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RESEARCH

Vegetation Response to Western Juniper Slash Treatments

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Abstract The expansion of piñon–juniper woodlands the past 100 years in the western United States has resulted in large scale efforts to kill trees and recover sagebrush steppe rangelands. It is important to evaluate vegetation recovery following woodland control to develop best management practices. In this study, we compared two fuel reduction treatments and a cut-and-leave (CUT) treatment used to control western juniper (*Juniperus occidentalis* spp. *occidentalis* Hook.) of the northwestern United States. Treatments were; CUT, cut-and-broadcast burn (BURN), and cut-pile-and-burn the pile (PILE). A randomized complete block design was used with five replicates of each treatment located in a curl leaf mahogany (*Cercocarpus ledifolius* Nutt. *ex* Torr. & A. Gray)/mountain big sagebrush (*Artemisia tridentata* Nutt. spp. *vaseyana* (Rydb.) Beetle)/ Idaho fescue (*Festuca idahoensis* Elmer) association. In 2010, 4 years after tree control the cover of perennial grasses (PG) [Sandberg's bluegrass (*Poa secunda* J. Pres) and large bunchgrasses] were about 4 and 5 % less, respectively, in the BURN (7.1 ± 0.6 %) than the PILE (11.4 ± 2.3 %) and CUT (12.4 ± 1.7 %) treatments ($P < 0.0015$). In 2010, cover of invasive cheatgrass (*Bromus tectorum* L.) was greater in the BURN (6.3 ± 1.0 %) and was 50 and 100 % greater than PILE and CUT treatments, respectively. However, the increase in perennial bunchgrass density and cover, despite cheatgrass in the BURN treatment, mean it unlikely that cheatgrass will persist as a major understory component. In the CUT treatment mahogany cover increased 12.5 % and density increased in from 172 ± 25 to 404 ± 123 trees/ha. Burning, killed most or all of the adult mahogany, and mahogany recovery consisted of 100 and 67 % seedlings in the PILE and BURN treatments, respectively. After treatment, juniper presence from untreated small trees (<1 m tall; PILE and CUT treatments) and seedling emergence (all treatments) represented 25–33 % of pre-treatment tree density. To maintain recovery of herbaceous, shrub, and mahogany species additional control of reestablished juniper will be necessary.

Keywords Bunchgrass · *Cercocarpus* · Fire · Fuel reduction · Piñon–juniper

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Introduction

The expansion of piñon–juniper in the western United States has caused public and private sector land managers to apply various woodland control measures to restore forage productivity, wildlife habitat, and reduce fuel loading in sagebrush steppe ecosystems (Miller and others 2005, 2008). In the northern Great Basin, western juniper (*Juniperus occidentalis* Hook. var. *occidentalis*) has expanded its range 95 % since Euro-American settlement in the late 1800s (Miller and others 2005; Miller and others 2008). Presently, 3.5 million hectares of sagebrush (*Artemisia* L.) steppe and other plant communities are in various stages of conversion to juniper dominated systems (Miller and others 2005). Juniper dominance is detrimental as it may decrease herbage production and diversity (Bates and others 2005, 2011), cause increased erosion and runoff (Pierson and others 2007), and reduce habitat for sagebrush obligate wildlife species (Miller and others 2000; Noson and others 2006; Reinkensmeyer and others 2007). Expansion of juniper increases fuel loading and potentially places pre-settlement juniper stands (>150 years old) and dry ponderosa pine parklands at risk from high intensity fires (Bates and others 2011; O'Connor 2009; Tausch 1999). Thus, juniper control is one of the most important management actions for conserving sagebrush steppe and other plant communities (Davies and others 2011a).

Control of western juniper increases herbaceous production and cover following treatment such as: cutting and leaving (Vaitkus and Eddleman 1987; Rose and Eddleman 1994; Bates and others 2005), cutting and winter burning (Bates and Svejcar 2009), prescribed fire (Bates and others 2006, 2011), and reseeding following woodland treatment (Young and others 1985, Sheley and Bates 2008). Juniper control can reduce erosion and increase infiltration and availability of soil water (Bates and others 2000; Pierson and others 2007). Yet, failures occur after piñon–juniper treatment if sites lack herbaceous perennial vegetation to prevent invasive weed dominance (Bates and others 2006; Bates and Svejcar 2009; Condon and others 2011; Young and others 1985).

Land managers have used prescribed fire, mechanical cutting, and a combination of these treatments to control western juniper woodlands with the goal of recovering sagebrush–steppe, riparian, quaking aspen (*Populus tremuloides* Michx.), and open ponderosa pine (*Pinus ponderosa* P. & C. Lawson) plant communities (Miller and others 2005). On densely encroached sites, sparse understory vegetation will not support sufficient fire to kill invading junipers. On sites with limited ground fuels, tree removal methods are either mechanically based or use a combination of mechanical-fire applications (Miller and others 2005; Bates and others 2006, 2011). Cutting with chainsaws has been the mechanical method most commonly used on western juniper, however, this method creates a potential wildfire risk when down trees are left on site, particularly the first 2–3 years post-cutting when needles remain suspended aboveground on cut trees (Miller and others 2005; Bates and Svejcar 2009). Therefore, subsequent fuel reduction methods such as burning individual downed trees and hand or machine piled trees are frequently applied on private and public lands. These methods, applied in other woody vegetation types, have been shown to reduce fire line intensities, heat per unit area, rate of spread, area burned, and scorch heights (Stephens 1998). However, vegetation response following implementation of a various fuel reduction treatments has yet to be compared and quantified in western juniper woodlands.

The objective of this study was to determine if tree, shrub, and herbaceous response differed among two fuel reduction treatments, which combine mechanical and fire prescriptions, and a traditional clear cutting project without burning to control western juniper. The fuel reduction treatments were clear cutting followed by broadcast burning and clear cutting followed by machine piling and pile-burning. We hypothesized that broadcast burning would slow recovery of native herbaceous vegetation, cause high mortalities of curl leaf mountain mahogany (*Cercocarpus ledifolius* Nutt. *ex* Torr. & A. Gray) and non-sprouting shrub species, and potentially reduce ponderosa pine cover and density. Mahogany is rated as excellent browse and also provides cover for mule deer and elk and other wildlife (Smith and Hubbard 1954; Stevens 2004). There is no information on response of mahogany to juniper control treatments. We also expected cheatgrass would be more problematic after broadcast burning because fires in dense piñon–juniper woodlands have the potential for largely eliminating native perennials and non-sprouting woody plants, thereby enhancing the potential for invasive species occupancy (Miller and Tausch 2001; Bates and others 2006; Condon and others 2011). We hypothesized the cut-and-leave (CUT) treatment would result in greater herbaceous, shrub and mahogany cover and density than the other treatments because of lower disturbance impacts. Herbaceous cover and production, and woody plant density tend to increase within the first 2 years after cutting or chaining treatments in western juniper and one-seeded piñon–Utah juniper (*Pinus monophylla* Torr Frem.—*Juniperus osteosperma* (Torr.) Little) woodlands (Tausch and Tueller 1977; Bates and others 2005). We expected an intermediate vegetation response in the cut-pile-and-burn (PILE) treatment with respect to the other treatments, as site disturbance would be less than the cut-and-burn (BURN) and, due to the fire application, greater than the CUT treatment.

Methods

Study Area

The study was in the High Desert Ecological Province (Anderson and others 1998), located ~25 km northeast of Burns, Oregon, in the Devine Ridge watershed (43N45′13; 48W57′25) (Fig. 1). The study was within the Devine Ridge–Poison Creek vegetation management project developed by the Bureau of Land Management (BLM). The project objectives were to reduce western juniper abundance on the landscape to improve herbage and browse production for wild ungulates and cattle, restore sagebrush habitat, reduce fuels associated with juniper, maintain mountain mahogany stands and reduce fire risk into nearby ponderosa pine stands.

Elevation at the study site was about 1,890 m on gentle (0–10 %) south facing slopes. Soils were classed as an Anatone complex with parent material consisting of welded ash tuff (Orr and Orr 1999; Soil Survey Staff 2005). Soils are loamy-skeletal, mixed, superactive, frigid, Lithic Haploxerolls (Soil Survey Staff 2005). Climate is typical of the northern Great Basin with the bulk of precipitation arriving in winter and spring. Based on the Parameter-elevation Regressions on Independent Slopes Model (PRISM) (PRISM Group, Oregon State University 2004), crop year precipitation (September–August) averages 450 mm (data from 1971–present). Mean annual temperatures at the Burns airport (23 km south; 625 m lower elevation) average −3 °C in the winter (December–February), and 17 °C in the summer (June–August).

Ecological site maps for this location indicate it was a MAHOGANY MOUNTAIN LOAM 14–18 PZ (precipitation zone) (NRCS 2010). Characteristic vegetation is curl-leaf mountain mahogany, scattered ponderosa pine, mountain big sagebrush (*Artemisia tridentata* Nutt. spp. *vaseyana* (Rydb.) Beetle), Idaho fescue (*Festuca idahoensis* Elmer) and lesser amounts of antelope bitterbrush (*Purshia tridentata* (Pursh) DC.) and western needlegrass (*Achnatherum occidentale* (Thurb. ex S.Wats.) Barkworth). This site had shifted from a co-dominant mix of mahogany,

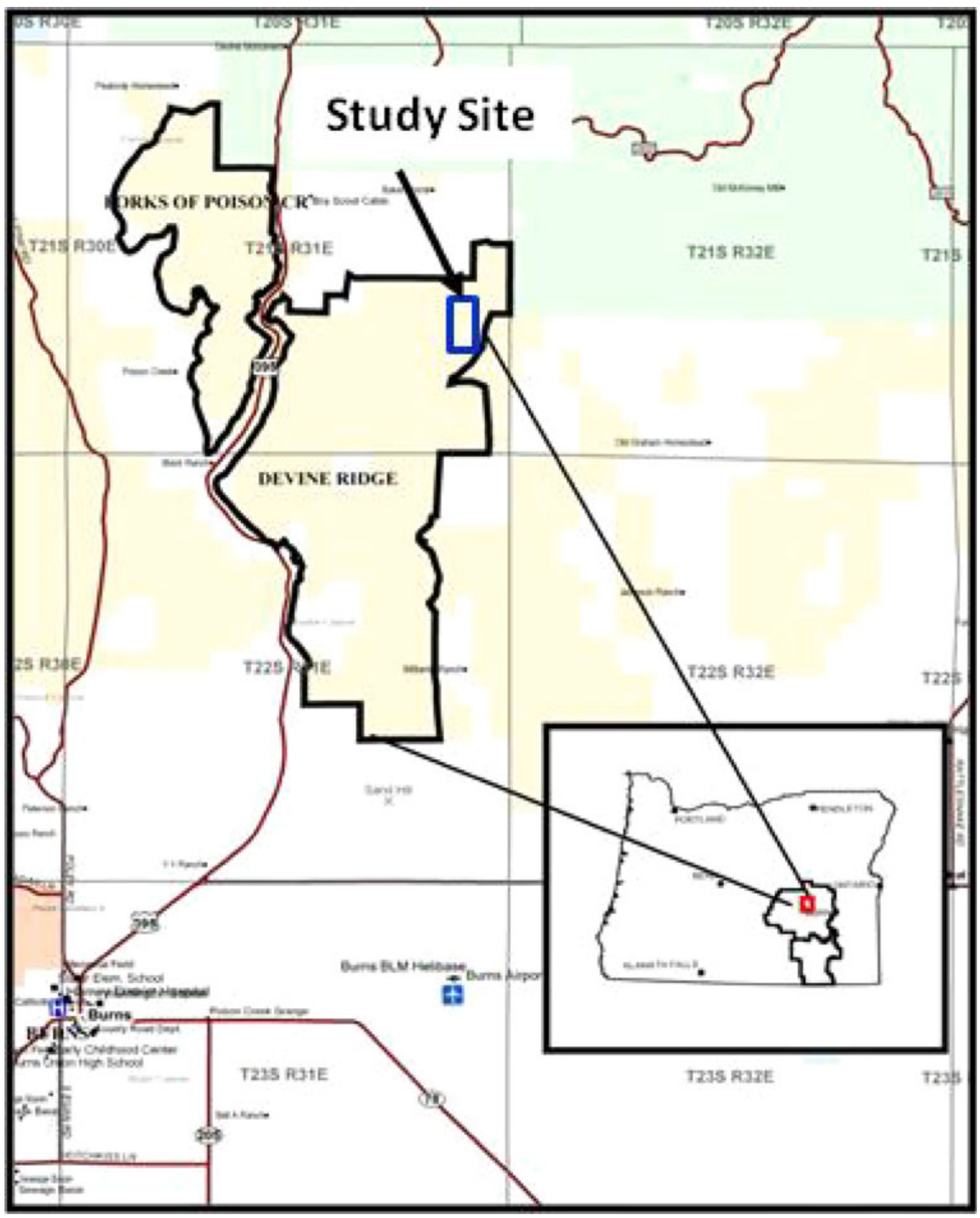

Fig. 1 Study area location of the western juniper treatments (BURN, PILE, and CUT) within the Devine Ridge/Forks of Poison Creek vegetation management project, Harney County, Oregon, 2005–2010

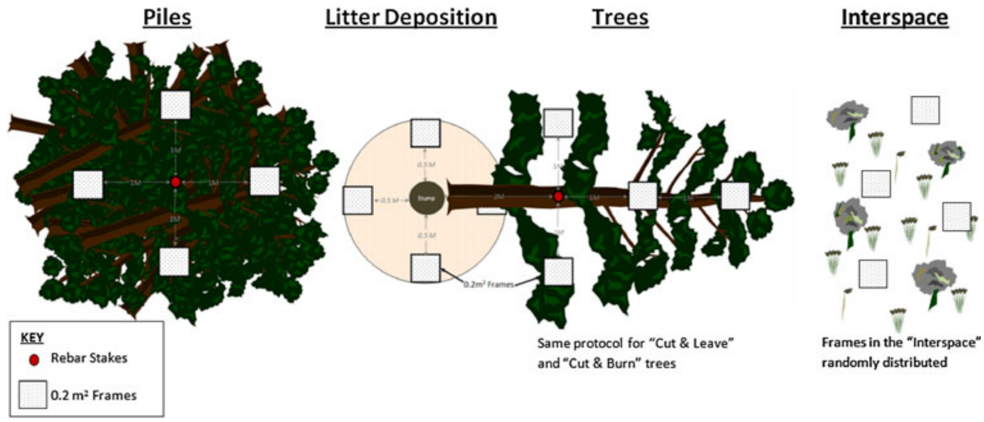

Fig. 2 Herbaceous sampling scheme indicating frame placement beneath tree piles, cut trees, litter deposition mats, and interspaces among BURN, PILE, and CUT treatments in a study evaluating recovery after western juniper control on Devine Ridge, Harney County, Oregon, 2005–2010

mountain big sagebrush, and herbaceous species to overstory dominance by post-settlement (<140 years old) western juniper. Trees were not aged but morphological characteristic indicated that all juniper established after the regions settlement in the 1880s (Miller and others 2005). Western juniper canopy cover averaged 35.2 ± 1.6 % with mature tree densities of nearly 300± trees/ha. Mahogany cover averaged 7.2 ± 0.8 % and density averaged 200 ± 23.8 trees/ha of which 20 % were dead. Pre-settlement ponderosa pine was distributed through the site (16 ± 5.8 trees/ha) with cover averaging 2.8 ± 1.0 %. Post-settlement ponderosa pine density was 9 ± 5.2 trees/ha and were mostly trees under 2 m height. Fire history for this site is not known; however, this type of plant community, dominated by mountain big sagebrush grassland with scattered ponderosa pine and mahogany, typically has fire return intervals <25 years (Arno and Wilson 1986; Miller and Heyerdahl 2008; Miller and Rose 1999). Fires of this nature would likely be of low severity, and historic plant communities were typically dominated by herbaceous species with low amounts of sagebrush and scattered mahogany stands and individual ponderosa pine.

The area has been seasonally grazed since the late 1800s (Burns-BLM District Office, personnel communication). Grazing was discontinued for 2 years prior to the prescribed fire treatment to increase fine fuels. To ensure no conflicting disturbances from grazing, the site was fenced the spring following the burn treatments.

Experimental Design

The experiment was a randomized complete block design (RCBD) with five, 1 hectare blocks. Each block was composed of three treatment plots; CUT, BURN, and PILE. Treatment plot locations were chosen randomly within blocks. The PILE treatment plots covered half of each block (0.5 ha; 50 × 100 m), while the remaining two treatment plots each occupied one-quarter (0.25 ha; 50 × 50 m) of each block (Fig. 2). The PILE treatment plots were larger than the others in order to provide enough juniper slash to create a minimum of 10 piles per replicate. All juniper trees (>1 m height) in each plot were cut in September 2005 with chainsaws. After cut trees dried for 1 year, the prescribed fires for the BURN treatments were applied October 12th 2006. In the PILE treatment, cut trees were lifted and placed into piles consisting of 10–15 trees, in October 2005, using a 160LC John Deere tracked excavator with a grapple attachment (John Deere Inc., Moline, IL). The piles were burned on October 19th, following a precipitation event of about 2.5 mm, as was written into the treatment prescription to restrict fire spread.

Burn Measurements

Gravimetric soil water (0–10 cm) and fuel moisture for herbaceous fine fuels, litter, 1, 10, 100, and 1,000 h fuels were measured the day of fire application (Table 1). Fuel moisture and soil water content were determined by drying samples at 100 °C to a constant weight. Fuel moisture for 1 and 10 h fuels was different between BURN and PILE treatments. Weather data (RH, wind speed, temperature) were recorded prior to and during fire applications. Temperature and relative humidity were typical for fall prescribed fire applications in the area. Burn duration (active flame) and flame lengths were also estimated.

Soil temperatures during the fires were estimated using Tempilaq[1] paints applied to 25 × 80 × 0.4 mm steel tags. Tempilaq paints melt or discolor at specific temperatures when heat is applied. Five sets of tags were placed 1 cm below the soil surface in BURN and PILE treatments in three of the blocks. Tags were placed in interspaces (BURN and PILE), beneath individual cut trees (BURN),

[1] Tempilaq paints are manufactured by Tempil, South Plainfield, New Jersey, 07080, USA. Mention of trade names does not imply endorsement by USDA-ARS, Eastern Oregon Agricultural Research Center, and Oregon State University.

and beneath outer edge of the piles (PILE). Sets consisted of 20 individual indicator tags and each tag was marked with its own indicator paint. Twenty temperature paints were used from 79 to 1,093 °C (intervals between temperatures varied from 14 °C at the lower temperatures to about 56 °C at the higher temperatures). Temperature values were etched on the metal tags for identification.

Vegetation Sampling

On each plot, four 40-m transects were used to measure canopy cover of trees and shrubs by line intercept (Canfield 1941). For the CUT and BURN treatments, the first transect was located off the northeast plot corner 4–5 m in from the plot edges. Transects were spaced about 10 m apart and were parallel to each other and ran, approximately, east–west or north–south, with direction chosen by a coin flip. For the PILE treatment, the first transect starting point was located off a plot corner about 10 m along the long side and then 4–5 m into the plot. Transects were parallel, spaced about 20 m apart, and ran perpendicular to the long edge of the plot. All transect end points were marked with re-bar for re-measurement. Density of western juniper (>2 m height) was estimated by counting individuals inside four, 6 × 40 m belt transects. Density of shrubs and small trees (<2 m height) were estimated by counting rooted plants inside four, 2 × 40 m belt transects. The percentage area of each microsite (pile areas, litter deposition areas around stumps, areas occupied by felled trees [unburned and burned] and interspace) was also estimated by line intercept (Table 2).

Herbaceous canopy cover (Daubenmire 1959) and density were measured by species in three microsites (tree slash, litter deposition mats, and interspace) in each treatment plot. Tree slash microsites were areas directly beneath cut juniper in CUT and BURN treatments and beneath piles in the PILE treatment (Fig. 2; Table 2). Litter deposition mat areas are where needle and other juniper litter accumulated beneath juniper trees (accumulated prior to cutting) and remain in place after trees are cut (Fig. 2). Interspaces are areas not covered by cut trees (or piles) and not in litter deposition areas around the trees (or stumps after cutting). Herbaceous canopy cover by species and coverage of bare ground, litter, and biotic crust (moss and cryptogamic crust) were visually estimated in 40, 0.2 m^{-2} (0.4 × 0.5 m) for each microsite per treatment plot in June, 2005 and 2007–2010. Density of herbaceous perennials was measured by counting all individuals rooted within each frame.

Interspace herbaceous cover and density was measured in close proximity to transect line placements. Measurements began at or near transect rebar stakes, however, because transect lines were only measured in 2005 and 2011 frames

Table 1 Weather, fuel moisture, and fire behavior during prescribed burning for BURN (Oct 12, 2006) and PILE (Oct 19, 2006) treatments in a study evaluating vegetation recovery after western juniper control on Devine Ridge, Harney County, Oregon

Measurement (units)		BURN	PILE
Weather			
Temperature (°C)		16–19	9–11.5
Relative humidity (%)		26–28	70–79
Wind (km/h)		3–8	<1
Gravimetric soil water content (%)[a]			
Under slash	(±SE)	15.8 ± 1.08	15.3 ± 0.83
Interspace	(±SE)	13.9 ± 0.79	13.4 ± 0.73
Fuel moisture (%)[b]			
1 h[c]	(±SE)	4.9 ± 0.20a	14.9 ± 0.81b
10 h	(±SE)	4.4 ± 0.20a	10 ± 1.79b
100 h	(±SE)	6.1 ± 0.38	7.17 ± 0.34
1,000 h	(±SE)	11.8 ± 1.75	11.8 ± 0.99
Fire behavior			
Flame lengths (m)		2.5–7.5	5–9
Burn duration (min)		5.5–7.5	44–72
Surface soil temp (°C)[d]		704–982	704 to >1093
Soil temp, 2 cm deep (°C)		135–316	204–538

[a] Collected at 0–4 cm

[b] Collected from juniper slash

[c] 1 h fuels are fuels consisting of dead herbaceous plants and wood <0.64 cm in diameter; 10 h fuels is wood 0.64–2.54 cm in diameter and litter below and near the soil surface; 100 h fuels are dead plant material 2.54–7.62 cm in diameter and material ¾ to 4 in. below the surface; 1,000 h fuels are dead fuels in the 7.62–20.32 cm diameter class and the litter layer of the forest floor 4 in. below the surface

[d] Temperatures were estimated using Templelac® welding paints

Table 2 Microsite percentage areas example for used to develop pooled average treatment means for herbaceous cover and density response variables for the BURN, CUT, and PILE treatments on Devine Ridge, Harney County, Oregon

Microsite	Treatment		
	BURN (%)	CUT (%)	PILE (%)
Intercanopy[a]	38	40	56
Litter mats[a]	31	30	28
Tree slash[b]	31	30	16

Example calculation for perennial bunchgrass (PG) cover for the BURN treatment: pooled PG treatment mean = 0.38*(intercanopy PG cover) + 0.31*(slash PG cover) + 0.31*(litter mat PG cover)

[a] Intercanopy area for block one by treatment. Intercanopy areas are those not covered by felled trees (burned or unburned) or tree piles, or within litter mat areas

[a] Litter mat areas are where needle and other juniper litter accumulated beneath living juniper but remaining in place after cutting

[b] Tree slash areas are where cut trees lay (BURN and CUT treatments) or where piles of 10–15 trees were made (PILE treatment)

were placed and measured every 5 paces (about 4 m) or the nearest interspace location to avoid measurement of slash or litter mat areas. This gave four rows of 10 measured frames per plot for a total of 40 interspace subsamples. To sample beneath cut trees (CUT, BURN treatments) and piles (PILE), 10 randomly distributed points were marked with rebar stakes. At each stake, four frames, located 1–2 m from the rebar (Fig. 2), were sampled for herbaceous cover and density (10 points $\times$ 4 frames = 40 frames per treatment replicate). In the CUT and BURN treatments, trees (>4 m tall) were felled or hand-placed and centered on the marked (rebar) points. Trees shorter than 4 m tall were not large enough to cover the four subsamples around the rebar. The rebar served to identify pre-treatment frame locations for measurement in years following treatment (Fig. 2). Trees were also marked with green spray paint after cutting (and burning) to facilitate re-measurement in subsequent years. In the PILE treatment, juniper trees were piled on the marked rebar points (Fig. 2). The rebar point assisted in identifying frame locations for repeat measurement after treatment. For litter mat areas, 10 trees (stumps after cutting) per treatment replicate were selected (randomly distributed throughout each plot). Four frames were sampled at the edge of the litter mat with the long side of the frame toward the stump (1–2.5 m from the tree/stump) in the four cardinal directions (Fig. 2). Stumps were marked permanently after cutting with green spray paint for re-measurement in subsequent years.

Statistical Analyses

Repeated measures using a mixed model analysis (PROC MIX procedure, SAS 2009) for a RCBD design was used to test for treatment and year effects on the following response variables; herbaceous cover and density (species and life form), shrub and tree cover, and cover of bare ground, rock, litter, and biotic crust. Life forms included: deep-rooted perennial grasses (PG), perennial forbs (PF), and annual forbs (AF). *Poa secunda* is treated separately from other PG as it is a shallow-rooted perennial grass that develops earlier than deeper-rooted perennial grass species (Davies 2008; Link and others 1990). The objective of this study was to compare overall treatment impacts on vegetation recovery. Therefore, microsite means for herbaceous cover and density response variables were weighted (pooled) by the relative area of each zone (per replicate) for each treatment (Table 2).

The mixed model included: block (5 blocks; df = 4), year [2005 (pre-treatment), 2007–2010; df = 4], treatment (CUT, BURN, PILE; df = 2), and the year by treatment interaction (df = 8). An auto regressive order one covariance structure was used in the mixed model because it provided the best fit for data analysis (Littell and others 1996). All data were tested for normality using the Shapiro–Wilk test (Shapiro and Wilk 1965) and were log-transformed before analyses when necessary. Back transformed means are reported. Because of strong year $\times$ treatment effects, years were also analyzed separately using an ANOVA generalized linear model (PROC GLM, SAS Institute, 2007) for a randomized complete block to simplify presentation of results and to assist in explaining interactions (model: 5 blocks, df = 4; 3 treatments, df = 2). Statistical significance was set at $P < 0.05$ and mean separations used Fisher's protected LSD procedure. Because the study lacks untreated controls the design does not permit separation of interannual variation, thus any comparisons made between pre- and post-treatment response variables should be interpreted with caution.

Results

Fire Behavior

In the BURN plots, individual trees produced flames for about 6½ min before going into the smoldering phase of combustion (Table 1). Large portions of the trunk and some large diameter limbs remained on the site as charred wood, indicating that most fuels up to the 100 h class size (2.5–7.6 cm diameter) were consumed. Surface and subsurface (2 cm) soil temperatures beneath the burned trees were 704–982 and 135–316 °C, respectively. The fire spread quickly across the plots but persisted where trees were cut and in the litter mats around stumps for long periods in the smoldering phase (exceeding 24 h). The fire spread in the BURN treatment, killing many of the associated shrubs and curl-leaf mountain mahogany. The PILE treatment burned up to 10 times longer than the BURN, with active flaming averaging about an hour for each pile, while consuming the majority of the slash, indicating that most fuels up to the 1,000 h class size (7.6–20.3 cm diameter) were eliminated. Surface and subsurface (2 cm) soil temperatures reached 704 to >1,093 °C and 204–538 °C, respectively. Fire was limited to the piles and did not spread within the PILE plots.

Woody Cover and Density

The treatments killed all trees taller than >1 m, however, junipers smaller than 1 m were largely unaffected in the PILE and CUT treatments and we observed emergence of juniper seedlings in all treatments (Fig. 3a; Tables 3 and 4). Four years after treatment (2010) juniper densities were about 25–33 % of pre-treatment densities. Juniper cover in the three treatments did not exceed 1 % in 2010 nor differ

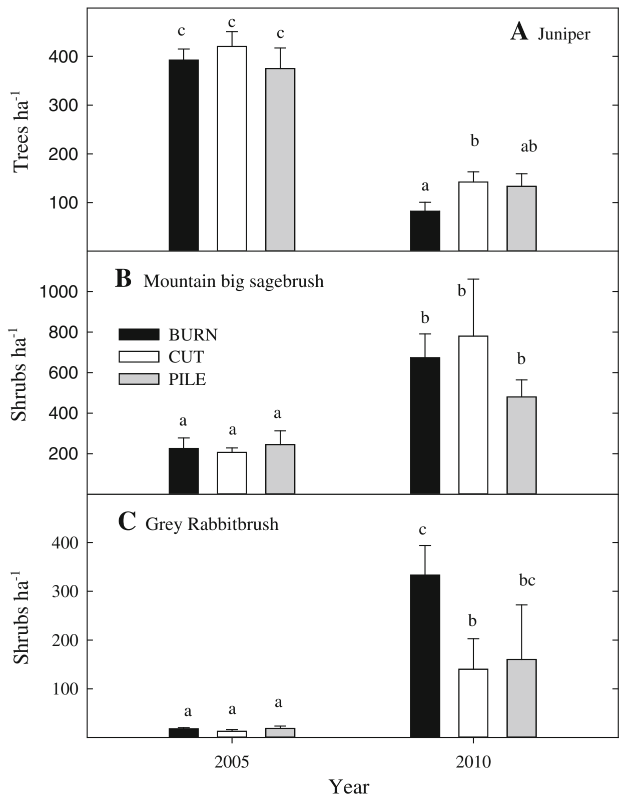

Fig. 3 Density of **a** western juniper (trees/ha), **b** mountain big sagebrush (plant/ha), and **c** gray rabbitbrush (plant/ha) for the CUT, PILE, and BURN treatments, 2005 and 2010; Devine Ridge, Harney County, Oregon. Data are in means + one standard error. Treatment means with different *lower case letters* are significantly different within each year ($P < 0.05$)

among treatments. Total shrub cover did not exceed 4 % and there were no differences among treatments ($P = 0.099$). Although shrub cover remained low, there was a large increase in shrub densities as a result of seedling establishment in all treatments. Shrub density increased for mountain big sagebrush and gray rabbitbrush (Fig. 3b, c). Densities of rabbitbrush were greater in the BURN than the CUT treatment. Curl-leaf mountain mahogany cover was unchanged in the CUT and decreased in BURN and PILE treatments as the fires killed mature trees (Fig. 4a). Mahogany density was lowest in the BURN and increased in the CUT treatment from 172 ± 25 to 404 ± 123 trees/ha (Fig. 4b). Density of mahogany in the BURN treatment consisted entirely of seedlings following treatment. Mahogany seedlings made up 73 and 67 % of total density in the CUT (313 ± 125 seedlings/ha) and PILE (100 ± 37 seedlings/ha) treatments, respectively. Other shrub species [e.g., bitterbrush, wax currant (*Ribes cereum* Dougl.)] were uncommon and exhibited no treatment or year effects. A small number of ponderosa pine was killed in the BURN, however, density and cover of trees did not differ among treatments.

Ground Cover

Prior to treatment, ground cover variables did not differ among study plots. Total herbaceous canopy cover was temporarily (2008–09) greatest in the CUT. However, by 2010 cover did not differ among the three treatments (Fig. 5a; Table 3). Biological crust, largely consisting of *tortula* moss [*Tortula ruralis* (Hedw.) Gaertn., Mey. & Scherb], declined by 66–88 % among the treatments from pre-treatment values, though the decrease was greater in the BURN and PILE treatments (Fig. 5b). Cover provided by litter was unaffected in the CUT, fluctuating between 55 and 60 %, and was 85–120 % and 35–65 % greater than BURN and PILE treatments, respectively (Fig. 5c). Bare ground cover was greatest in the BURN, followed, respectively, by PILE and CUT treatments (Fig. 5d). Though bare ground began declining in BURN and PILE treatments in 2010, values were 2.3 and 1.9 times greater, respectively, than the CUT.

Herbaceous Cover and Density

Prior to treatment herbaceous cover and density variables did not differ among study plots. Sandberg's bluegrass (*Poa secunda*) cover (2007–2010) and perennial bunchgrass cover (2008–2010) were generally 2–3 % points greater in the PILE and CUT than the BURN treatment (Fig. 6a–b; Table 3). In 2010, 4 years after tree control, the cover of PG [Sandberg's bluegrass (*Poa secunda* J. Pres) and bunchgrasses] were about 4 and 5 % less, respectively, in the BURN (7.1 ± 0.6 %) than the PILE (11.4 ± 2.3 %) and CUT (12.4 ± 1.7 %) treatments ($P < 0.0015$). Year × treatment effect indicated that cover of PF was 2–4 times greater in the CUT than the PILE and BURN treatments in 2008 and 2009 (Fig. 6c). Annual forb cover differed among treatments in 2010 when cover in the BURN was about twice as great as the PILE treatment (Fig. 6d). Year × treatment effect indicated there was an initial flush of cheatgrass in 2007 where cover was nearly 80 % greater in the CUT treatment than the BURN treatment (Fig. 6e). Cheatgrass cover did not increase in the CUT and PILE treatments after 2007. The fourth year following burning (2010), cheatgrass cover was about twice as great in the BURN compared to the other treatments.

There were differences in species cover that remained consistent following treatment (2007–2010) that are worth highlighting (Table 3). Squirreltail [*Elymus elymoides* (Raf.) Swezey] cover was greater in the CUT (3.2 ± 0.4 %) and PILE (2.9 ± 0.3 %) treatments than the BURN ($B = 1.4 \pm 0.1$). Cover of whitestem blazing star [*Mentzelia albicaulis* (Hook.) Torr. & A. Gray] was greater in the BURN (0.53 ± 0.12 %) than CUT (0.16 ± 0.07 %) or PILE (0.25 ± 0.06 %) treatments. Cover of willow-weed

Table 3 *P*-values for vegetation canopy cover response variables comparing differences among BURN, PILE, and CUT treatments in a study evaluating recovery after western juniper control on Devine Ridge, Harney County, Oregon, 2005–2010

	Treatment	Years	Year × treatment
Woody plants			
Juniperus occidentalis	0.6689	**<0.0001**	0.6013
Pinus ponderosa	0.5389	0.9033	0.6438
Cercocarpus ledifolius	**0.0005**	**0.0046**	**0.0012**
Purshia tridentata	0.1981	0.4415	0.2393
Chrysothamnus spp.	0.2897	**0.0049**	0.2818
A.t. spp. *vaseyana*	0.0617	**0.0125**	0.6562
Life forms, ground cover			
All perennial grasses	**0.0015**	**0.0001**	0.0559
Perennial bunchgrass	**0.0155**	**<0.0001**	0.2578
Poa sandbergii	**0.0016**	**0.0003**	0.0574
Perennial forb	0.1064	**<0.0001**	**0.0065**
Annual forb	**<0.0001**	**0.0621**	0.6600
Bromus tectorum	0.2824	**<0.0001**	**0.0020**
Herbaceous	0.4019	**<0.0001**	0.1120
Bare ground	**<0.0001**	**<0.0001**	**<0.0001**
Litter	<0.2460	**<0.0001**	0.6919
Biological crust[a]	**0.0003**	**<0.0001**	0.0610
Perennial bunchgrasses			
Festuca idahoensis	0.0119	**<0.0001**	0.5324
Pseudoroegneria spicata	0.3051	0.0091	0.8336
Elymus elymoides	**0.0062**	**<0.0001**	**0.0062**
Achnatherum occidentale	0.4052	**<0.0001**	0.6977
Perennial forbs			
Agoseris glauca	**0.0380**	**<0.0001**	0.0639
Allium acuminatum	0.6769	**<0.0001**	0.0540
Senecio integerrimus	**0.0304**	**<0.0001**	**0.0021**
Annual forbs			
Claytonia perfoliata	0.1007	**<0.0001**	0.4738
Collinsia parviflora	0.7003	**<0.0001**	0.6158
Cyrptantha torreyana	**0.0388**	**0.0004**	0.1783
Epilobium brachycarpum	**0.0298**	**<0.0001**	0.1252
Latuca serriola	0.3990	**<0.0001**	0.1660
Mentzelia albicaulis	**0.0134**	**<0.0001**	0.0750
Polygonum douglasii	0.0749	**<0.0001**	**0.0084**

Bolded *P*-values highlight significant differences ($P < 0.05$) for the response variables

[a] Biological crust includes moss and cryptogamic crust

Table 4 *P*-values for perennial plant density response variables comparing differences among BURN, PILE, and CUT treatments in a study evaluating recovery after western juniper control on Devine Ridge, Harney County, Oregon, 2005–2010

	Treatment	Years	Year × treatment
Woody plants			
Juniperus occidentalis	0.3362	**<0.0001**	0.3275
Pinus ponderosa	0.6721	0.7243	0.7726
Cercocarpus ledifolius	**0.0356**	**0.0271**	**0.0024**
Purshia tridentata	0.2371	0.4503	0.4651
Chrysothamnus spp.	**0.0407**	**<0.0001**	**0.0411**
A.t. spp. *vaseyana*	0.0617	**0.0002**	**0.0072**
Life forms			
Perennial grass	0.1396	**0.0192**	0.4365
Poa sandbergii	**0.0020**	**0.0182**	0.0670
Perennial forb	0.7320	**<0.0001**	0.4326
Perennial bunchgrasses			
Festuca idahoensis	**0.0062**	**0.0013**	0.5378
Pseudoroegneria spicata	0.0933	**<0.0001**	0.5614
Elymus elymoides	**0.0028**	**<0.0001**	**0.0011**
Achnatherum occidentale	0.4991	**0.0009**	0.3058
Perennial forbs			
Agoseris glauca	**0.0416**	**<0.0001**	**0.0407**
Allium acuminatum	0.2713	**<0.0001**	0.1261
Senecio integerrimus	**0.0132**	**<0.0001**	**0.0014**

Bolded *P*-values highlight significant differences for the response variables

(*Epilobium brachycarpum* C. Presl) was greater in the BURN (1.96 ± 0.36 %) and PILE (1.46 ± 0.21 %) than the CUT (0.66 ± 0.17 %). Cover of Torrey's cryptantha [*Cyrptantha torreyana* (Gray) Greene] was greater in the BURN (0.62 ± 0.11 %) and CUT (0.61 ± 0.10 %) than the PILE (0.24 ± 0.04 %) treatment. Miner's lettuce (*Claytonia perfoliata* Donn ex Wild. ssp. *perfoliata*) cover was higher in the CUT (0.50 ± 0.13 %) than PILE (0.11 ± 0.04 %) and BURN (0.16 ± 0.04 %) treatments. Cover of lambstongue ragwort [*Senecio integerrimus* Nutt. var. *major* (A. Gray) Cronquist] was greater in the CUT (0.82 ± 0.17 %) than PILE (0.32 ± 0.06 %) and BURN (0.23 ± 0.03 %) treatments. The only exotic forb, prickly lettuce (*Latuca serriola* L.), increased in all treatments the last measurement year (2010) and averaged 1.0 ± 0.24 %.

Sandberg's bluegrass density decreased in the BURN and was about 50 % less than CUT and PILE treatments (Fig. 7a; Table 4). Perennial bunchgrass density did not differ among treatments across the study period, though in 2008 grass density was two times lower in the BURN than the CUT treatment (Fig. 7b). Perennial grass density in the BURN was able to recover the final 2 years of the study with slight increases in densities of most grass species, in particular western needlegrass and squirreltail. In 2010, western needlegrass density was more than twice as great in the BURN (3.0 ± 0.6 plants/m^2) than CUT (0.8 ± 0.2 plants/m^2) and PILE (1.3 ± 0.5 plants/m^2) treatments. Squirreltail density

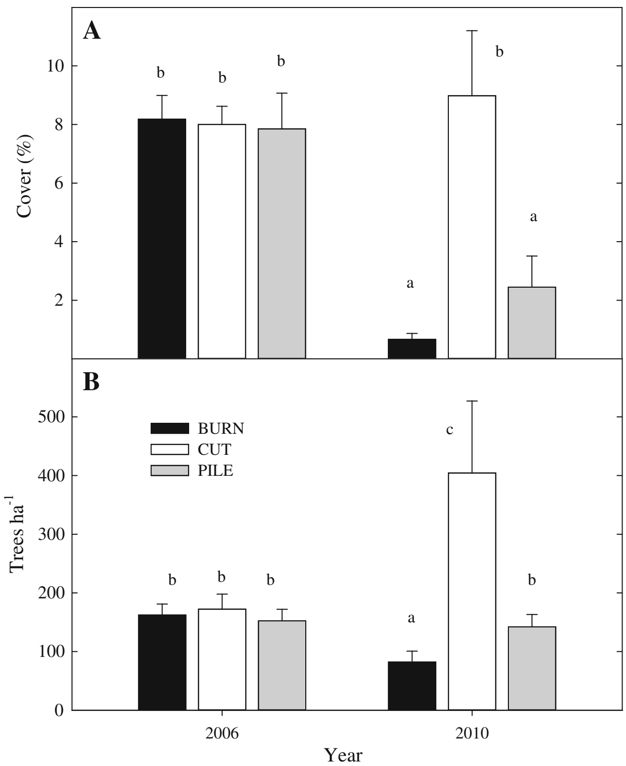

Fig. 4 Curl-leaf mountain mahogany **a** cover (%) and **b** density (trees/ha) for the CUT, PILE, and BURN treatments, 2005 and 2010; Devine Ridge, Harney County, Oregon. Data are in means + one standard error. Treatment means with different *lower case letters* are significantly different within each year ($P < 0.05$)

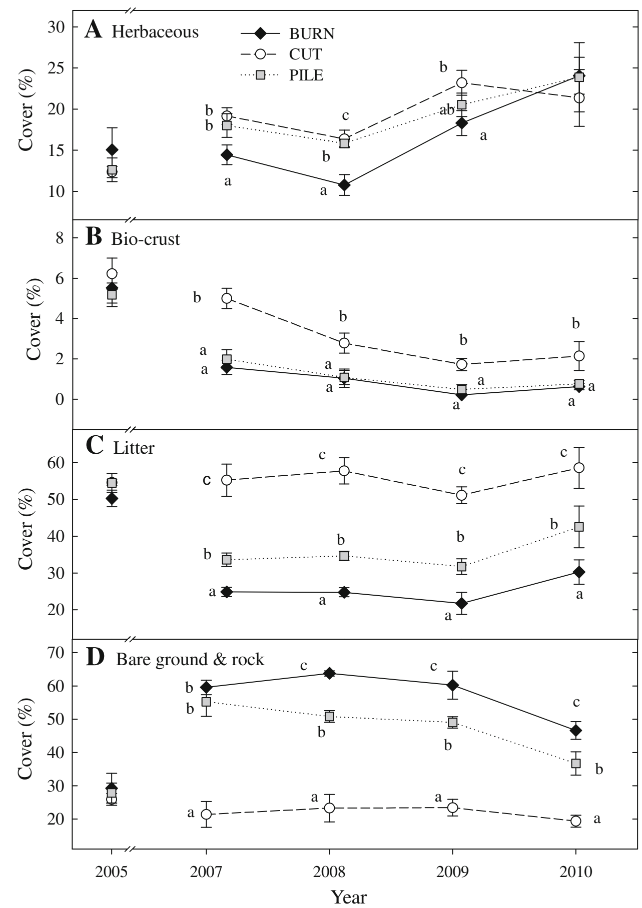

Fig. 5 Ground cover (%) values for the CUT, PILE, and BURN treatments, Devine Ridge, Harney County, Oregon, 2005–2010. **a** Herbaceous, **b** biological crust, **c** litter, and **d** bare ground and rock. Data are in means + one standard error. Treatment means with different *lower case letters* are significantly different within each year ($P < 0.05$)

was nearly twice as great in the CUT (3.5 ± 0.3 plants/m^2) and PILE (3.0 ± 0.2 plants/m^2) compared to the BURN (1.7 ± 0.2 plants/m^2). Idaho fescue density was greater in the CUT than the PILE and BURN treatments after fire application, but densities remained below 1 plant/m^2 in all treatments. Density of PF (life form) did not differ among treatments (Fig. 7c), though there was a strong year effect in 2008, primarily resulting from high densities of pale *Agoseris* [*Agoseris glauca* (Pursh) Raf.] and taper-tip onion (*Allium acuminatum* Hook.). However, individual perennial forb species *did* exhibit differences among treatments after fire application (Table 4). Density of pale *Agoseris* was greater in the BURN (2.6 ± 0.4 plants/m^2) and PILE (2.0 ± 0.4 plants/m^2) than the CUT (0.7 ± 0.1 plants/m^2) treatment. Density of lambstongue ragwort was greater in the CUT (1.3 ± 0.3 plants/m^2) than the PILE (0.7 ± 0.1 plants/m^2) and BURN (0.5 ± 0.1 plants/m^2) treatments.

Discussion

Woody Plant Response

All treatments were effective at eliminating western juniper taller than 1 m. The BURN treatment also removed all smaller junipers (O'Connor 2009). However, fire in the BURN treatment was probably not effective at entirely eliminating western juniper present in the seed bank, as evidenced by the establishment of tree seedlings. Some seedlings may also have originated from seed disseminated by cone-eating birds and other wildlife species after fire (Miller and others 2008). This was unexpected, as broadcast fire in other western juniper woodlands has resulted in no measurable establishment of trees within the first 5 years after fire (Bates and others 2006, 2011). The presence of trees in the CUT and PILE treatments was expected as mechanical methods, such as by cutting or chaining, are not effective at removing small trees (<1 m height) or reducing the seed bank, which may result in earlier re-occupancy of sites by western juniper (Bates and others 2005; Miller and others 2005). How quickly trees restock will likely vary widely and be dependent on site characteristics, weather, and woodland treatment method. In the CUT and PILE treatments about 30 % of the juniper

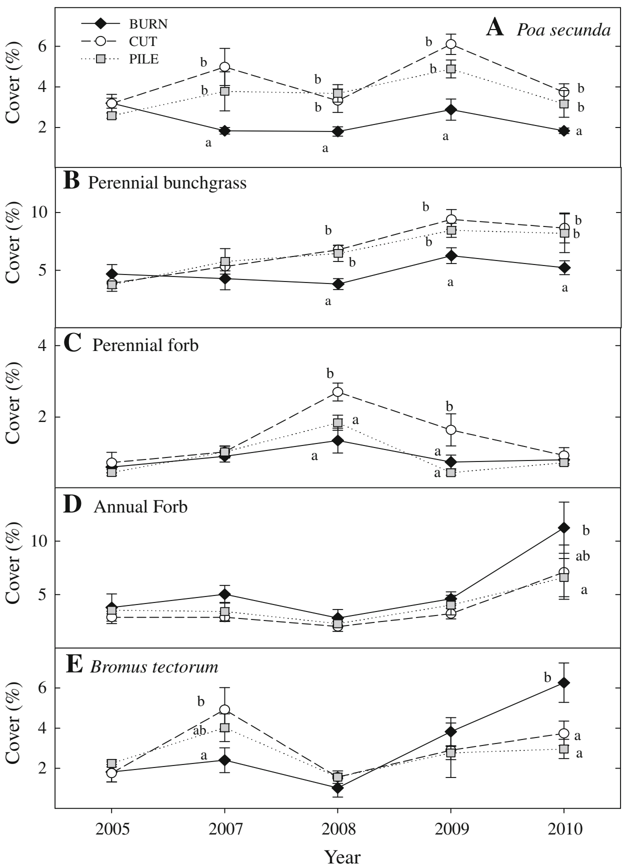

Fig. 6 Functional group cover (%) for the CUT, PILE, and BURN treatments, Devine Ridge, Harney County, Oregon (2005–2010). **a** Sandberg's bluegrass, **b** perennial bunchgrasses, **c** perennial forbs, **d** annual forbs, and **e** *Bromus tectorum*. Data are in means + one standard error. Treatment means with different *lower case letters* are significantly different within each year ($P < 0.05$)

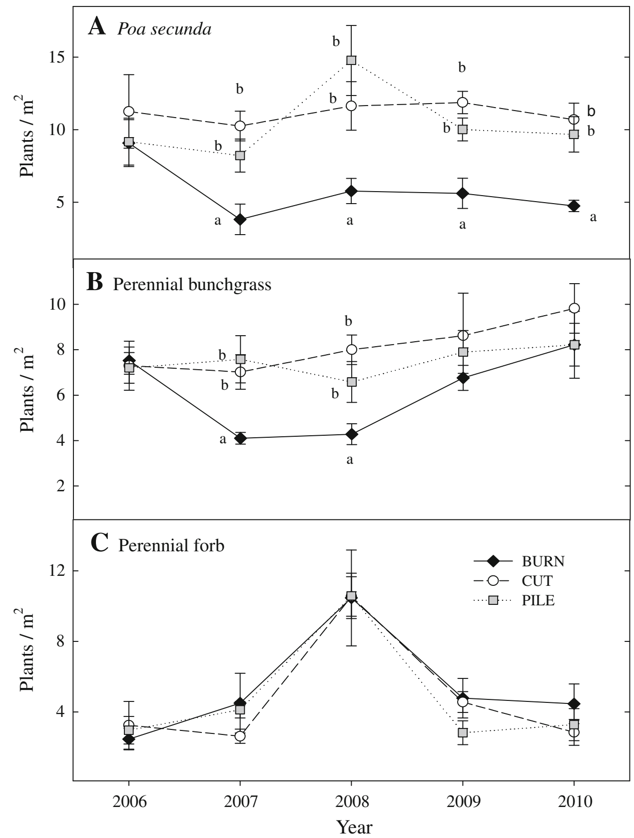

Fig. 7 Herbaceous perennial densities (# m^{-2}) for the CUT, PILE, and BURN treatments, Devine Ridge, Harney County, Oregon, 2005–2010. **a** Sandberg's bluegrass, **b** perennial bunchgrass, and **c** perennial forbs. Data are in means + one standard error. Treatment means with different *lower case letters* are significantly different within each year ($P < 0.05$)

trees established from seed following treatment, with the balance being trees too small to cut with chainsaws (O'Connor 2009). Because of the survival of saplings and seedling emergence it has been estimated that western juniper may re-dominate within 50 years after cutting (Bates and others 2005, 2006).

In our study, there was substantial shrub recruitment by the fourth year (2010) after treatment and recruitment appeared to have occurred in two pulses. The first establishment pulse was from plants likely emerging from the seed bank the first or second year after treatment. Most of these new plants, gray rabbitbrush and mountain big sagebrush, matured in 2 years and produced seed in all treatments the third year (2009) post-treatment. The second establishment pulse was noted the fourth year after treatment and likely originated from seed produced by the newer plants that established in the first pulse (all treatments) and from residual shrubs present prior to treatment (CUT and PILE treatments). Shrub recovery will probably continue to progress in all treatments as the literature suggests that gray rabbitbrush cover is likely to peak 10–15 years after treatment and mountain big sagebrush between 15 and 30 years after treatment (Wright and others 1979; Sieg and Wright 1996; Ziegenhagen and Miller 2009; Lesica and others 2007). Rapid shrub recovery following fires in mountain big sagebrush communities or mechanical control in other piñon–juniper woodlands appears to depend on the level of residual shrub densities and seed banks. Mountain big sagebrush and rubber rabbitbrush have increased rapidly within 10 years following mechanical control of piñon–juniper when sites possessed low to moderate pre-treatment shrub densities (Tausch and Tueller 1977; Skousen and others 1989; Wright and others 1979). Earlier recovery of mountain big sagebrush after fire occurs when propagules from the seed bank are able to establish within 2 years post-fire (Ziegenhagen and Miller 2009).

In our study, there was greater recruitment of mahogany in the CUT treatment. This could be caused by residual trees on site augmenting the seed pool via greater seed production after juniper control. We did not measure seed production of mahogany; however, we observed that in 2008 and 2009 heavy seed crops were produced on mahogany trees. Fire has been recommended as a management tool to restore curl-leaf mahogany stands, particularly in decadent stands and those invaded by conifers (Arno and Wilson 1986; Gruell and others 1985).

Herbaceous Plant Response and Ground Cover

We cannot be sure that treatments were responsible for the changes pre- to post-treatment. However, all juniper treatments appeared to have resulted in greater herbaceous cover by the third year after fire or cutting, though responses varied by life form and species. The responses to the treatments in this study followed patterns similar to those measured in other studies comparing vegetation dynamics between juniper treatments and untreated controls. These studies indicate that total herbaceous and life form cover typically increases within the first 2–3 years following cutting or burning of western juniper woodlands (Vaitkus and Eddleman 1987; Rose and Eddleman 1994; Bates and others 2000; Bates and Svejcar 2009). Our results for the CUT reflect findings from the other cutting studies with one exception. Native AF in our study required 5 years before increasing in cover. In other cutting treatments annual forb cover typically increases the second year post-treatment and declines by year 5 as perennial vegetation increases (Bates and others 2000; Bates and Svejcar 2009). The lag in annual forb response in the CUT as well as PILE and BURN treatments may be a result of weather events. Drought affected the 2007 growing season and in 2008 and 2009 the early spring was dry and temperatures remained cold into late May. These factors depress forb emergence and growth (Sneva 1982; Passey and others 1982). Prickly lettuce, the only other exotic species measured in the study, did increase on all treatments the final measurement year. Prickly lettuce is a temporary increaser on many western juniper treatments, though it apparently is not a strong competitor as it has never been shown to become problematic and does not persist on sites within 7–10 years after woodland control (Bates and others 2007, 2011; Bates and Svejcar 2009).

Herbaceous dynamics in the PILE were nearly identical to the CUT except for perennial forb cover in several post-treatment years. This may indicate a difference in micro-environment. There was less litter in the PILE, and in the CUT treatment shading from down trees potentially benefited perennial forb growth, particularly lambstongue ragwort. In other western juniper studies establishment and cover of several species was measured to be greater beneath cut trees than interspaces, including squirreltail, prickly lettuce and thistle species (*Cirsium* Mill.) (Bates and others 1998; Bates and Svejcar 2009). Though we did not measure an increase in invasive species in the PILE treatment, there is the potential for species such as cheatgrass to increase after burning piles. Elsewhere, exotic species densities were four times greater in areas where two-needle piñon (*Pinus edulis* Engelm.) and Utah juniper (*Juniperus osteosperma* Torr.) slash was hand-piled and burned compared to unburned areas (Haskins and Gehring 2004).

The BURN treatment was slowest of the three treatments to recoup perennial herbaceous cover and appears to have the potential to enhance establishment of invasive species. The main reason for the early decline in densities of Sandberg's bluegrass and perennial bunchgrasses was that fire intensity and residence time killed many of the plants beneath cut trees and in litter mats surrounding the stumps (O'Connor 2009). Subsurface soil (2 cm) temperatures were between 135 and 538 °C beneath the cut trees in the BURN treatment and mortality of plant roots and seeds can occur between 48 and 94 °C (Neary and others 1999). The greater level of fuel consumption also resulted in higher percentages of bare ground which remained open to colonization by invasive annual grasses and forbs. It is well established that high intensity fires in the summer and fall in western juniper and other piñon–juniper woodlands often foster post-fire dominance by cheatgrass and exotic weeds due to a lack or loss of herbaceous perennial species (Tausch 1999; Dhaemers 2006; Bates and others 2006; Condon and others 2011). However, the increase in cheatgrass may be of only short duration. In our region, cheatgrass is a concern in drier Wyoming big sagebrush (*A.t.* spp. *wyomingensis* Beetle & Young) associations and areas with mesic soil temperature regimes (NRCS 2010; Miller and Heyerdahl 2008). In addition, perennial grass density had recovered 4 years after fire in the BURN treatment. As PG increase in productivity and cover after fire (or cutting) cheatgrass is largely eliminated and becomes only a minor component of the plant community (Bates and others 2005, 2011; Bates and Svejcar 2009). If invasive annual grasses remain a concern, then altering the season of fire application when burning cut western juniper can reduce the impact of fire on native plant species. Winter or early spring burning of cut trees when soils were frozen and near field capacity resulted in lower native plant mortality, faster recovery of native herbaceous species and limited weed presence (Bates and others 2006; Bates and Svejcar 2009).

The decline in biological crust was a result of fire application in the BURN and what is suspected to a change in the microenvironment in the PILE and CUT treatments. Tortula moss was found in shaded areas beneath juniper canopies. Once these areas were exposed, ground cover provided by moss was steadily lost in the CUT and PILE treatments. Similar losses in moss cover have been measured after cutting other western juniper woodlands and after mowing Wyoming big sagebrush (Bates and others 2005; Davies and others 2011b).

Conclusions and Management Implications

The results from this study augment previous control studies in post-settlement western juniper woodlands (Bates and others 2005, 2006, 2011; Bates and Svejcar 2009). Though this study has covered only the early years after juniper control, herbaceous recovery patterns were generally similar to other studies and the results appear to support the importance of perennial species in potentially limiting cheatgrass dominance. One of the main concerns when treating not only western juniper but other piñon–juniper woodlands is the potential for invasive weeds to dominate, particularly when using fire for tree control, because post-fire response is often less predictable than mechanical treatments (Miller and others 2005; Bates and others 2011). A number of studies indicate that sites retaining a residual of 2–3 perennial bunchgrasses/m^2 following western juniper control tend to recover their native understories despite temporary cheatgrass increases (Eddleman 2002; Bates and others 2005; Bates and others 2006, 2011). In our study, the lowest perennial bunchgrass density was 4 plants m^2 in the BURN treatment and this value doubled in a 2-year period as new plants established despite the increase of cheatgrass. The increase in perennial bunchgrass density and cover mean it unlikely that cheatgrass will persist as a major understory component.

Earlier studies especially those involving broadcast fire, have not measured as significant a recovery of juniper seedlings as our study. Western juniper in the form of small trees (>1 m; CUT and PILE treatments) and seedlings (all treatments) represented about one-quarter to one-third of the pre-treatment tree density. To prolong desired vegetation conditions, follow up management will be necessary to control small trees and seedlings, after the initial juniper treatment. Options include; further cutting, using drip torches in the late fall through early spring or herbicide application during the active growing season (mid-late spring) to kill individual trees shorter than 2 m in height. To minimize revisiting sites, control of small trees can be delayed a few years until seedlings grow and become easily visible.

This is the first study evaluating curl-leaf mahogany recovery after western juniper control although this is an important species for wildlife habitat and common to the region. To promote faster recovery of curl-leaf mahogany we suggest juniper control using mechanical methods may provide the best management alternative. Mature trees provided an important seed source after juniper control, as noted in the CUT treatment. Fire disturbance killed all or a portion of the mature trees in the BURN and PILE treatments. Fire severity was moderate enough to allow some regeneration of mahogany from seed in the PILE and BURN treatments and initiate mahogany recovery. Continued monitoring may provide a better assessment of mahogany recovery from these treatments.

Though cutting treatments offer several advantages in vegetation response and providing greater ground cover because of higher levels of litter, land management agencies do not prefer this treatment as they consider it doing little to mitigate the potential fire hazard when cut western juniper remains on site. Controlled broadcast burning and pile-burning may alleviate the wildfire risk by eliminating woody fuel loads from downed trees. Pile-burning (this study) and winter/spring burning of cut trees have several advantages over broadcast burning including; breaking up the fuel continuity after cutting, localizing the fire disturbance to small areas, and have fewer weather or logistical constraints when implementing the fire portion of the treatments (Bates and others 2006; Bates and Svejcar 2009; O'Connor 2009). Another advantage of pile-burning or winter and spring burning of cut western juniper is the minimized impact of fire on non-target herbaceous, shrub and tree species.

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