Witte, 1987).

Overstory reduction, leaving a residual density of 15 trees/ha, created a savanna-like condition where herbaceous plant biomass dramatically increased from 300–400 kg/ha to 900–1000 kg/ha. These values are of similar magnitude to those reported elsewhere in New Mexico for a range of pinyon-juniper woodland sites (Pieper, 1995). With herbs being minor, this herbaceous biomass was principally composed of various grasses that responded positively to being released from competition with overstory junipers. However, herbaceous biomass also increased progressively through time across the entire site, including the unharvested control plots. This overall trend may be indicative of the benefits derived from resting the site from livestock grazing during this period.

Nutrient dynamics

It was not surprising that foliar nutrient levels and soil chemical properties were unaffected by fuelwood harvest and slash management alternatives during the initial time interval following treatment. Significant redistribution of nutrients among the components of an ecosystem is typically associated with a multi-year latency period. Therefore, the early changes observed in vascular plant cover, diversity and productivity were most likely the result of reallocation of available water resources among the remaining plants. As residual organic debris decomposes and is consumed by future prescribed fires, changes in the vegetation pattern will very likely also be related to shifts in nutrient allocation among plant species. While tree removal and slash burning is known to affect the rates of nutrient mineralization and nitrification in the soils of pinyon-juniper woodlands (DeBano *et al.*, 1987), leaving slash on the ground to gradually decay along with other litter permits a slower release of nutrients and retards the loss of nitrogen from the ecosystem (Evans, 1988). Slash scattered upon the soil also aids in nutrient conservation by acting as concentration points for nutrients lost from source areas elsewhere on the site (Ludwig and Tongway, 1995).

Nutrients in semiarid woodlands, shrublands and grasslands are typically clustered in association with vegetation, while the surrounding areas of exposed soil are frequently resource depleted and function as source areas for soil erosion (Hook *et al.*, 1991; Bolton *et al.*, 1993; Kieft, 1994; White *et al.*, 1997). Juniper trees influence site nutrient distribution by extracting nutrients from interstitial spaces between trees and concentrating them beneath the tree canopy (Klopatek, 1987a,b), forming 'fertility islands' (Garcia-Moya and McKell,

1970). The levels of nutrients (C, N, P, K, Ca, Mg, Na, S, Fe, Mn, Cu, Zn), rates of N mineralization, numbers of nitrifying bacteria and various physical and chemical properties of the soil have been found to be significantly higher and more favourable beneath tree canopies than in the interstitial spaces (Barth, 1980; Everett *et al.*, 1986; Klopatek, 1987a,b; Klopatek and Klopatek, 1987; Klopatek *et al.*, 1990; Davenport *et al.*, 1996). Once established this spatial pattern is apparently quite persistent, since the differential distribution of nutrient resources between impoverished interstitial spaces and enriched areas formerly beneath the canopy is still evident 5 to 8 years following tree harvest (Thran and Everett, 1987).

Litter cover, soil exposure and erosion

Fuelwood harvest produced an immediate increase in litter cover which resulted in a significant decrease in soil exposure on the study site. Although finer logging slash materials began to disappear through decomposition by the second post-treatment season, the amount of exposed soil continued to decline as the cover of living plants, principally understory grasses, progressively increased. Also, since no significant differences for litter cover or soil exposure were noted among the slash treatment alternatives (removing, clustering, scattering), it is possible that the cover of living understory plants is as important in providing soil protection as is the residual coarse debris and fine litter left on-site following overstory reduction. In the long-term, the cover of living plants (including cryptogams) may very likely be more important to soil protection than slash or litter. However, slash cover does provide a degree of protection against soil erosion (Evans, 1988) by preventing sheet erosion and creating debris dams which slow the rate of runoff from a site (Ernest *et al.*, 1993). Scattering slash across a harvested site, was elsewhere found to result in the least surface runoff and sediment loss (Wood and Javed, 1992).

Although no significant differences in soil erosion rates were discernable among the experimental treatments, there was a fairly consistent pattern of small soil losses. Since our erosion measurement bridges were located within intercanopy areas, it was surprising that high rates of soil loss were not observed, as soils in interstitial spaces are known to have greater erosion rates than those beneath the tree canopy (Wilcox *et al.*, 1996b). However, many pinyon-juniper woodlands are subject to accelerated erosion while others are undergoing little or no soil loss (Davenport *et al.*, 1998). Apparently, summer thunderstorms are the most important source of surface runoff on many pinyon-juniper sites (Wilcox *et al.*, 1996a). Soil loss through water erosion is a prominent pathway by which pinyon-juniper woodlands lose nutrient resources, thus progressively degrading site productivity (Baker *et al.*, 1995). Large exports of soil and nutrients did not appear to be a problem on our study site, during this time period.

Restoring the savanna ecosystem

Extensive evidence indicates that pinyon-juniper ecosystems have been highly variable in their range of occupancy and physiognomy during past millennia, as climate change has broadly influenced plant growth and natural fire regimes (Betancourt, 1987, 1996; Betancourt *et al.*, 1993; Miller and Wigand, 1994). A semiarid site at various points in time may have been occupied by native grassland, savanna or pinyon-juniper woodland, depending on the prevailing environmental conditions and/or activities of aboriginal people. However, the progressive expansion of pinyon-juniper woodlands into semiarid grasslands during the past century has caused substantial concern about declines in understory plant diversity and productivity and increases in soil erosion and nutrient loss (Parker, 1945; Johnsen, 1962; West, 1984; Davenport *et al.*, 1996). Juniper invasion of grasslands may also adversely affect the hydrological cycle by promoting soil compaction, decreased infiltration, increased surface water runoff, increased interception loss of precipitation and increased evapotranspiration which result in lower levels of available soil moisture (Angell and Miller, 1994; Miller and Wigand, 1994). While one may argue that the recent trend of juniper expansion is yet another in a long series of fluctuations in this quite changeable ecosystem, evidence to the contrary suggests that the current situation is a result of human interference with natural ecological processes, principally heavy grazing by non-native ungulates that have reduced fine fuels to levels so low as to almost completely thwart the life functions in these ecosystems that are dependent upon periodic fire (Grover and Musick, 1990; Jeltsch *et al.*, 1996). Continuing fire suppression efforts by humans have further facilitated development of high-density woodlands, for which there are few historical analogs except those present on rocky sites with fuels insufficient to sustain a fire. Therefore, as an artifact of

human management, high-density pinyon-juniper woodlands may be appropriately considered as candidates for ecological restoration to lower-density woodlands or savannas, where scattered pinyon pines and juniper trees coexist with a vigorous understory of native grasses and forbs which will contribute to soil stabilization and conservation of site nutrient and water resources.

While grassland savannas are known to persist for long periods in semiarid ecosystems (Risser, 1995), it is worth noting that selection of this condition as the preferred ecological status of a particular site is somewhat arbitrary and based on the objectives of the land manager. A wide range of tree densities naturally occur in this ecosystem, providing managers with a variety of options ranging from no trees in a grassland to a low number per unit area typical of a savanna to a moderate number characteristic of an open woodland. Restoration neither implies returning this ecosystem to conditions prevailing during pre-Columbian times nor any other arbitrarily chosen point in history. The now widespread occurrence of non-native species, extirpation of native species and our lack of detailed data concerning understory and overstory composition, structure and function during these early times would make such attempts generalized efforts that might overlook key ecosystem components and processes. Rather, restoration in this context was primarily focused on restoring the functional processes that will sustain the numerous ecological, economic and social values associated with this ecosystem. In achieving functional restoration, the objective was to employ fuelwood harvesting as a means of (1) reducing use of site resources by highly competitive junipers while retaining the pinyon pine component in the overstory, (2) encouraging establishment and growth of understory herbaceous plants and (3) utilizing slash to slow surface runoff, stabilize soils and conserve site nutrients and water. By stabilizing and protecting the physical environment and rebalancing composition among overstory and understory plant species, this effort sought to improve biological productivity and diversity.

Restoring biological diversity is perhaps the greatest challenge to restoration efforts, with even the best examples able to restore only a fraction of the natural plant species richness (Allen, 1995). The plant community response following juniper removal in woodlands is quite variable and highly dependent upon understory conditions prior to harvest (Miller and Wigand, 1994). However, evenly scattering residual logging slash across a harvested site will promote growth of grasses and forbs by providing partial shade for microsites, stabilizing the soil surface from erosion and armoring microsites against close grazing by ungulates (Loftin *et al.*, 1995). On a larger scale, restoration efforts might be best pursued by implementing treatments which create a vegetation mosaic across the landscape. This would result in the widest variety of ecological conditions, ranging from grasslands to savannas to open woodlands to dense woodlands, and ensure that many diverse habitats are provided for numerous resident and transient organisms. Although techniques such as creating numerous 'sunspots' (0·5 – 1 ha patch-clearcuts) could be employed to increase habitat edge and augment understory plant production and diversity in woodlands (Evans, 1988), juniper removal across larger contiguous areas may sometimes be appropriate when benefits are intended for obligate grassland species.

Mechanical treatments provide an effective means of more rapidly restoring pinyon-juniper woodland to a grassland savanna ecosystem than could be achieved by other means such as fire alone. Indeed, with larger junipers fairly resistant to fire and understory fuels often insufficient to carry fire, intervention by mechanical means may be essential for achieving restoration (phase I). The restored site can then be more quickly scheduled for fire maintenance (phase II). The next phase of this study will examine the differential recovery effects in this ecosystem resulting from fuelwood harvest and slash treatments followed by prescribed burning as contrasted with those resulting from treatment with prescribed fire alone.

Conclusion

Within two growing seasons, fuelwood harvesting which left a residual overstory density of 15 trees/ha caused substantial changes in a relatively dense pinyon-juniper woodland that had a depauperate herbaceous understory and nearly 70% bare soil exposure. The decline in juniper was associated with increases in foliar cover of graminoids, forbs and broom snakeweed. Plant species richness and diversity generally increased following treatment, while species evenness remained unaffected during this period. The standing biomass of herbaceous plants (primarily grasses) progressively increased through time and was significantly greater on all harvested plots than on uncut controls. Foliar nutrient status and soil chemical properties were not affected by treatment. Litter cover significantly

increased and bare soil exposure decreased on all harvested plots, but rates of soil erosion remained low and unaffected by treatment.

Generally, very few differences resulted from application of the slash management alternatives, indicating that relief from intense competition with junipers was the primary effect of experimental treatment. Complete removal of slash following fuelwood harvest appeared to require greater levels of on-site activity and likely resulted in somewhat more disturbance of the soil surface than other alternatives. The resulting availability of new microsites for plant establishment and growth quite possibly contributed to the significantly higher degree of species richness on these plots following harvest. Conversely, leaving slash clustered at the base of harvested trees required lower levels of on-site activity and likely resulted in less disturbance of the soil surface. Lower diversity values for this alternative are consistent with this conclusion. Scattering slash across the plots following harvest also required appreciable on-site activity and likely resulted in a fair degree of disturbance of the soil surface. In addition to creating new favourable microsites, much of the area was also covered by slash which served as a mulch, ameliorating environmental conditions. This dual effect very likely accounted for the significant increases in species richness and plant diversity observed on slash-scattered plots following treatment. Therefore, while the difference among slash treatment alternatives appears modest, we recommend evenly scattering slash across harvested pinyon-juniper sites as the preferred means of ameliorating microsite conditions, abating soil loss, conserving nutrient and water resources and augmenting plant productivity and diversity.

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