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A comparison of fire hazard mitigation alternatives in pinyon–juniper woodlands of Arizona

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ABSTRACT

Concern over uncontrollable wildfire in pinyon–juniper woodlands has led public land managers in the southwestern United States to seek approaches for mitigating wildfire hazard, yet little information is available concerning effectiveness and ecological responses of alternative treatments. We established a randomized block experiment at a pinyon–juniper site in northern Arizona and tested effects of no treatment (Control), thinning only (Thin), prescribed fire only (Burn), and thinning followed by prescribed fire (Thin + Burn) on overstory structure, hazardous fuels reduction, and woody understory responses. One year after implementation, mean trees per hectare (TPH) of Utah juniper (*Juniperus osteosperma*) and pinyon pine (*Pinus edulis*), and basal area (BA) of pinyon, were significantly ($P < 0.05$) less in Thin and Thin + Burn treatments than Control. Additionally, pinyon TPH was less in Burn than Control. Quadratic mean diameter was significantly greater in Thin and Thin + Burn than in Control and Burn treatments. Thinning shifted diameter distributions from uneven- to even-sized. Crown fuel load (CFL) of both pinyon and juniper was significantly lower in Thin and Thin + Burn compared with Control and Burn treatments. Thin, Burn, and Thin + Burn treatments resulted in significantly greater 1-h surface fuel loads compared with the Control. The Thin treatment resulted in significantly greater mean load of the 1000-h fuel class compared with Burn and Control treatments, but did not differ from Thin + Burn. Forest floor Oi (litter) layer was not significantly affected by the treatments but Oe + Oa (duff) depth was significantly less in the Burn treatment compared with Thin and Control. Live shrubs and tree regeneration showed no differences among treatments. We concluded that thinning and thinning followed by prescribed fire were effective approaches for fuels reduction; however, resulting stand structures may be novel and outside the historical range of variability. Prescribed fire alone had minimal effects on structure and fuels reduction. Woody shrubs and tree regeneration in the understory suggested that these treatments may not have long-term deleterious ecological effects.

1. Introduction

Presently, there is strong interest in the development and testing of approaches for mitigating fire hazards in forests of the western United States (USDA Forest Service, 2000). Treatments that attempt to balance fuels reduction objectives with conservation of ecological integrity are highly desirable (Dellasala et al., 2004). Fuels reduction treatments may complement ecological restoration goals in seasonally dry, frequent fire-adapted forest types such as ponderosa pine (*Pinus ponderosa*) and lower elevation mixed-conifer forests (Stephens, 1998; Miller and Urban, 2000; Fulé et al., 2002; Brown et al., 2004). In these ecosystems, recruitment of young trees into lower canopy layers and accumulation of surface and ground fuels as a result of 20th century fire exclusion have shifted fire regimes from low- to high-severity (Covington et al., 1994). However, in moderate or infrequent-fire types, such as pinyon–juniper woodlands, post-settlement fire exclusion may have minimally affected ecosystem physiognomy (Baker and Shinneman, 2004; Floyd et al., 2004). Fuels reduction treatments in these forest types have potential to degrade ecological conditions by creating novel stand structures and altering natural disturbance regimes (Romme et al., 2003). Nonetheless, fuel hazard reduction activities in such ecosystems are being enthusiastically pursued, particularly to mitigate wildfire hazard in wildland–urban interface (WUI) zones. Presently, science-based information to help guide fuels treatments in pinyon–juniper woodlands is scarce.

Principles of fuel hazard reduction treatments have been formulated for frequent fire-adapted forests; these same principles

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also are applied for wildfire mitigation in infrequent-fire types such as pinyon–juniper woodlands (Brown et al., 2004; Agee and Skinner, 2005). According to these principles, the main focus of fuels reduction treatments is to increase forest resilience to crown fire by reducing key elements of fuel complexes and retaining large, fire-resistant trees. Mechanical thinning, prescribed fire, or combinations of the two approaches are commonly used to meet these objectives. Mechanical thinning allows managers to precisely select small trees for removal, thereby reducing ladder and canopy fuels, raising crown base heights, and interrupting surface-canopy fuel continuity. In more productive forest types, flaming combustion of surface fuels can initiate and support spread of crown fires. Surface fuels loads may be effectively reduced by application of prescribed fire (Fulé et al., 2002). In untreated pinyon–juniper woodlands, however, surface fuel loads are typically low and crown fires may be more often initiated by live understory fuels such as shrubs (Baker and Shinneman, 2004). Benefits of mechanical thinning can be negated if slash increases surface fuel loading, and if these fuels are not subsequently treated (Graham et al., 1999).

Prescribed fire alone may be used to accomplish some fuels reduction objectives, but its effectiveness is variable and dependent upon fire intensity and tree characteristics (Sackett et al., 1994; Erskine and Goodrich, 1999). For example, prescribed fire used without mechanical thinning can reduce ground and surface fuels but may not produce desired effects on stand structure (Peterson et al., 1994; Sackett et al., 1996; Fulé et al., 2002). Mechanical thinning followed by prescribed fire is an intensive approach that can precisely reduce fuel complexes and increase forest resilience to wildfire (Fulé et al., 2001; Pollet and Omi, 2002; Strom and Fulé, 2007). Presently, it is unclear whether principles developed for frequent fire systems can be used to effectively mitigate wildfire hazard and conserve ecological integrity of pinyon–juniper woodlands.

In this study, we were interested in comparing alternative fire hazard mitigation treatments in terms of their effects on fuel hazard reduction and woodland structure. We established a replicated experiment on the Kaibab National Forest in northern Arizona, where a mitigation project had been planned with the intent of providing fire protection to Grand Canyon National Park and the nearby community of Tusayan. We tested differences between no treatment, mechanical thinning only, prescribed fire only, and thinning followed by prescribed fire. We asked the following questions: (1) How do thinning and prescribed fire treatments differ in their effects on pinyon–juniper stand structure? (2) Are treatments that follow general fuels reduction principles (*sensu* Agee and Skinner, 2005) effective for mitigating wildfire hazard in pinyon–juniper woodlands? (3) What are the potential long-term ecological effects of implementing these fuels treatments in pinyon–juniper woodlands?

2. Methods

2.1. Study area

The study area for our experiment was a 760-ha site (latitude 36°01′24″ to 35°59′43″, longitude 112°11′55″ to 112°07′38″) located on the Tusayan Ranger District of the Kaibab National Forest in northern Arizona (Fig. 1). The site ranges 2005–2073 m in elevation. Annual precipitation in the area averages about 420 mm and falls bi-modally in winter as snow and in late summer as monsoonal rain (WRCC, 2007). Average maximum and minimum temperatures are 17 and 0 °C, respectively. Soils at the site are mainly Typic Haplustalfs of gravelly loam texture, derived from limestone parent material (USDA Forest Service, 1991). Pinyon–juniper vegetation of the area is classified as Great Basin Conifer Woodland (Brown, 1994). Overstory composition was mainly Utah juniper (*Juniperus osteosperma*) and pinyon pine (*Pinus edulis*). Woodlands at the site were considered mature with some stands greater than 400 years in age. Presettlement fire regime at the site was one of infrequent, stand replacing fire (Huffman et al., 2008). Ponderosa pine (*P. ponderosa*) trees were present on low-lying microsites but were only a minor component of the woodlands in our study. Because of its sparse occurrence in our study plots, we do not report treatment effects on ponderosa pine. Woody understory species at the site were mainly big sagebrush (*Artemisia tridentata*), cliffrose (*Purshia mexicana*), and Apache plume (*Falugia paradoxa*). Shrub-form Gambel oak (*Quercus gambelii*) was also variably present. Herbaceous communities were comprised of grasses such as blue grama (*Bouteloua gracilis*) and Muhlenbergia (*Muhlenbergia* spp.) as well as forbs such as buckwheat (*Eriogonum* spp.) and gilia (*Ipomopsis* spp.).

2.2. Experimental design

In order to evaluate alternative fuels treatments, we established a completely randomized block experiment at the Tusayan study site in 2004. Six experimental blocks were identified based on location and stand delineations done by US Forest Service staff (Fig. 1). Within each block, eight experimental treatment units were randomly selected from a systematic grid (200 m × 200 m) of points generated in a geographic information system ($N = 48$ units). Treatment units, each one-hectare in size, were randomly assigned one of four possible treatments: (1) no treatment (Control); (2) tree thinning from below according to a species-specific prescription (Thin; see Section 2.4); (3) prescribed fire only (Burn); and (4) thinning from below followed by prescribed fire (Thin + Burn). One sample plot, 0.04-ha in size, was established in the center of each treatment unit ($N = 48$ plots).

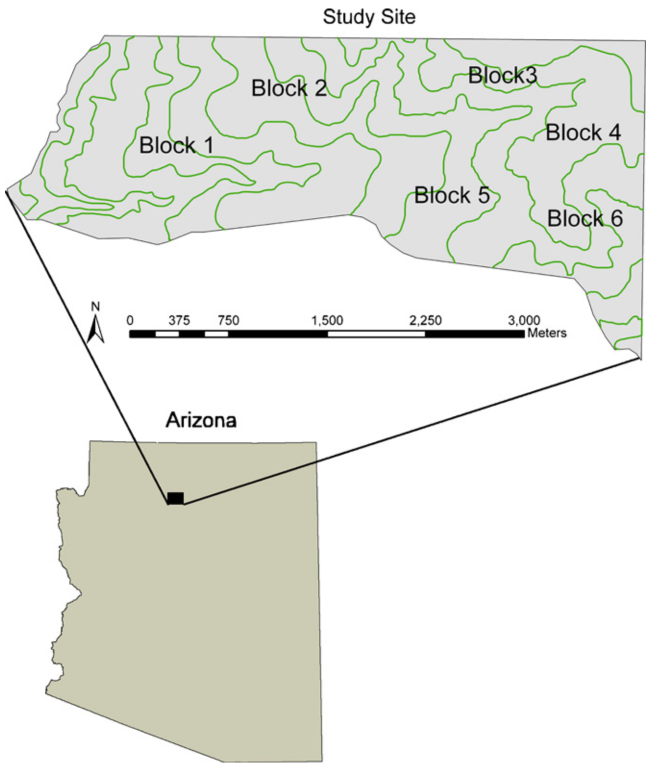

Fig. 1. Tusayan study site and general location of six experimental blocks.

2.3. Field measurements

Sample plots were measured in early summer 2004 before treatment (pretreatment) and again in 2007, 1 year after full treatment implementation (post-treatment). On each sample plot, all live overstory trees (>1.37 m in height) were tallied, identified to species, and measured for stem diameter, average crown diameter, crown base height, and total height. Tree diameter was measured at root collar (drc) and average crown diameter was estimated by taking measurements perpendicular to the main stem and parallel with the longest and shortest crown axes. Tree seedlings (<1.37 m in height) and shrubs were tallied by species on a 100-m^2 (5.64 m radius) plot nested within the larger overstory plot. Woody surface fuels were tallied according to Brown (1974) on one 5.24-m transect established in a random direction from each plot center. Fuels were tallied in the following diameter size classes that correspond to moisture release lag times: (1) <0.6 cm (1-h); (2) 0.6–2.5 cm (10-h); (3) 2.5–7.6 cm (100-h); (4) >7.6 cm, mostly sound wood (1000-h sound); and (5) >7.6 cm, mostly rotten wood (1000-h rotten). Hereafter, woody surface fuels are referred to by their timelag classes (e.g., 1-h fuels). In addition, we used surface fuel transects to record depth of forest floor O horizons. At 10 regularly spaced points on each transect, depth of Oi and Oe + Oa layers were measured to the nearest 0.25 cm. These ground fuel layers are also known as litter and duff, respectively (Pyne et al., 1996).

2.4. Treatment implementation

The experimental thinning prescription we tested was intended to emulate actual fuels reduction treatments planned for the study site (personal communication, H. McRae, Tusayan Ranger District, Kaibab National Forest). On all units selected for thinning, juniper trees up to 30.5 cm drc and pinyon pine trees up to 25.4 cm drc were cut. Tree spacing was not considered. In addition, ponderosa pine trees up to 22.9 cm diameter at breast height (1.37 m above ground) were cut. Gambel oak, tree seedlings, and shrubs were not cut. Thinned trees were lopped (piece length around 61 cm) and thinning slash was scattered. Thinning was done in 2004–2005 by hand crews using chainsaws.

In September 2006, units selected for prescribed fire treatments were burned. Burning was done September 10–27 using hand ignition with drip torches. On these days, relative humidity ranged about 20–60%, daytime temperatures were 10–30 °C, and wind speeds at 6.1 m were <16 km h^{-1}. Lack of continuous surface fuels, particularly on plots that had not been previously thinned, made broadcast burning using either backing or head fires impossible. Instead, crews targeted areas of apparent fuel accumulation (e.g., surface "jackpot" fuels and areas of deeper forest floor) for ignition. We considered burning to be representative of operational fuels reduction tactics for grounds crews.

2.5. Data analysis

Plot data were analyzed using one-way analysis of variance (ANOVA) to test for pretreatment differences in parameters related to overstory structure, woody understory, canopy fuels, and surface fuels. Differences among treatment groups were considered statistically significant when $P \leq 0.05$. Overstory parameters estimated were mean tree density (TPH: number of trees ha^{-1}), quadratic mean diameter (QMD: cm) and basal area (BA: m^2 ha^{-1}). Understory parameters were mean tree seedling and shrub density (number ha^{-1}). Canopy fuels parameters were canopy fuel load (CFL: kg m^{-2}) and canopy base height (CBH: m). Woody surface fuel parameters were weight per unit area by timelag class, which were calculated according to Brown (1974). Forest floor parameters estimated were Oi, Oe + Oa, and total forest floor depths.

To calculate CFL, we used allometric equations that related tree diameter to crown biomass. Allometric relationships we used were from Miller et al. (1981) and Grier et al. (1992) for *J. osteosperma* and *P. edulis*, respectively. Because there were inconsistencies in the literature for classification of fine branch diameters, we restricted our estimates of crown biomass to foliage weight only. Although this underestimates total canopy fuels, tree needles are the main fuel consumed in a crown fire and thus should provide reasonable indication of treatment effects on canopy fuel hazard (Cruz et al., 2003). Crown biomass was estimated for individual live trees and summed at the plot level; this value was then divided by plot area to derive CFL (kg m^{-2}) for each species on each plot.

No significant pretreatment differences among treatment groups were found. Main effects on post-treatment parameters were analyzed using one-way analysis of variance (ANOVA). When main effects were indicated, Fisher's least significant difference (LSD) post-hoc tests were used to assess differences among treatment means. For data that did not meet ANOVA assumptions of equal variance and normal distribution, Kruskal–Wallis non-parametric tests were used to examine treatment effects. When treatment effects were indicated, we used Mann–Whitney tests to analyze rank differences between individual treatment pairs. Main effects and differences among treatment means were considered statistically significant when $P \leq 0.05$.

3. Results

3.1. Overstory structure

Thinning from below (Thin), prescribed fire (Burn), and thinning followed by fire (Thin + Burn) differentially affected tree density and overstory structure compared with untreated controls (Control) (Table 1). Thin and Thin + Burn resulted in significantly fewer trees ha^{-1} (TPH) for both juniper and pinyon pine than the Control treatment. The year following full treatment implementation, mean TPH of juniper was 56% and 66% lower on Thin and Thin + Burn plots, respectively, than on Control plots. Compared to pretreatment conditions, Thin and Thin + Burn TPH decreased by 68% and 78%, respectively. Pinyon pine TPH in Thin and Thin + Burn treatments was 82% and 86% lower, respectively, than the Control mean (Table 1). TPH of pinyon decreased on both Thin and Thin + Burn treatments by 81% compared to pretreatment conditions. Juniper TPH in the Burn treatment was not significantly different from the Control but decreased 22% compared to pretreatment conditions. Pinyon TPH was significantly lower (35%) in the Burn treatment than the Control, and decreased 25% compared to pretreatment conditions (Table 1). Post-treatment decreases of TPH in the Control were 4% and 3% for juniper and pinyon, respectively.

Before treatment, plots generally showed right-skewed diameter distributions with relatively high proportions of trees <30 cm drc (Fig. 2). Thin and Thin + Burn treatments shifted stand structure toward even-sized distributions by removing small-diameter trees. Thin and Thin + Burn treatments resulted in significantly higher quadratic mean diameter compared with Burn and Control treatments (Table 1). Although the Burn treatment reduced the number of juniper and pinyon pine trees in the smallest diameter classes (<20 cm drc), diameter distributions did not appear to be substantially affected (Fig. 2).

None of the alternatives significantly affected juniper basal area (BA) when compared to the Control treatment (Table 1). However, juniper BA decreased in Thin, Burn, and Thin + Burn

Table 1
Means (and standard error) of overstory structure and canopy fuels variables[a] for Utah juniper (JUOS) and pinyon pine (PIED) in pretreatment (2004) and post-treatment (2007) years.

Species	Year-treatment	Structure			Canopy fuels	
		TPH (no. ha^{-1})	QMD (cm)	BA (m^2 ha^{-1})	CFL (kg m^{-2})	CBH (m)
JUOS	*Pretreatment*					
	Control	237 (26.0)	31.5 (2.06)	18.3 (2.27)	0.47 (0.06)	2.0 (0.36)
	Thin	310 (46.4)	26.9 (1.98)	15.5 (1.39)	0.47 (0.28)	1.3 (0.08)
	Burn	302 (39.6)	29.9 (2.90)	21.1 (3.34)	0.55 (0.08)	1.8 (0.20)
	Thin + Burn	344 (43.5)	28.1 (2.97)	19.9 (2.73)	0.48 (0.05)	1.4 (0.13)
	Post-treatment					
	Control	227 (24.5) a	31.9 (2.09) a	17.8 (2.10) a	0.46 (0.06) a	2.0 (0.36) a
	Thin	100 (10.7) b	38.4 (2.12) b	11.4 (1.28) a	0.30 (0.03) b	2.0 (0.16) a
	Burn	235 (27.9) a	28.8 (3.10) a	17.2 (3.58) a	0.46 (0.08) a	1.9 (0.22) a
	Thin + Burn	77 (15.8) b	43.9 (3.30) b	12.0 (2.59) a	0.24 (0.04) b	2.7 (0.20) a
PIED	*Pretreatment*					
	Control	723 (78.4)	17.6 (0.64)	17.1 (1.60)	0.65 (0.06)	1.1 (0.13)
	Thin	510 (56.0)	19.5 (1.28)	15.4 (2.25)	0.54 (0.07)	0.9 (0.14)
	Burn	608 (47.2)	19.6 (1.04)	17.9 (1.43)	0.64 (0.05)	1.2 (0.15)
	Thin + Burn	664 (93.8)	19.7 (1.20)	19.2 (2.77)	0.67 (0.08)	1.1 (0.11)
	Post-treatment					
	Control	700 (77.1) a	17.7 (0.69) a	16.7 (1.64) a	0.64 (0.06) a	1.1 (0.13) a
	Thin	98 (19.1) c	28.4 (4.23) b	8.6 (1.56) b	0.26 (0.05) b	1.2 (0.26) a
	Burn	458 (42.9) b	19.4 (0.95) a	13.5 (1.51) a	0.49 (0.05) a	1.3 (0.16) a
	Thin + Burn	127 (21.0) c	27.6 (2.70) b	8.9 (1.51) b	0.28 (0.05) b	2.1 (0.40) b

Different lowercase letters in post-treatment year indicate significantly different means at $P < 0.05$.
[a] See text for variable acronym definitions.

treatments by 26%, 18%, and 40%, respectively, compared with pretreatment conditions. Thin and Thin + Burn treatments resulted in significantly lower pinyon pine BA compared with Burn and Control treatments, which were not statistically different. The year following treatment, pinyon BA in Thin and Thin + Burn treatments was 51–53% lower than pinyon BA in the Control (Table 1). Pinyon BA decreased in Thin, Burn, and Thin + Burn treatments by 44%, 24%, and 54%, respectively, compared with pretreatment conditions. Juniper and pinyon BA decreased in the Control treatment by 3% and 2%, respectively, compared with pretreatment conditions (Table 1).

In general, treatments had minor effects on overstory species composition. At pretreatment, pinyon pine importance values ranged 1.12–1.24 across all treatments (a value of 1.0 represents equivalent importance among species; values >1 suggest dominance; 2.0 is a maximum value and represents monotype conditions). One season after treatment, pinyon importance ranged 0.92–1.24. Thin and Thin + Burn treatments resulted in shifts toward relatively greater juniper importance, whereas little change in species composition was observed for the Burn treatment.

3.2. Canopy fuels

Overall, canopy fuels were most affected by Thin and Thin + Burn treatments (Table 1). Mean crown fuel load (CFL) of juniper in Thin and Thin + Burn treatments was 35% and 48%, respectively, lower than the Control; pinyon pine CFL in these treatments was 56% and 59%, respectively, lower than the Control. Prescribed fire alone (Burn) did not significantly affect CFL compared with the Control treatment. Juniper CFL in Thin, Burn, and Thin + Burn was reduced by 36%, 16%, and 50%, respectively, compared with pretreatment conditions. Pinyon CFL in Thin, Burn, and Thin + Burn was reduced by 52%, 23%, and 58%, respectively, compared with pretreatment conditions. CFL of both juniper and pinyon in the Control decreased by 2% compared with pretreatment conditions. Crown base height of juniper was not significantly affected by treatment, whereas Thin + Burn resulted in significantly higher CBH of pinyon compared with the Control (Table 1).

3.3. Surface and ground fuels

Treatments significantly affected 1- and 1000-h sound surface fuel classes as well as depth of the Oi + Oe forest floor layer (Table 2). Thin, Burn, and Thin + Burn treatments resulted in 1-h fuel loads that were greater than the Control by 170–240%. No significant differences among treatments were found for 10- or 100-h classes. The Thin treatment produced a significantly greater 1000-h sound fuel load than Burn and Control whereas Thin and Thin + Burn loads were statistically similar (Table 2). Loading of 1000-h rotten fuels showed no differences among treatments.

Depth of the Oi forest floor layer (litter) was not significantly affected by treatment (Table 2). In contrast, depth of the Oe + Oa layer (Duff) was 60% less in the Burn treatment than the Control, which was a statistically significant difference. No differences were found among treatments for total forest floor depth (Oi + Oe + Oa) (Table 2).

3.4. Woody understory

Tree seedling densities as well as densities of the three most common shrub species at the study site showed high variability and no significant effects of treatment (Fig. 3). Pinyon pine seedlings ranged 650–1217 ha^{-1} and were roughly 2–6 times more numerous than juniper seedlings (208–292 ha^{-1}) the year following treatment. Densities of the three most abundant shrubs at the site ranged 500–1208, 42–225, and 50–700 ha^{-1} for *A. tridentata*, *P. mexicana*, and *F. paradoxa*, respectively (Fig. 3).

4. Discussion

4.1. Treatment effects on woodland structure

Thinning treatments (Thin and Thin + Burn) removed juniper and pinyon trees less than 30.5 and 25.4 cm in diameter (drc), respectively, and decreased tree densities by 56–86% compared to the Control treatment. Natural mortality resulted in small decreases (3–4%) in Control tree densities. Prescriptions tested in this study followed general fuels reduction principles in which

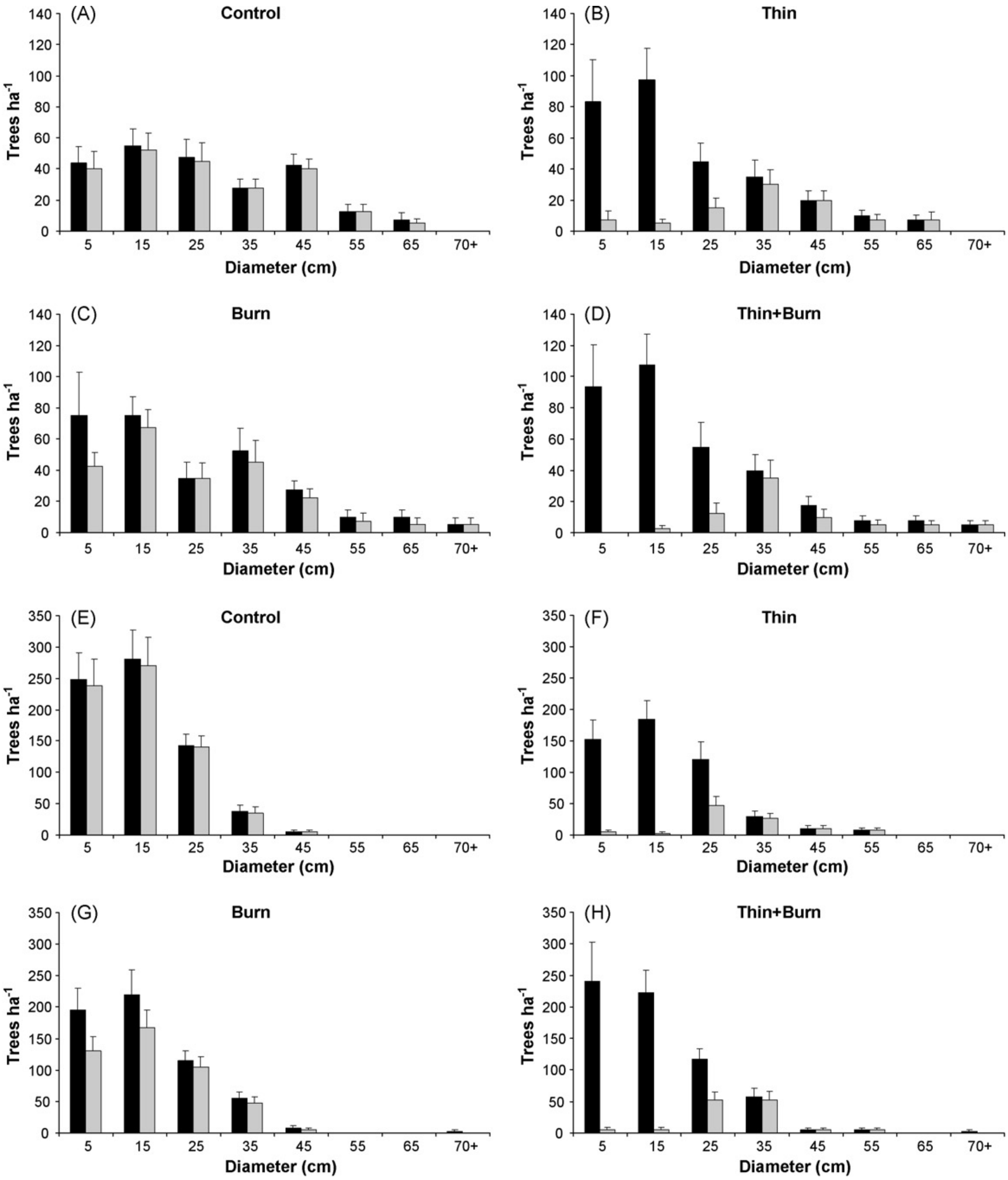

Fig. 2. Diameter distributions of Utah juniper (A–D) and pinyon pine (E–H) in pretreatment (2004; dark bars) and post-treatment (2007; grey bars) years for four fuels treatment alternatives. Bars show one standard error of the mean in each diameter class.

small trees are removed to reduce ladder and live canopy fuel loads (Agee and Skinner, 2005). Thinning only the smallest cohorts in the experimental units did not affect BA of juniper but significantly reduced BA of pinyon compared to the Control treatment. This was likely due to pretreatment stand structures composed of relatively few small juniper trees, many small pinyon pines, and relatively numerous large junipers (Fig. 2). Thinning altered tree diameter distributions from uneven- to even-sized structures and increased QMD of both species. Stand structures in which all sizes (and ages) are present likely develop in undisturbed woodlands as a result of 'nurse effects', where seedling establishment increases in shaded environments, such as those produced by large trees, shrubs, or other features (Chambers, 2001; Pearson and Theimer, 2004). Thus, uneven-sized diameter distributions may be expected at sites like ours with historically long fire-free periods (Huffman et al., 2008). This suggests that the even-sized distributions, dominated by mid to large size classes, which were created by thinning treatments in this study, may represent novel stand structures with little historical precedent (Bassett, 1987; Romme et al., 2003; Landis and Bailey, 2005).

Prescribed burning without thinning had little effect on total juniper tree density and size distribution. However, pinyon density was significantly affected by burning and was reduced to 35% less than the Control treatment. Burning mainly affected trees <20 cm drc, but minimally changed tree diameter distributions. Minimal effects of low-intensity prescribed fire on stand structure have been described for other pinyon–juniper ecosystems. For example, Bunting (1987) attributed a lack of prescribed fire spread and

Table 2
Means (and standard error) for surface fuel loading by timelag class, and ground fuel depth by organic soil horizon[a], for experimental fuel treatments in pretreatment (2004) and post-treatment (2007) years.

	Pretreatment				Post-treatment			
	Control	Thin	Burn	Thin + Burn	Control	Thin	Burn	Thin + Burn
Surface fuel load (Mg ha^{-1})								
1-h	0.52 (0.18)	0.42 (0.18)	0.29 (0.10)	0.48 (0.12)	0.42(0.11) a	0.86 (0.14) b	0.71 (0.13) b	1.00 (0.17) b
10-h	1.04 (0.31)	1.08 (0.36)	0.86 (0.38)	1.54 (0.41)	0.90 (0.12) a	1.66 (0.28) a	1.08 (0.15) a	1.72 (0.20) a
100-h	2.15 (0.94)	1.67 (0.82)	1.67 (0.74)	0.95 (0.41)	1.91 (0.45) a	2.38 (0.38) a	1.19 (0.25) a	2.87 (0.79) a
1000-h (sound)	4.63 (2.77)	0.60 (0.34)	0.66 (0.49)	4.24 (2.23)	1.55 (1.06) ab	3.00 (0.65) c	0.36 (0.28) a	2.40 (0.90) bc
1000-h (rotten)	0.37 (0.25)	0.11 (0.11)	0.06 (0.06)	0.48 (0.27)	0.77 (0.41) a	0.44 (0.44) a	0.00 (0.00) a	0.56 (0.56) a
Ground fuel depth (cm)								
Oi	0.6 (0.25)	0.3 (0.80)	0.5 (0.23)	0.3 (0.10)	0.7 (0.20) a	0.3 (0.08) a	0.6 (0.15) a	0.4 (0.08) a
Oe + Oa	1.3 (0.35)	0.8 (0.18)	0.9 (0.23)	1.0 (0.25)	1.0 (0.25) a	0.7 (0.18) a	0.3 (0.13) b	0.4 (0.10) ab
Oi + Oe + Oa	1.9 (0.41)	1.1 (0.20)	1.3 (0.36)	1.3 (0.23)	1.7 (0.41) a	1.0 (0.23) a	0.9 (0.25) a	0.8 (0.13) a

Different lowercase letters in post-treatment year indicate significantly different means for surface fuel class or ground fuel layer at $P < 0.05$.
[a] Ground fuel layers: Oi = litter layer; Oe + Oa = duff layer; Oi + Oe + Oa = total forest floor.

negligible stand-level effects to low surface and fine fuel loading in mature pinyon–juniper woodlands. Similarly, Erskine and Goodrich (1999) found that weather conditions that allowed crownfire activity were needed in order to reduce pinyon and juniper density in Utah. In our study, we applied fire under controlled conditions with hand crews and did not experiment with other types of ignition or weather conditions that would allow for crown fire activity. Similar to the conclusions of Bunting (1987), minimal effects of the Burn treatment in our study were likely due to discontinuous and low surface fuel loads.

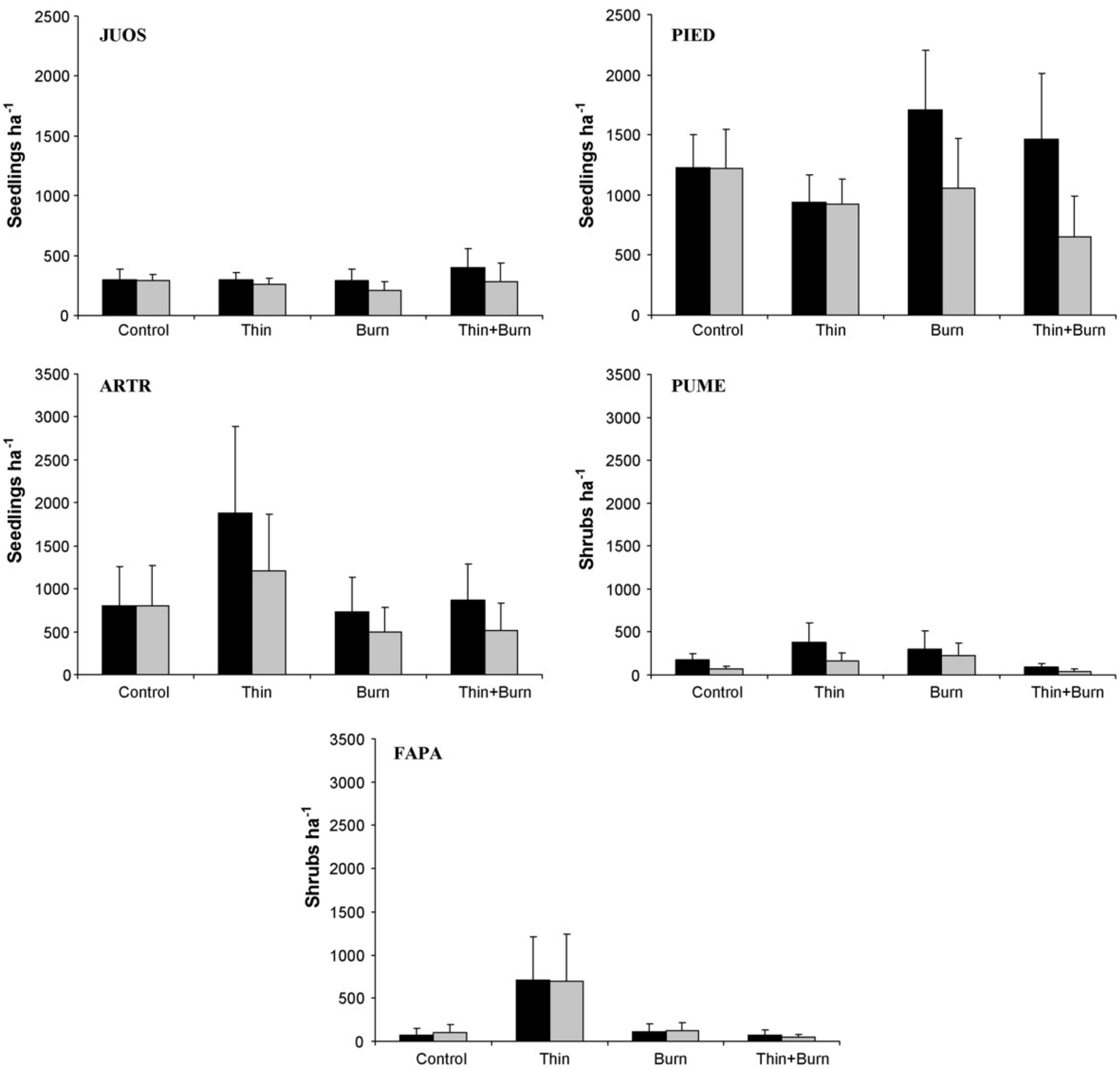

Fig. 3. Mean density (no. ha^{-1}) of Utah juniper (JUOS) and pinyon pine (PIED) tree seedlings, and big sagebrush (ARTR), cliffrose (PUME), and Apache plume (FAPA) shrubs in pretreatment (2004; dark bars) and post-treatment (2007; grey bars) years for four fuels treatment alternatives. Bars show one standard error of the mean.

4.2. Effectiveness of fuels treatments for mitigating wildfire hazard

In this study, Thin and Thin + Burn treatments effectively lowered crown fuel load of both juniper and pinyon pine compared with the Control treatment. Prescribed fire alone (Burn) had no significant effects on CFL. Little research has addressed treatment effects on crown fuels in pinyon–juniper ecosystems; however, our results were similar to those from other western forest types. For example, Fulé et al. (2002) showed that "full restoration" treatments, that included selective thinning from below followed by prescribed fire, reduced CFL of ponderosa pine in Arizona by 66% whereas prescribed fire alone resulted in CFL decreases of 27%. Stephens and Moghaddas (2005) reported similar patterns for fuels treatments in mixed-conifer forests of California.

Mean crown base height was minimally affected by treatments in our study, although Thin + Burn raised pinyon CBH. An increase in CBH can reduce crown fire initiation potential if CBH is greater than the critical fireline intensity (α flame length) required for crown ignition (Van Wagner, 1977; Keyes and O'Hara, 2002). Effectiveness of tree thinning for raising CBH depends on crown form and tree architecture at the stand level (Graham et al., 1999). In our study, minimal treatment effects on CBH were likely related to a lack of crown base height variation among individual juniper and pinyon trees; for both species CBH ranged 0.9–2.7 (Table 1). It is unclear whether CBH of either species would allow crown fire initiation and modeling fireline intensity was beyond the scope of this study. Reduction in CFL is likely to lower the potential for active crown fire, although rate of spread is more closely linked to canopy bulk density than crown fuel load (Van Wagner, 1977). Reducing CFL is particularly important in mitigating wildfire hazard in southwestern pinyon–juniper woodlands since large crown fires in this forest type are often weather-driven and fire spread is independent of surface fuel loading (Romme et al., 2003).

Treatments produced few changes in surface and ground fuels, although responses were highly variable (Table 2). Although surface fuel loads have not been widely reported for pinyon–juniper woodlands, our values for 1–100-h fuels were generally similar to those described by Floyd et al. (2003) for an undisturbed site in Mesa Verde National Park. All treatments increased 1-h timelag fuels, and the Thin treatment increased 1000-h sound fuels relative to the Control. Thus, on highly dense or intensively thinned sites, thinning alone may in fact increase crown fire initiation potential (Agee and Skinner, 2005) and counteract benefits related to decreases in live canopy fuels.

Treatments had few effects on forest floor layers, although the Burn treatment significantly decreased Oe + Oa layer (duff) depth. In forests where historical regimes of frequent fire have been interrupted, accumulation of organic forest floor layers reduce infiltration and slow nutrient cycling (Covington and Moore, 1994). In drier pinyon–juniper systems with historically infrequent-fire intervals, forest floor accumulation is likely not a serious concern. Litter and duff layers in these systems are important for reducing soil movement and retaining soil moisture and nutrients (Davenport et al., 1998).

Abundance of understory shrubs and tree regeneration was not significantly affected by any treatment in this study. This is probably due to lack of prescribed fire spread and variability in shrub and seedling density. This suggests that potential remains for initiation of crown fires at this site (Baker and Shinneman, 2004). Further, it is plausible that increased growth and reproduction of woody understory components as a result of decreased overstory competition may lead to increased chance of crownfire initiation over the next decade (Tausch and Tueller, 1977; Bates et al., 2005). Reduction in tree density and CFL likely decreases the potential for crownfire spread.

4.3. Implications

Results from this study suggest that mechanical thinning and thinning plus prescribed fire treatments can reduce wildfire hazard in pinyon–juniper woodlands, primarily by decreasing stand density and canopy fuel loads. Reduction of canopy cover in dense woodlands may provide ecological benefits such as increased resource availability for understory vegetation and improved habitat for a variety of vertebrate and invertebrate species (Pieper, 1990; Albert et al., 2004; Kleintjes et al., 2004). Long-term ecological consequences of altering stands from uneven- to even-sized diameter distributions are unclear and merit further research. In our study, treatments did not significantly affect pinyon or juniper seedling densities, suggesting uneven-sized tree distributions could redevelop in the near future. Other alternatives that reduce fuel hazards while conserving woodland structure warrant investigation. Although not tested in this study, treatments such as group selection thinning plausibly could reduce canopy fuel loads, maintain uneven-size distributions, and mimic historical fire patterns (Huffman et al., 2008).

Prescribed fire, when implemented by hand crews, produced few reductions in hazardous fuel loads. Fuel reduction by fire alone probably requires more extreme weather conditions and fire behavior than those of this study. Broadening the range of acceptable weather and fire behavior increases the risk of fire escape. Thus, a burn-only approach is likely to be better suited for large wildland landscapes than projects in the wildland–urban interface.

Since increases in 1- and 1000-h fuel loads produced by thinning may amplify crown fire initiation hazards, mitigation activities should exert more effort toward reducing these components than was put forth in this study. Such efforts could include repeated entries with prescribed fire or mechanical treatments such as mastication. It should be noted that downed wood can improve soil conditions in degraded woodlands and provide safe sites for establishment of understory vegetation (Jacobs and Gatewood, 1999; Stoddard et al., 2008), but downed wood may also provide host sites for *Ips* sp. bark beetles (Fettig et al., 2007).

5. Conclusions

As human communities of the southwest continue to grow and expand wildland–urban interface boundaries, more work will be needed to develop management approaches that provide protection from uncontrollable wildfire while simultaneously conserving ecosystem integrity. This is particularly true for infrequent-fire ecosystems that may exhibit minimal structural changes since Euro-American settlement and fire exclusion. In this study, we examined alternatives for reducing crown fire hazard in pinyon–juniper woodlands of Arizona. Results suggested that managers face tradeoffs between altering stand structures and producing novel characteristics versus accomplishing fire mitigation goals. More research is needed to gain better understanding of the ecological consequences of such manipulations. These studies will aid in assuring sustainability of southwestern pinyon–juniper woodlands.

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