Research Article

Vegetation Recovery and Fuel Reduction after Seasonal Burning of Western Juniper

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ABSTRACT

The decrease in fire activity has been recognized as a main cause of expansion of North American woodlands. Piñon-juniper habitat in the western United States has expanded in area nearly 10-fold since the late 1800s. Woodland control measures using chainsaws, heavy equipment, and prescribed fire are used to restore sagebrush steppe plant communities. We compared vegetation recovery following cutting and prescribed fire on three sites in late Phase 2 (mid succession) and Phase 3 (late succession) western juniper (*Juniperus occidentalis* Hook.) woodlands in southeast Oregon. Treatments were partial cutting followed by fall broadcast burning (SEP); clear-cut and leave (CUT); and clear-cut and burn in early winter (JAN), late winter (MAR), and spring (APR); and untreated controls. Cover and density of herbaceous, shrub, and tree layers were measured. Five years after treatment, perennial bunchgrasses dominated two sites and co-dominated, with invasive annual grasses, at one site. Except for Sandberg bluegrass (*Poa secunda* J. Presl), cover and density of bunchgrasses, perennial

RESUMEN

El decrecimiento en la actividad de los incendios ha sido reconocido como la causa principal de la expansión del monte bajo de matorral en Norteamérica. En el oeste de los EEUU, la superficie del hábitat del pino piñonero-enebral se ha expandido por 10 desde finales del siglo 19. Para la restauración de comunidades vegetales en estepas conformadas mayoritariamente por matorral de artemisa (*Artemisia tridentata* Nutt.), las medidas de control incluyen el uso de motosierras, equipo pesado, y quemas prescritas. En este estudio hemos comparado la recuperación de la vegetación después de su corta con la ocurrida tras la realización de quemas prescritas sobre tres sitios en fase 2 (sucesión media) y fase 3 (sucesión tardía) en matorrales de enebro occidental (*Juniperus occidentalis* Hook.) en el sudeste de Oregón. Los tratamientos fueron de corte parcial seguidos por quemas prescritas de otoño (SEP); matarrasa (CUT); y matarrasa combinada con quema a principios del invierno (JAN), al final de esta estación (MAR), y en primavera (APR); y control sin tratamiento. Posteriormente medimos la cobertura y densidad de especies herbáceas, matorral y del estrato arbóreo. Cinco años después de los tratamientos, los pastos perennes dominaron dos sitios y co-dominaron, junto con pastos anuales invasores, en el otro sitio. A excepción de Sandberg bluegrass (*Poa se-*

and annual forbs, and annual grasses increased following treatments at all three sites and were greater than in controls. At each site, shrub, herbaceous, and ground cover response variables equalized or had begun to converge among treatments during the fourth or fifth year following application. SEP and APR treatments were mostly effective at reducing fuel sizes up to and including 1000-hr fuels while JAN and MAR treatments only consumed 1-hr and 10-hr fuels. Winter burning treatments (JAN, MAR) and the CUT treatments did not kill small junipers and seedlings and require additional tree control for sites to fully recover to functional sagebrush-herbaceous plant communities. The results demonstrate that juniper treatments are needed to recover sagebrush steppe plant communities.

cunda J. Presl), la cobertura y densidad de los pastos perennes, de las hierbas de hoja ancha y de los pastos anuales se incrementaron en los tres sitios y fueron mayores que en los controles. En cada sitio, los matorrales, la vegetación herbácea y las respuestas variables de la cobertura del suelo igualaron o habían comenzado a converger entre tratamientos durante el cuarto y quinto año después de su aplicación. Los tratamientos SEP y APR fueron efectivos para reducir el tamaño de los combustibles de hasta 1000-hr, mientras que los tratamientos JAN y MAR solo consumieron combustibles de 1-hr y 10-hr. Las quemas de invierno (JAN, MAR) y la matarrasa (CUT) no mataron a los enebros juveniles, y requieren de un control adicional de árboles en los sitios para recuperar las funciones de las comunidades herbáceas de artemisa. Los resultados demuestran que los tratamientos sobre los enebrales son necesarios para la recuperación de las comunidades de estepa de artemisa.

Keywords: cheatgrass, fuel reduction, Great Basin, *Juniperus*, prescribed fire, sagebrush

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INTRODUCTION

The decrease in fire activity in many semi-arid ecosystems has fostered expansion and infilling of conifer and deciduous woodlands (Brown and Archer 1989, MacDonald and Wissel 1992, Holmes and Cowling 1997, Van Auken 2000, Ansley *et al*. 2001). Woodland expansion can replace grassland and shrubland habitat, decrease herbaceous productivity and diversity, and alter nutrient cycling and hydrologic processes (Miller *et al*. 2000, 2005). Thus, fire or mechanical treatments have been used to maintain or recover grassland and shrubland systems (Burrows *et al*. 1990, Angassa 2002, Owens *et al*. 2002, Smit 2004, Teague *et al*. 2010).

In the western United States, the expansion of piñon-juniper woodlands has caused conversion of big sagebrush (*Artemisia tridentata* Nutt.) steppe to woodlands. The lack of fire, a consequence of fine fuel reductions by grazing livestock and fire suppression, is the main cause of woodland expansion (Burkhardt and Tisdale 1976, Miller and Rose 1995, Soule *et al*. 2004, Miller *et al*. 2008). In the northern Great Basin and Columbia Plateau, western juniper (*Juniperus occidentalis* ssp. *occidentalis* Hook.) woodlands have increased from 0.3 million ha to 4 million ha over the past 140 years (Miller *et al*. 2005, Johnson and Miller 2008). Historic fire return intervals in mountain big sagebrush (*Artemisia tridentata* Nutt. ssp. *vaseyana* [Rydb.] Beetle) steppe, a main area of juniper expansion, has been estimated to range between 12 years to 80 years (Miller *et al*. 2005, Miller and Heyerdahl 2008).

Prescribed fire, cutting, and cutting-fire combinations have been commonly used to control western juniper and restore sagebrush steppe and other plant communities (Bates *et al*. 2005, 2006, 2011; Coultrap *et al.* 2008) and reduce wildland fuel loading (Stebleton and Bunting 2009, O'Connor *et al*. 2013). Late successional woodlands are often treated mechanically because fuel deficiencies (shrub and herbaceous layers) make prescribed burning problematic. Late successional woodlands, termed Phase 3 woodlands, are tree dominated, with shrubs largely eliminated and herbaceous productivity reduced (Miller *et al*. 2005). In the past, mechanically killed trees were left on site; however, downed trees present a significant fire hazard. Thus, felled trees are commonly burned in place, piled and burned, or used to augment broadcast burning of large areas (Bates *et al*. 2006, 2013; Bates and Svejcar 2009; O'Connor *et al*. 2013).

Major goals following juniper control treatments are the recovery of native perennial herbaceous species and preventing invasion and dominance of exotic weeds (Miller *et al*. 2005). Recovery appears dependent on vegetation composition, site potential, and fire severity. Low and moderate severity fires do not result in weed infestations because mortality of perennial herbaceous vegetation is minimal, allowing native species to dominate (Bates *et al.* 2006, Davies *et al*. 2007, Bates and Svejcar 2009). Severe fires in juniper woodlands causing high levels of native herbaceous mortality may result in post-fire weed dominance (Bates *et al.* 2006, Condon *et al*. 2011, Bates *et al*. 2013). However, comparative evaluations of the ecological impacts of various juniper treatments across multiple sites are lacking and are needed to coordinate and implement woodland control and fuel reduction measures.

In this study, we evaluated shrub and herbaceous cover and density, and ground cover (litter, bio-crust, bare ground) responses to seasonal burning of western juniper in three distinct plant communities in eastern Oregon. We hypothesized that herbaceous and shrub vegetation and ground cover variables would not change in response to seasonal burning of juniper, or to cutting and leaving trees on site compared to untreated controls. We hypothesized that herbaceous and shrub vegetation and ground cover variables would not be different among seasonal burning or cutting treatments of juniper. Finally, we hypothesized that density of juniper seedlings and saplings would not be different among seasonal burning and cutting treatments of juniper.

METHODS

Study Sites

Three study sites were located in southeast Oregon: two on Steens Mountain (Bluebunch, Fescue), 80 km south of Burns, and one site at the Northern Great Basin Experimental Range (NGBER), 57 km west of Burns. The Bluebunch and Fescue sites were classed as Phase 3 woodlands as juniper was the dominant vegetation. The NGBER site was a late Phase 2 woodland because trees co-dominated with shrub and herbaceous plants. Woodland phase was classified using criteria developed by Miller *et al*. (2000, 2005).

The Bluebunch site (42° 56′ 10″ N, 118° 36′ 30″ W) was located on a west aspect (slope 15 % to 22 %) at 1550 m to 1600 m elevation. The plant association was basin big sagebrush/bluebunch wheatgrass-Thurber's needlegrass (*Artemisia tridentata* Nutt. ssp. *tridentata* [Rydb.] Beetle/*Pseudoroegneria spicata* [Pursh] A. Löve-*Achnatherum thurberianum* [Piper] Barkworth). The ecological site was a Droughty Loam 11-13 (280 mm to 330 mm) PZ (precipitation zone) (NRCS 2006, 2010). Prior to treatment, juniper canopy cover averaged 26 % and tree density (>1.5 m tall) averaged 246 trees ha^{-1}. The intercanopy was 95 % bare ground, and Sandberg bluegrass (*Poa secunda* J. Presl) was the main understory species.

The Fescue site (42° 53′ 25″ N, 118° 34′ 18″ W) was an east facing slope (20 % to 45 %) at 1650 m to 1730 m elevation (Figure 1). The plant association was mountain big sagebrush/Idaho fescue (*Festuca idahoensis* Elmer). The ecological site was a North Slope 12-16 (304 mm to 406 mm) PZ. Juniper canopy cover averaged 31 % and tree density averaged 289 trees ha^{-1}. The intercanopy was 60 % bare ground and Idaho fescue and perennial forbs were understory dominants.

Figure 1. An untreated western juniper woodland (control) at the Fescue site, Steens Mountain, Oregon, USA.

The NGBER site (43° 29′ 42″ N, 119° 42′ 33″ W) was on a northeast slope (10 % to 20 %) at 1455 m to 1480 m elevation. The plant association was mountain big sagebrush/Idaho fescue and the ecological site was identified as a Droughty Loam 11-13 PZ. Prior to treatment, juniper canopy cover was 18 % and tree density was 195 trees ha^{-1}. The intercanopy was 60 % bare ground and Idaho fescue and perennial forbs were the main herbaceous species.

Precipitation in the northern Great Basin occurs mostly from late fall into spring. Water year precipitation (1 Oct to 30 Sep) at the NGBER averaged 284 mm over the past 75 years and during the study ranged from 182 mm to 335 mm. Water year precipitation at the Steens Mountain Bluebunch site averaged 358 mm over the past 10 years, ranging from 275 mm to 543 mm during the study. Precipitation is likely to be greater at the Fescue site as it is 100 m higher than the Bluebunch site. Drought (precipitation <75 % of average) occurred twice at the NGBER site and once at the Bluebunch and Fescue sites after treatment.

Experimental Design and Treatment Application

The experimental design at each site was a randomized complete block (Peterson 1985) with four cut-and-burn treatments and one cut-and-leave (CUT) treatment. Woodland (control) plots were present at the Bluebunch and Fescue sites. Treatments were designated by the month that fire was applied: September (SEP), January (JAN), March (MAR), and April (APR). All trees in the JAN, MAR, APR, and CUT treatments were felled in June and July, 2006. About one-third of the trees were cut in the SEP treatment; these trees were used to carry fire and kill remaining live trees. Treatment plots ranged from 0.2 ha to 0.4 ha in size with five replicates at the Bluebunch and Fescue sites and four replicates at the NGBER site. The SEP fires (strip head fires) were applied on 24, 25, and 26 Sep 2006, on the NGBER, Bluebunch, and Fescue sites, respectively. JAN fires were applied on 9, 17, and 19 Jan 2007, at the NGBER, Bluebunch, and Fescue sites, respectively. There was 5 cm to 12 cm of snow on the ground when the Fescue and NGBER sites were burned in January. MAR fires were applied on 6, 9, and 14 Mar 2007, on the NGBER, Bluebunch, and Fescue sites, respectively. APR fires were applied on 6 Apr 2007, on the Bluebunch and Fescue sites, and on 10 Apr 2007, at the NGBER site. Winter and spring burns required igniting individual or clusters of trees as snow or wet ground fuels prevented fire from carrying. Burn conditions were typical for applications used to fall broadcast burn and reduce fuel loading in winter and spring (Appendices 1 through 3).

Gravimetric soil water (0 cm to 10 cm) and fuel moisture for herbaceous fine fuels, litter, 1-hr, 10-hr, 100-hr, and 1000-hr fuel classes were measured the day of fire application (Appendices 1 through 3). Fuel moisture and soil water content were determined by drying samples at 100 °C to a constant weight. Weather data (relative humidity, wind speed, temperature) were recorded during fire applications. Soil temperatures were estimated using Tempilaq welding paints (Tempil, South Plainfield, New Jersey, USA) applied to 25 mm × 80 mm × 0.4 mm steel tags. Tempilaq paints melt or discolor at specific temperatures when heated. Five sets of tags were placed approximately 2 cm below the soil surface in the interspaces, litter mats surrounding stumps, and beneath cut trees. Sets consisted of 20 steel tags and each tag was marked with an indicator paint spanning 79 °C to 1093 °C. Temperature values were etched on the metal tags for identification.

Fire severity was estimated by indexing juniper fuel consumption and shrub mortality. Severity categories were light (fuels up to 10-hr fuels consumed; shrub mortality <49 %), moderate (fuels up to 100-hr fuels consumed; shrub mortality 50 % to 80 %), and high (fuels up to 1000-hr fuels consumed; shrub mortality >80 %). Juniper fuel consumption was estimated by wiring tags to the different size classes on three felled trees per plot. In each tree there were three tags each for 1-hr, 10-hr, and 100-hr fuels, and two tags for 1000-hr fuels. Tags were located between 25 cm and 50 cm above the ground surface. Tags that fell to the ground indicated consumption of the fuel class.

Vegetation Measurements

Density and canopy cover of herbaceous species were measured inside 0.2 m^2 (0.4 m × 0.5 m) frames in May 2006 and June 2007 to 2011. Herbaceous canopy cover and density were estimated spatially by zone: intercanopy, stump (litter mats beneath formerly standing trees), and debris (beneath cut trees). Stump zones were measured in the cardinal directions around eight randomly selected tree stumps in each plot. Frames were placed on the inside edge of the litter area or drip line (1 m to 2.5 m from stump). For the debris zone, frames were arbitrarily placed under eight randomly selected cut juniper trees (four frames per tree). Debris zones were former interspaces covered by felled trees and identical to interspaces in herbaceous cover and density prior to cutting. Stumps and debris zone trees were marked with metal tags for re-measurement. Intercanopy zones were randomly sampled in areas between cut trees and litter mats within each plot (32 frames). Shrub and tree cover were measured by line intercept on three 40 m transects in 2006 and 2011. Transects were spaced 10 m apart and parallel to one another in east-west or north-south directions. Densities of shrubs and small juniper (<1.5 m height) were measured in 2 m × 40 m belt transects. Juniper (>1.5 m height) density was estimated in 6 m × 40 m belt transects.

Analysis

Repeated measures analysis of variance using a mixed model (PROC MIXED procedure; SAS Institute, Cary, North Carolina, USA) for a randomized complete block design tested for year, treatment, and year by treatment effects for herbaceous, shrub, and western juniper response variables. Because of significant differences, the three sites were analyzed separately for most response variables, including juniper, shrub, and herbaceous (species and life form) cover and density. Herbaceous life forms and species were grouped as *Poa secunda* (shallow rooted grass), perennial bunchgrass (e.g., Idaho fescue), annual grass, perennial forb, and annual forb to simplify presentation of results. Because of similar patterns among treatments and controls, main cover groupings (total herbaceous cover, litter, bare ground, bio-crust [moss, lichen]) were blocked by site, using treatment plots as subplots. An auto regressive order one covariance structure was used because it provided the best model fit (Littell *et al*. 1996). The objective of our study was to compare overall treatment impacts on vegetation recovery. Microsite means for herbaceous cover and density response variables were weighted by the relative area of each zone (intercanopy, debris, stump). On the Bluebunch, Fescue, and NGBER sites, respectively, intercanopy zones were 53 %, 51 %, and 63 % of the study areas; stump zones were 27 %, 26 %, and 21 % of study areas; and debris zones were 20 %, 23 %, and 16 % of the study areas. Weighted means were summed to obtain pooled plot averages for response variables. Data were tested for normality using the Shapiro-Wilk test (Shapiro and Wilk 1965) and log-transformed for analyses when necessary. Back transformed means are reported. Because of year by treatment effects, years were analyzed separately using general linearized models and means separated using Fisher's protected Least Significant Difference. Statistical significance for all tests was set at $P < 0.05$.

RESULTS

Fire Severity and Western Juniper

Fire severity varied by time of burning and site (Appendices 1 through 3). At all sites, fire severity was rated light in JAN and MAR treatments as only 1-hr fuels were consumed and shrub mortality was less than 10 %. At the Bluebunch and NGBER sites, severity was rated high in the SEP and the APR treatments as 1-hr, 10-hr, and 100-hr western juniper fuels were consumed, 1000-hr fuels were partly consumed and charred, and shrub mortality was 80 % (APR) to 100 % (SEP) (Appendices 1 and 2). All junipers remaining after prep-cutting were killed by fire. In the CUT, JAN, and MAR treatments, all trees >1.5 m height were killed by cutting; however, 50 % to 100 % of small juniper (<1.5 m) survived (Figure 2A and 2B). Juniper cover was eliminated on the SEP treatment and in the other treatments (CUT, JAN, MAR, APR), cover was below 0.1 %.

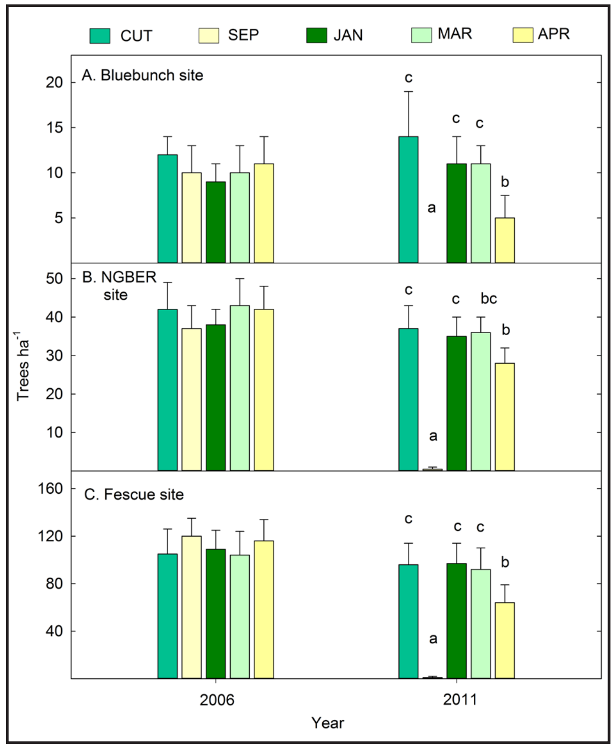

Figure 2. Density of small western juniper (<1.5 m tall) at the (A) Bluebunch site, (B) NGBER site, and (C) Fescue site for the various western juniper treatments in southeast Oregon, USA, in 2006 and 2011. Data are in means ±1 SE. Means sharing a common lower case letter are not significantly different ($P > 0.05$). The pre-treatment year was 2006.

At the Fescue site, fire was of moderate severity in the SEP treatment as juniper 1-hr and 10-hr fuels were fully consumed, 100-hr fuels were partially consumed, and shrub mortality was less than 75 % (Appendix 3). Fire severity was moderately high in the APR treatment as 1-hr, 10-hr, and 100-hr fuels were consumed; 1000-hr fuels were partly consumed and charred; and shrub mortality averaged 35 %. Most small juniper (<1.5 m height) survived the CUT, JAN, and MAR treatments (Figure 2C), and juniper cover was reduced to less than 0.5 % on all treatments.

Ground Cover, All Sites

Prior to juniper treatment, ground cover response variables did not differ among treatments and the control; after treatments, there were strong year-by-treatment interactions. Beginning in the second year after treatment, total herbaceous cover increased ($P < 0.001$), and by the fifth year after treatment applications (2011), herbaceous cover was 2.5 times greater (34.9 ± 4.2 %) than the control (Figures 3 and 4A; $P = 0.004$). Herbaceous cover among the five juniper treatments, however, was not different ($P = 0.415$). In the first year (2007) after treatment, litter cover increased in CUT (+50 %), Jan (+33 %), MAR (+38 %), and APR (+27%) treatments, and decreased in the SEP (−40 %) treatment (Figure 4B, $P < 0.001$). By 2010, differences in litter cover among most treatments (APR, JAN, MAR, SEP) and the control were equalizing and did not differ from pre-treatment values. Litter cover was greater in the CUT than in other treatments for most of the study, and in 2011 was 21 % to 59 % greater than the other treatments and control ($P < 0.006$). Bare ground increased in 2007 in SEP (+20 %) and APR (+8 %) treatments, and declined 14 % to 19 % in the other treatments (Figure 4C; $P = 0.006$). Bare ground eventually declined in all treatments to below pre-treatment levels ($P < 0.001$); however, it remained 9 % to 20 % greater in the SEP treatment than in the CUT, JAN, and MAR treatments ($P = 0.046$). Bio-crust cover declined from 3 % to below 1 % in

Figure 3. Cut-and-burn and cut western juniper woodland treatments (five years post-fire) at the Fescue site, Steens Mountain, Oregon, USA. The treatments for this study, applied in 2006 to 2007, are in the foreground; behind in the canyon is a prescribed burn from 2002.

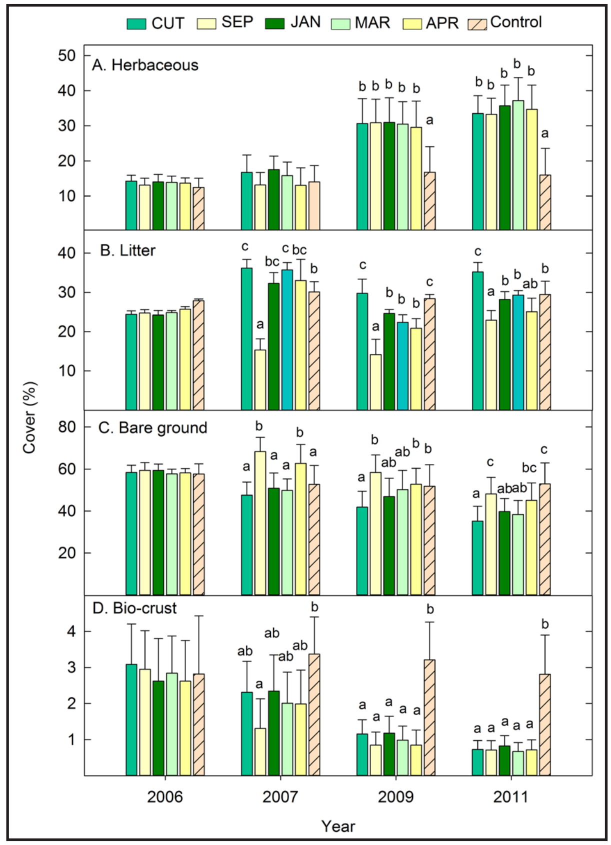

Figure 4. Ground cover (%) of (A) herbaceous, (B) litter, (C) bare ground, and (D) bio-crust for the various western juniper treatments averaged across the three sites (Bluebunch, Fescue, NGBER) on Steens Mountain and at the NGBER, Oregon, USA, from 2006 to 2011. Data are in means ±1 SE. Means sharing a common lower case letter are not significantly different ($P > 0.05$). The pre-treatment year was 2006.

all treatments and were less than the control (Figure 4D, $P < 0.007$).

Life Form Canopy Cover

Poa secunda. Treatment response of *P. secunda* was site dependent. On the Bluebunch site, cover declined among treatments from 2.2% in 2006 (pre-treatment) to less than 0.5% in 2011, significantly less than in the control ($P = 0.021$). On the Fescue site, *P. secunda* cover fluctuated in response to year ($P < 0.001$); however, treatment differences were not significant ($P = 0.283$), with cover averaging 3.5 ± 0.2%. On the NGBER site, cover of *P. secunda* treatments did not differ ($P = 0.719$); however, cover increased across years from 1.8% to 2.5% ($P = 0.002$).

Perennial bunchgrasses. Cover of perennial bunchgrasses increased the third year (2009) after treatment at all sites ($P < 0.001$), and by 2011 were 2.5 to 3 times greater on the treatments than the control on the Bluebunch site (Figure 5A, $P < 0.001$); 1.5 to 2 times greater than pre-treatment (2006) values on the NGBER site (Figure 5B, $P < 0.001$); and 2 to 2.8 times greater on the treatments than the control on the Fescue site (Figure 5C, $P < 0.001$). On the Bluebunch site, bunchgrass cover was greater in the JAN treatment than in the SEP and APR treatments ($P < 0.045$). At the NGBER site, perennial bunchgrass cover was 3% to 5% greater in the JAN, MAR, and CUT treatments compared to the SEP treatment from 2009 to 2011 ($P < 0.001$). On the Fescue site, bunchgrass cover was greater by 3% to 7% in the JAN and MAR treatments compared to the CUT, SEP, and APR treatments ($P = 0.011$).

Perennial forbs. On the Bluebunch site, perennial forbs did not respond to treatment as dramatically as other life forms ($P = 0.007$; Figure 6A). In three of the post-treatment years, (2007 to 2009) perennial forb cover in

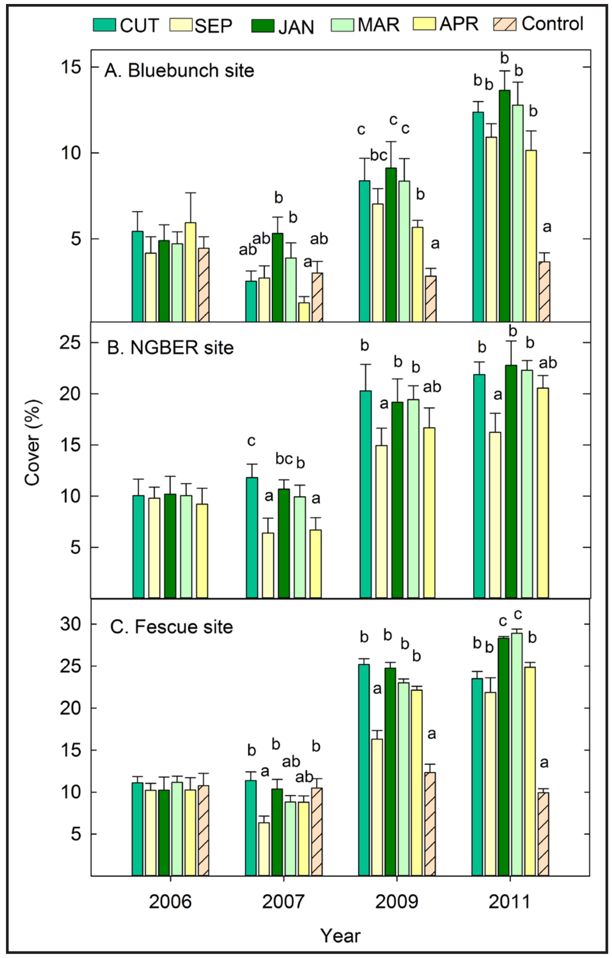

Figure 5. Perennial bunchgrass cover (%) at the (A) Bluebunch site, (B) NGBER site, and (C) Fescue site for the various western juniper treatments in southeast Oregon, USA, from 2006 to 2011. Data are in means ±1 SE. Means sharing a common lower case letter are not significantly different ($P > 0.05$). The pre-treatment year was 2006.

all treatments (except APR) was greater than in the control; however, forb cover never exceeded 2%, nor did it differ from the controls during the final two years of measurement. On the NGBER site, perennial forb cover increased in all treatments except the SEP treatment compared to pre-treatment values ($P = 0.002$). Perennial forb cover in the SEP treatment was consistently 2% to 3% lower than the other treatments (Figure 6B; $P < 0.001$). On the Fescue site, perennial forb cover increased in all treatments and in the control

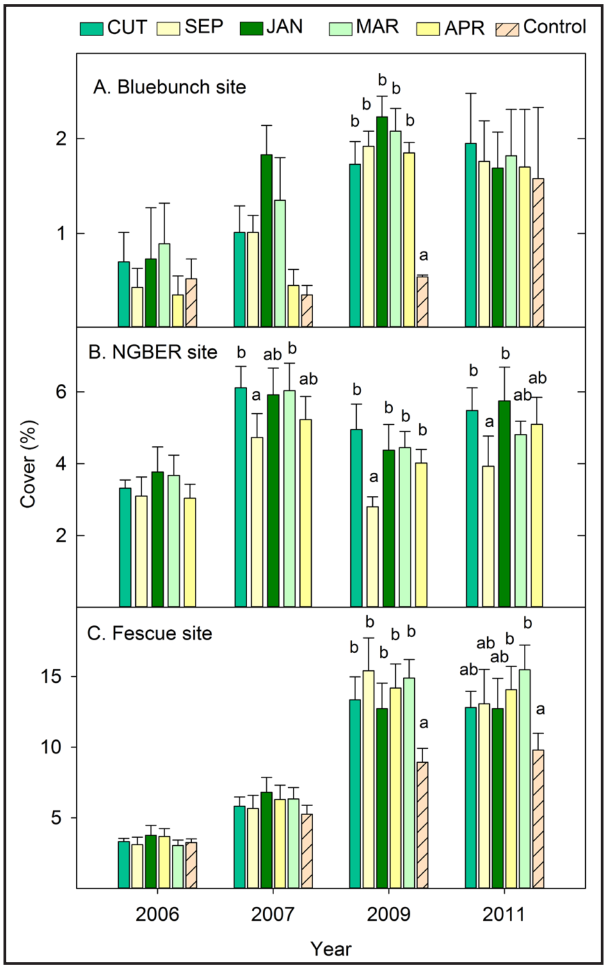

Figure 6. Perennial forb cover (%) at the (A) Bluebunch site, (B) NGBER site, and (C) Fescue site for the various western juniper treatments in southeast Oregon, USA, from 2006 to 2011. Data are in means ±1 SE. Means sharing a common lower case letter are not significantly different ($P > 0.05$). The pre-treatment year was 2006.

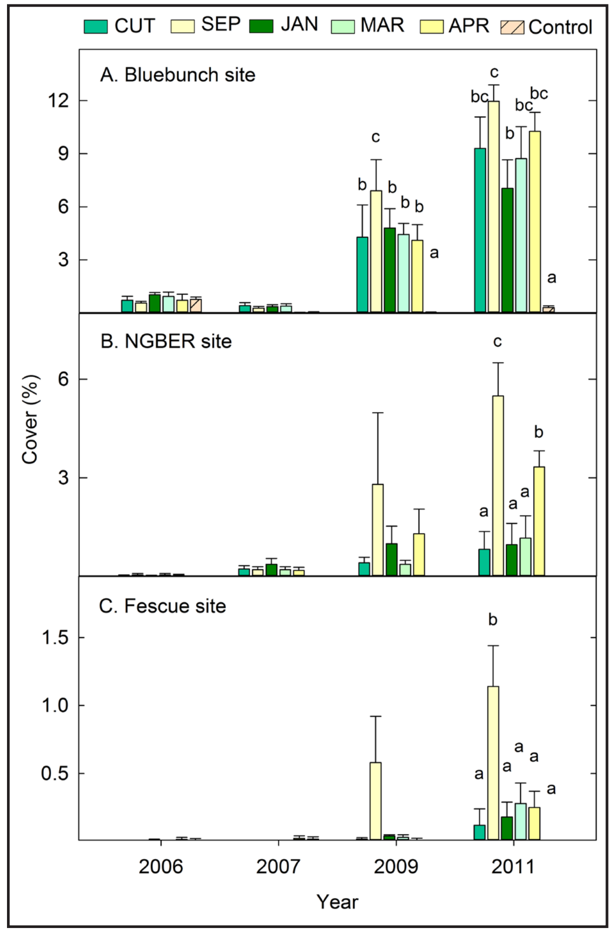

Figure 7. Annual grass cover (%) at the (A) Bluebunch site, (B) NGBER site, and (C) Fescue site for the various western juniper treatments in southeast Oregon, USA, from 2006 to 2011. Data are in means ±1 SE. Means sharing a common lower case letter are not significantly different ($P > 0.05$). The pre-treatment year was 2006.

(Figure 6C, $P = 0.019$); however, cover was about 50 % greater in the treatments than in the control ($P = 0.001$).

Annual grass. On the Bluebunch site, invasive annual grass (cheatgrass [*Bromus tectorum* L.] and field brome [*Bromus arvensis* L.]) began increasing during the third year (2009) following treatment, after which annual grass cover was significantly greater than in the control (Figure 7A; $P < 0.001$). In the final two measurement years, annual grass cover was nearly 50 % greater in the SEP treatment than in the JAN treatment. On the NGBER site, cheatgrass increased in the SEP and APR treatments and was greater than in the JAN, MAR, and CUT treatments (Figure 7B; $P = 0.003$). In 2011, cheatgrass cover represented about 12 % and 20 % of total herbaceous cover in SEP and APR treatments, respectively. On the Fescue site, *B. tectorum* cover was greater in the SEP treatment than in other treatments in 2011 (Figure 7C; $P = 0.017$); however, cover of *B. tectorum* in the SEP treatment (1.0 ± 0.3 %) represented only a small part (2.5 %) of total herbaceous cover.

Annual forbs. On the Bluebunch site, annual forb cover increased and was 2 to 6 times greater in all treated areas compared to the control from 2009 to 2011 (Figure 8A; P < 0.001). Annual forb cover was greatest in the SEP and APR treatments, in 2009; however, differences among treatments disappeared by 2011. Annual forbs were almost exclusively comprised of two non-natives (prickly lettuce [*Lactuca serriola* L.] and desert madwort [*Alyssum desertorum* Stapf.]) and a native species (western tansy mustard [*Descurainia pinnata* {Walter} Britton]). On the NGBER site, annual forb cover increased in all treatments (Figure 8B; P < 0.001) and was greatest in the SEP treatment (P < 0.001), although this relationship was not consistent and by 2011 treatment differences had faded. On the Fescue site, annual forb cover increased in all treatments and in the control; however, cover of annual forbs was 2 to 8 times greater in the treatments (Figure 8C, P < 0.001). Among the treatments, annual forb cover was greatest in the SEP treatment in 2009 to 2010. Annual forbs on the Fescue and NGBER sites consisted exclusively of native species.

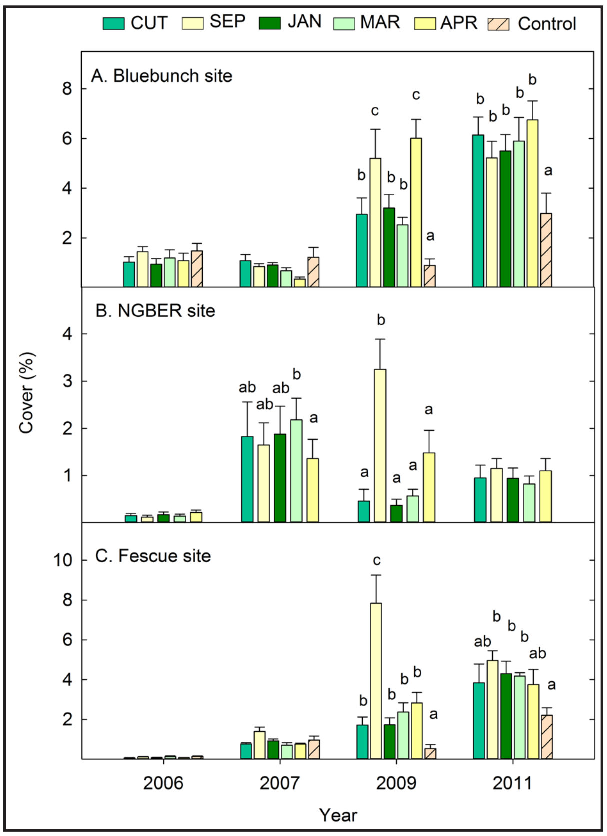

Figure 8. Annual forb cover (%) at the (A) Bluebunch site, (B) NGBER site, and (C) Fescue site for the various western juniper treatments in southeast Oregon, USA, from 2006 to 2011. Data are means ±1 SE. Means sharing a common lower case letter are not significantly different (P > 0.05). The pre-treatment year was 2006.

Shrub cover. On the Bluebunch site, shrubs were largely absent prior to treatment and there was no measurable change or difference in cover six years following treatment applications (P = 0.758). Shrub cover was below 0.5 % and species were represented by rubber rabbitbrush (*Ericameria nauseosa* [Pall. ex Pursh] G.L. Nesom & Baird) and spineless horsebrush (*Tetradymia canescens* DC). On the Fescue site, *Artemisia tridentata* ssp. *vaseyana* cover declined in the SEP treatment to <0.1 % and remained about 2 % in the other treatments and in the control during the study. On the NGBER site, *A.t.* ssp. *vaseyana* cover declined (CUT, JAN, MAR, APR) or was eliminated (SEP) during the year of treatment (P = 0.007). However, by 2009, sagebrush cover did not differ among treatments or from pre-treatment values of about 3.8 % to 5.2 % (P = 0.097).

Perennial Herbaceous Density

On the Bluebunch site, densities of *P. secunda* declined in all treatments from pre-treatment values of 6.3 ± 0.3 plants m^{-2} to 3.8 ± 0.3 plants m^{-2}, and were 75 % to 50 % less than in the control in 2011 (P = 0.006). Densities of perennial bunchgrasses increased (CUT, JAN, MAR) or recovered to pre-treatment (SEP, APR) values during the third year (2009) after treatment. In 2011, perennial grass densities in the treatments (5.5 plants m^{-2} to 6.8 plants m^{-2}) were 1.5 to 2 times greater than in the control (Figure 9A; $P < 0.007$). Perennial forb densities were impacted by year ($P < 0.001$), increasing from about 1.0 ± 0.4 plants m^{-2} to peak at 2.8 plants $\pm$ 0.4 plants m^{-2} in the treatments in 2009. Although there were treatment differences for perennial forb densities within individual years, these differences were not sustained at the end of the study ($P = 0.266$).

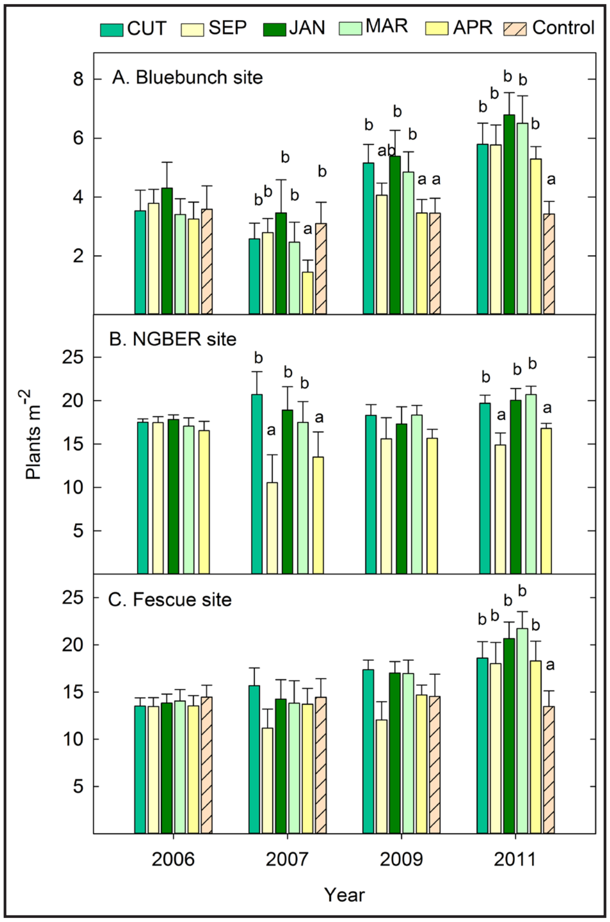

Figure 9. Perennial bunchgrass densities (plants m^{-2}) at the (A) Bluebunch site, (B) NGBER site, and (C) Fescue site for the various western juniper treatments in southeast Oregon, USA, from 2006 to 2011. Data are ±1 SE. Means sharing a common lower case letter are not significantly different ($P > 0.05$). The pre-treatment year was 2006.

On the NGBER site, densities of *P. secunda* were unaffected by year ($P = 0.648$) or treatment ($P = 0.938$l), averaging 14.3 ± 0.9 plants m^{-2}. Densities of perennial bunchgrasses increased in CUT, JAN, and MAR treatments from pre-treatment levels and were greater than the SEP and APR treatments (Figure 9B, $P = 0.001$). Perennial bunchgrass densities decreased by 20% and 40% during the first year after fire in the SEP and APR treatments, respectively. Perennial forb densities were significantly impacted by year ($P < 0.004$) and, over the course of the study, densities were slightly greater in CUT and JAN treatments (12.3 ± 0.4 plants m^{-2}) than in the SEP treatment (9.6 ± 1.2 plants m^{-2}; $P = 0.032$).

On the Fescue site, *P. secunda* density in all treatments and in the control increased 40% from pre-treatment values of 7.8 ± 0.6 plants m^{-2} to 11.7 ± 0.8 plants m^{-2} by 2011 ($P = 0.006$). Bunchgrass density increased (CUT, JAN, MAR) or recovered to pre-treatment (SEP, APR) values during the third year (2009) after treatment. By 2011, treatment bunchgrass densities were 1.3 to 1.7 times greater than the control (Figure 9C; $P < 0.007$). Perennial forb densities increased 2- to 4-fold from a pre-treatment value of 8 ± 0.7 plants m^{-2} in all treatments and in the control ($P < 0.001$). In the last two measurement years, perennial forb densities were 1.2 to 1.8 times greater in the treatments (25 plants m^{-2} to 33 plants m^{-2}) than in the control (18.7 ± 0.6 plants m^{-2}; $P = 0.027$).

DISCUSSION

Woody Plant Response

All treatments eliminated western juniper taller than 1.5 m. However, treatments differed in their ability to kill small trees (<1.5 m tall), thus rejecting our null hypothesis. The SEP treatments were most effective at killing small trees as flame lengths were longer and fuel continuity was adequate for carrying fire through plots. The results in the SEP treatment were typical for prescribed fires in the fall (Sept and Oct) as they commonly have not had detectable juniper establishment 5 years to 10 years following fire (Bates *et al*. 2006, 2011, 2013), although O'Connor *et al*. (2013) found that emergence from the seed bank allowed juniper to restock to 25% of pre-treatment density 5 years after burning. The APR treatment was somewhat effective and the JAN and MAR treatments were not effective at reducing small junipers, probably because higher herbaceous fuel moisture or the presence of snow prevented fire from carrying across plots. The retention of small trees in these treatments and in the CUT treatment parallel results from other cutting and winter and spring burning treatments (Bates *et al*. 2006, Bates and Svejcar 2009, O'Connor *et al*. 2013). It is likely that juniper will recover faster on JAN, MAR, APR, and CUT treatments because of the presence of surviving small trees, particularly on the Fescue an NGBER sites where small tree densities represented 14% to 33% of pre-treatment densities of large trees. Western juniper on the Bluebunch site (all treatments) will likely take longer to reoccupy because small trees represented only 2% to 8% of large-tree pre-treatment densities.

For the Bluebunch site, we failed to reject our hypothesis that shrub cover would differ among the treatments or from the control. This is because shrubs were largely absent prior to treatment and likely lacked a seed bank or adjacent sources of seed to respond following treatment. The lack of shrub recovery 4 years to 10 years following prescribed burning or cutting of Phase 3 juniper woodlands appears typical on sites where shrubs had been largely absent prior to treatment (Bates *et al*. 2005, 2006, 2011). On the Fescue and NGBER sites, treatments differed in their ability to retain or recover shrubs, primarily *Artemisia tridentata* ssp. *vaseyana*, thus rejecting our null hypotheses. The SEP treatments at both sites initially lost all shrub cover. On the Fescue site, shrubs on the SEP treatment did not recover and remained less than the other treatments and control. However, *A.t.* ssp. *vaseyana* on the SEP treatment NGBER site recovered during the third year after treatment. This response appears to have been from the seed bank as clumps of *A.t.* ssp. *vaseyana* established on severely burned patches and on patches lacking competing vegetation around stumps and downed juniper. O'Connor *et al*. (2013) reported similar increases of *A.t.* ssp. *vaseyana* and rubber rabbitbrush (*Ericamerica nauseosa* [Pall. ex. Pursh] G.L. Nesom & Baird) in severely burned areas after cutting and broadcast burning or pile burning of juniper. These results suggest that severely burned areas might be good locales to seed shrub species. Davies *et al*. (2014) reported some success reestablishing *A.t.* ssp. *vaseyana* in such areas after seeding. A common thread for early recovery of *A.t.* ssp. *vaseyana* appears to be linked to plants establishing within 2 years after fire (Ziegenhagen and Miller 2009).

Ground Cover

We hypothesized that ground cover variables would not change in response to seasonal burning of juniper or cutting trees compared to untreated controls. This hypothesis was rejected as total herbaceous, litter, bio-crust, and bare ground cover values differed from the control in some capacity immediately following treatment and throughout the course of the study. Total herbaceous cover exhibited similarities and differences with early-secondary successional (1 year to 5 years after treatment) patterns described in other studies that compared vegetation response between woodland treatments and untreated controls. Herbaceous cover tended to increase on all treatments at all three sites during the second year and peaked or stabilized during the fourth to fifth year following treatment applications. This has been a widespread trend following juniper cutting or burning treatments in several plant associations including *A.t.* ssp. *tridentata*/*A. thurberianum* (Bates *et al*. 2005, Bates and Svejcar 2009), quaking aspen (*Populus tremuloides* Michx; Bates *et al*. 2006), other *A.t.* ssp. *vaseyana*/*Festuca idahoensis* (Davies *et al*. 2012, Bates *et al*. 2013), and *A.t.* ssp. *vaseyana*/needlegrass species (*Achnatherum* spp.) (Bates *et al.* 2011, O'Connor *et al*. 2013). The differences in litter and bare ground cover were attributable to the level of fuel consumption, which, being higher in the SEP and APR treatments, explain their lower litter levels and greater amounts of bare ground than in CUT, JAN, and MAR treatments. The decline in bio-crust was a result of fire applications and a probable change in microenvironments. Star moss (*Tortula ruralis* [Hedw.] G. Gaertn., B. Mey. & Scherb) was the main bio-crust and was concentrated in shaded areas beneath juniper canopies. Once these areas burned or were exposed to direct sunlight, star moss was immediately lost (SEP treatment) or steadily declined (other treatments). Losses of bio-crust have been measured after cutting or burning of other juniper woodlands and sagebrush steppe (Bates *et al*. 2005, Davies *et al*. 2007, O'Connor *et al*. 2013).

Herbaceous Dynamics

We hypothesized that herbaceous cover and density variables (life forms and species) would not change in response to seasonal burning or cutting of juniper trees compared to untreated controls. This hypothesis was rejected for most herbaceous life forms and common species because their values increased relative to the controls following treatment at the Fescue and Bluebunch sites. The hypothesis was not rejected for *P. secunda* (Fescue site), annual grasses (Fescue site), and less common or infrequent species (both sites).

The increased cover and density of perennial bunchgrasses and forbs at both sites between the second and fourth growing seasons after treatment tracks a familiar pattern following many western juniper woodland treatments including: cutting (Bates *et al*. 2005), prescribed burning (Bates *et al*. 2006, 2011, 2013), and fuel reduction (Bates and Svejcar 2009, O'Connor *et al*. 2013). The flush of perennial and annual forbs, especially in early succession, was consistent with other studies in burned or cut piñon-juniper woodlands (Barney and Frischnecht 1974; Koniak 1985; Bates *et al*. 2005, 2011, 2013). These increases are attributable to greater availability of soil water and nitrogen (Bates *et al*. 2000, 2002). The prominence of forbs varied by site with forb cover representing 40% to 50% of total herbaceous cover on the Fescue site and, after initial flushes during the first year following treatment, 20% and 25% of total herbaceous cover on the NGBER and Bluebunch sites, respectively. On the Bluebunch site, non-native annual forbs *L. serriola* and *A. desertorum* are likely temporary increasers; in previous studies, they have not persisted 7 years to 10 years after woodland control (Bates *et al*. 2005, 2011; Bates and Svejcar 2009).

The lack of response (Fescue) or decline (Bluebunch) of *P. secunda* reflects a consistent pattern noted in other western juniper treatments (Bates *et al*. 2005, 2011, 2013). This suggests that *P. secunda* was not able to take advantage of greater availability of soil water and nutrients as were other life forms after juniper treatment. On the Bluebunch site, it was apparent that *P. secunda* declined as a result of mortality and lack of new recruitment.

Bromus tectorum and *B. arvensis* were present on Bluebunch and Fescue sites; however, only on the Bluebunch site did annual grasses become a significant component of the understory. The dissimilar response of annual grasses is likely a result of different site and vegetation characteristics. Invasiveness of annual grasses in the Great Basin is roughly regulated by temperature (at higher elevations), aspect, soil water variability (at lower elevations), and ecological condition as measured by cover or density of perennial species (Koniak 1985, Chambers *et al*. 2007, Davies *et al*. 2008, Condon *et al*. 2011). The Fescue site is cooler than the Bluebunch site because of higher elevation and an east aspect. The Fescue site had a more intact understory, as prior to treatment bunchgrass density was about 75 % of site potential, and recovered (to 20 plants m^{-2}) in the fourth or fifth year depending on treatment. The Bluebunch site was on a west aspect and at lower elevation and, coupled with shallower soils, soil water variability is likely higher than at the Fescue site. The understory was less intact on the Bluebunch site as, prior to treatment, bunchgrass density was 25 % of site potential and, in the fourth and fifth year after treatment, density was 50 % of potential (5 plants m^{-2} to 6 plants m^{-2}). Thus, conditions on the Bluebunch site made it favorable for annual grasses to co-dominate with perennial bunchgrasses.

We hypothesized that herbaceous cover and density would not differ among seasonal juniper burning and cutting and leaving trees. This hypothesis was rejected for perennial bunchgrasses at the Fescue and NGBER sites, for perennial forbs on the NGBER site, and for annual grasses at all three sites. The hypothesis was not rejected for *P. secunda* and most species at all three sites and for perennial forbs at the Fescue site. Treatment differences for perennial forbs at the NGBER and Bluebunch sites and annual forbs at all three sites were measured 1 year to 3 years after juniper treatment; however, these differences did not persist to the end of the study.

Fall burning (SEP) and spring burning (APR) at the Bluebunch and NGBER sites resulted in higher bunchgrass mortality and, thus, slower recovery of bunchgrasses and slight to considerably higher cover of annual grasses in comparison to winter burned treatments (JAN, MAR). We attributed the greater mortality of bunchgrasses to greater fuel consumption and fire temperatures in the SEP and APR treatments. The increase in annual grass in SEP and APR treatments also appears to be influenced by the level of fuel consumption and area burned. On the Fescue site, the maximum size fuels consumed in the SEP treatment were 100-hr fuels, and annual grasses represented only 5 % of total herbaceous cover. On the NGBER site, fuel consumption included up to 1000-hr fuels in SEP and APR treatments, and the area burned was 100 % on the SEP treatment and 18 % to 25 % on the APR treatment. Annual grass cover represented 20 % and 14 % of total plant cover on the SEP and APR treatments, respectively. In other similar studies, decreased perennial grass cover and increased cover of invasive species after fire was associated with greater fuel consumption (Armour *et al.* 1984, Griffis *et al.* 2001, Sabo *et al.* 2009).

On the Bluebunch site, there was a slight benefit to the JAN treatment as annual grass cover was lower than for the SEP treatment and bunchgrass cover was higher than for SEP and APR treatments. However, because bunchgrass cover and density remained below site potential for all treatments, annual grasses were able to colonize available space and represented 33 % to 40 % of total herbaceous cover in the last years of the study. On similar sites, it may take a decade or more for bunchgrasses and other herbaceous life forms to recover and for annual grasses to decrease (Eddleman 2002; Bates *et al*. 2005, 2011; Bates and Svejcar 2009). Nevertheless, south and west aspects often maintain a significant long-term presence of annual grasses after fire and other juniper woodlands treatments (Koniak 1985, Miller *et al*. 2005).

Management Implications

Treatment of piñon-juniper woodlands for recovery of sagebrush communities is important because of habitat needs of sage-grouse (*Centrocercus urophasianus*) and other wildlife, biological diversity, soil stability, and sustainability of grazing production (Miller *et al*. 2005, Pierson *et al*. 2007, Davies *et al*. 2011).

A main goal of western juniper control treatments is to maintain or increase perennial bunchgrasses because their abundance are key to preventing establishment of and dominance by non-native annual grasses (Miller *et al*. 2005, Chambers *et al*. 2007). In our study, western juniper control resulted in recovery (Fescue, NGBER sites) or a potential path to recovery (Bluebunch site) of native herbaceous understories within 5 years post-treatment. Sites with more intact understories appear able to recover within 5 years after treatment while sites with less intact understories likely require longer periods of time. An advantage to burning in the fall (SEP) and late spring (APR) was to reduce fuel loading created by the cut trees and to kill smaller junipers. When fuels were dry in the fall (September and October; NGBER and Bluebunch sites) and late spring, burning was effective at consuming fuel sizes up to 1000-hr fuels; results that others have also measured (Bourne and Bunting 2011, O'Connor *et al*. 2013). In our study, native herbaceous recovery in the SEP and APR treatments was slightly less than or equaled recovery in the winter burning and CUT treatments. However, land managers need to be aware that herbaceous responses to burning late Phase 2 and Phase 3 woodlands in the fall (September and October) is often less predictable because of depleted understories and the potential for greater mortality of native vegetation, which may promote weed dominance (Tausch 1999; Bates *et al*. 2006, 2011, 2013; Condon *et al*. 2011). Under these circumstances, seeding and weed control is required to advance vegetation recovery (Cox and Anderson 2004, Miller *et al*. 2005, Sheley and Bates 2008). To reduce the risk of weed dominance, winter or pile burning of cut trees may provide better guarantees of big sagebrush community recovery. There were benefits to winter burning treatments (JAN, MAR) with greater perennial bunchgrass recovery. However, there is a tradeoff with winter burning in that small junipers remain and fuels reduction only consumes, at most, 1-hr and 10-hr fuel types. Woodlands that are cut with trees left on site (CUT) or burned in the winter or early spring will require additional control of juniper saplings to maintain big sagebrush plant communities.

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Appendix 1. Burn date, weather, soil and fuel moisture, and fire behavior during prescribed burning for the burn treatments at the Bluebunch site, Steens Mountain, Oregon, USA. All juniper trees (>1.5 m) were cut in July 2006 in the JAN, MAR, and APR treatments. The SEP treatment was a partial cut (one third of trees >1.5 m tall were cut), fire killing the remaining live trees. Treatment means with different lower case letters are significantly different within rows (P < 0.05).

Measurement (units)	SEP 25 Sep 2006	JAN 17 Jan 2007	MAR 9 Mar 2007	APR 6 Apr 2007
Weather				
Temperature (°C)	20 to 27	3.5 to5.5	3.5 to 5.5	5.0 to 7.0
Relative humidity (%)	11 to 15	40 to 50	67 to 75	23 to 30
Wind speed (km hr^{-1}),	2 to 4, SW	0 to 2, SW	1to4, NE	6 to 13, SW
Sky	Clear	Clear	Overcast to snow	Clear
Soil water content (%)[1]				
Slash	12.4 ± 1.3a	32.8 ± 0.4c	29.6 ± 1.6c	24.3 ± 2.2c
Canopy	13.4 ± 1.1a	33.2 ± 0.9c	30.4 ± 1.2c	16.3 ± 1.0b
Interspace	11.9 ± 0.5a	32.8 ± 1.6d	26.1 ± 1.9b	17.1 ± 1.3b
Fuel moisture (%)				
Herbaceous	10.1 ± 0.2a	28.3 ± 1.4c	45.2 ± 3.3d	22.9 ± 3.2b
Juniper needles				
Suspended[2]	6.7 ± 0.5a	9.3 ± 1.1b	11.9 ± 0.9b	5.8 ± 0.4a
Ground surface[3]	9.2 ± 0.3a	35.6 ± 4.2c	37.8 ± 4.2c	11.1 ± 0.4b
Canopy mat	21.0 ± 3.4a	64.1 ± 11.6b	73.9 ± 12.8b	25.3 ± 0.6a
Cut juniper roundwood[4]				
1-hour	10.7 ± 1.2a	12.1 ± 1.1a	16.8 ± 1.7c	13.7 ± 0.2b
10-hour	20.7 ± 1.2b	13.8 ± 1.2a	14.6 ± 0.6a	14.5 ± 0.3a
100-hour	22.7 ± 1.6b	15.6 ± 2.2a	16.7 ± 0.7a	15.2 ± 0.9a
1000-hour	24.1 ± 0.6b	18.4 ± 2.7a	19.8 ± 2.0a	18.2 ± 0.3a
Shrub mortality (%)	100%	<5%	<5%	81%
Fire behavior				
Flame length (m)	5 to 11	4 to 7	3 to 6	4 to 7
Burn duration (minutes)	6 to 12	3 to 5	3 to 5	4 to 9
Surface soil temp. (°C)	961 ± 42	Not detected	680 ± 76	924 ± 103
2 cm deep soil temp. (°C)	201 ± 22	Not detected	Not detected	208 ± 57
Plot area burned (%)	95 to 100	15 to 20	15 to 20	20 to 28
Max. juniper fuel consumed	1000-hr	1-hr	10-hr	1000-hr

[1] Collected at 0 cm to 4 cm.
[2] Collected from cut junipers in direct contact with the ground.
[3] Collected from cut junipers suspended about 1 m above the ground.
[4] 1-hr fuels are juniper wood less than 0.64 cm in diameter; 10-hr fuels are juniper wood, 0.64 cm to 2.54 cm in diameter; 100-hr fuels are juniper wood, 2.54 cm to 7.62 cm in diameter; 1000-hr fuels are juniper wood, 7.62 cm to 20.32 cm in diameter. All juniper roundwood, except 1000-hr fuels, were collected from the surface up to 10 cm height. The 1000-hr juniper roundwood was suspended by branches above ground between 0.5 m to 1.5 m above the soil surface (refer to Figure 3).

Appendix 2. Burn date, weather, soil and fuel moisture, and fire behavior during prescribed burning for the burn treatments at the NGBER site, NGBER, Oregon, USA. All juniper trees (>1.5 m) were cut in July 2006 in the JAN, MAR, and APR treatments. The SEP treatment was a partial cut (one third of trees >1.5 m tall were cut), fire killing the remaining live trees. Treatment means with different lower case letters are significantly different within rows ($P < 0.05$).

Measurement (units)	SEP 24 Sep 2006	JAN 9 Jan 2007	MAR 6 Mar 2007	APR 10 Apr 2007
Weather				
Temperature (°C)	20 to 21	0 to 5.5	11.5 to 13.5	19 to 23
Relative humidity (%)	13 to 15	50 to 78	49 to 52	19 to 20
Wind speed (km hr^{-1}),	6 to 14, NE	Calm to 12, NE	2 to 12, NE	9 to 14, W
Sky	Clear	Clear	Clear	Clear
Soil water content (%)[1]				
Slash	9.8 ± 0.9a	30.2 ± 1.1c	33.1 ± 4.6c	22.1 ± 1.5b
Canopy	7.2 ± 0.2a	28.0 ± 0.8c	32.7 ± 3.1c	15.2 ± 1.3b
Interspace	8.7 ± 0.2a	27.0 ± 0.8c	28.6 ± 1.0c	13.4 ± 1.1b
Fuel moisture (%)				
Herbaceous	3.9 ± 0.3a	33.2 ± 0.7b	62.4 ± 12.3c	57.3 ± 14.3c
Juniper needles				
Suspended[2]	3.8 ± 0.2a	24.8 ± 1.6c	18.1 ± 0.6b	3.8 ± 0.2a
Ground surface[3]	8.5 ± 1.3a	80.0 ± 11.1b	97.5 ± 9.7b	8.5 ± 1.3a
Canopy mat	14.2 ± 1.3a	65.3 ± 8.1b	125.6 ± 15.4c	52.6 ± 12.7b
Cut juniper roundwood[4]				
1-hour	8.2 ± 0.3a	14.2 ± 1.3b	13.2 ± 1.2b	10.3 ± 1.2a
10-hour	13.7 ± 0.6a	16.4 ± 1.6ab	15.1 ± 1.8ab	17.1 ± 2.9b
100-hour	14.5 ± 1.3a	18.0 ± 2.4b	20.6 ± 3.7b	19.6 ± 2.2b
1000-hour	18.1 ± 0.7	20.4 ± 1.3	17.5 ± 5.2	17.3 ± 3.2
Shrub mortality (%)	100%	<5%	9%	82%
Fire behavior				
Flame length (m)	8 to 10	3 to 5	3 to 7	5 to 10
Burn duration (minutes)	6 to 12	2 to 4	3 to 6	9 to 15
Surface soil temp. (°C)	977 ± 67	Not detected	593 ± 31	864 ± 89
2 cm deep soil temp. (°C)	204 ± 30	Not detected	Not detected	220 ± 36
Plot area burned (%)	100	12 to 18	12 to 19	18 to 25
Max. juniper fuel consumed	1000-hr	1-hr	10-hr	1000-hr

[1] Collected at 0 cm to 4 cm.
[2] Collected from cut junipers in direct contact with the ground.
[3] Collected from cut junipers suspended about 1 m above the ground.
[4] 1-hr fuels are juniper wood less than 0.64 cm in diameter; 10-hr fuels are juniper wood, 0.64 cm to 2.54 cm in diameter; 100-hr fuels are juniper wood, 2.54 cm to 7.62 cm in diameter; 1000-hr fuels are juniper wood, 7.62 cm to 20.32 cm in diameter. All juniper roundwood, except 1000-hr fuels, were collected from the surface up to 10 cm height. The 1000-hr juniper roundwood was suspended by branches above ground between 0.5 m to 1.5 m above the soil surface (refer to Figure 3).

Appendix 3. Burn date, weather, soil and fuel moisture, and fire behavior during prescribed burning for the burn treatments at the Fescue site, Steens Mountain, Oregon, USA. All juniper trees (>1.5 m) were cut in July 2006 in the JAN, MAR, and APR treatments. The SEP treatment was a partial cut (one third of trees >1.5 m tall were cut), fire killing the remaining live trees. Treatment means with different lower case letters are significantly different within rows ($P < 0.05$).

Measurement (units)	SEP 26 Sep 2006	JAN 19 Jan 2007	MAR 14 Mar 2007	APR 6 Apr 2007
Weather				
Temperature (°C)	20 to 25.5	0 to 3	12.5 to 15.5	4.5 to 9.5
Relative humidity (%)	15 to 18	45 to 55	45 to 55	25 to 33
Wind speed (km hr^{-1}),	3 to 6, SW	Calm to 2, SW	1 to 4, NE	6 to 13, SW
Sky	Clear	Clear	Clear	Clear
Soil water content (%)[1]				
Slash	14.8 ± 0.7a	32.3 ± 0.6b	33.7 ± 0.9b	32.0 ± 3.4b
Canopy	15.9 ± 0.9a	31.6 ± 0.4b	30.9 ± 0.7b	31.2 ± 0.9b
Interspace	13.5 ± 1.1a	32.2 ± 0.5b	31.7 ± 1.0b	26.9 ± 1.4b
Fuel moisture (%)				
Herbaceous	13.5 ± 0.6a	15.4 ± 0.5a	73.1 ± 8.7c	45.1 ± 3.2b
Juniper needles				
Suspended[2]	22.4 ± 1.4c	11.5 ± 0.4b	9.6 ± 0.7ab	8.8 ± 0.5a
Ground surface[3]	37.6 ± 2.5b	48.7 ± 1.0c	44.1 ± 6.3c	30.1 ± 2.7a
Canopy mat	24.7 ± 2.4a	47.0 ± 6.1b	71.0 ± 4.9d	58.0 ± 8.7c
Cut juniper roundwood[4]				
1-hour	29.0 ± 3.3c	17.2 ± 0.7b	13.1 ± 1.0a	12.1 ± 0.7a
10-hour	29.2 ± 4.6b	16.1 ± 0.5a	15.0 ± 0.5a	17.1 ± 2.8a
100-hour	30.5 ± 4.3c	23.0 ± 1.2b	17.5 ± 1.3a	20.1 ± 3.8ab
1000-hour	26.3 ± 1.0b	25.8 ± 1.1b	20.7 ± 0.9a	21.7 ± 2.0a
Shrub mortality (%)	72%	<10%	<10%	35%
Fire behavior				
Flame length (m)	5 to 10	3 to 5	5 to 6	4 to 7
Burn duration (minutes)	6 to 12	3 to 4	3 to 5	7 to 13
Surface soil temp. (°C)	878 ± 48	Not detected	652 ± 81	704 ± 75
2 cm deep soil temp. (°C)	111 ± 10	Not detected	138 ± 42	178 ± 45
Plot area burned (%)	95 to 100	18 to 22	17 to 23	20 to 27
Max. juniper fuel consumed	100-hr	1-hr	1-hr	100-hr

[1] Collected at 0 cm to 4 cm.
[2] Collected from cut junipers in direct contact with the ground.
[3] Collected from cut junipers suspended about 1 m above the ground.
[4] 1-hr fuels are juniper wood less than 0.64 cm in diameter; 10-hr fuels are juniper wood, 0.64 cm to 2.54 cm in diameter; 100-hr fuels are juniper wood, 2.54 cm to 7.62 cm in diameter; 1000-hr fuels are juniper wood, 7.62 cm to 20.32 cm in diameter. All juniper roundwood, except 1000-hr fuels, were collected from the surface up to 10 cm height. The 1000-hr juniper roundwood was suspended by branches above ground between 0.5 m to 1.5 m above the soil surface (refer to Figure 3).