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Seasonal burning of juniper woodlands and spatial recovery of herbaceous vegetation

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ABSTRACT

Decreased fire activity has been recognized as a main cause of expansion and infilling of North American woodlands. Piñon-juniper (*Pinus-Juniperus*) woodlands in the western United States have expanded in area 2–10-fold since the late 1800s. Woodland control measures using chainsaws, heavy equipment and prescribed fire are used to restore big sagebrush (*Artemisia tridentata* Nutt.) steppe plant communities and reduce woody fuel loading. Immediate objectives in the initial control of piñon-juniper are; (1) recovery of perennial herbaceous species to restore site composition, structure and processes (resilience) and resist invasion and dominance by invasive annual grasses (resistance) and (2) reducing woody fuel accumulations. Spanning a 7 year period (2006–2012), we compared herbaceous recovery following cutting and prescribed fire on three sites in mid and late succession western juniper (*Juniperus occidentalis* spp. *occidentalis* Hook.) woodlands in southeast Oregon. Treatments were untreated controls, partial cutting followed by fall broadcast burning (SEP), clear-cut and leave (CUT), and clear-cut and burn in winter (JAN), and spring (APR). Cover of herbaceous species was measured in three zones; interspace, litter mats around tree stumps (stump), and beneath felled trees. In interspace zones of all treatments, comprising between 51% and 63% of site areas, perennial bunchgrasses dominated two sites and co-dominated with invasive annual grasses at one site after treatment. Burning in the JAN treatments, when fuel moisture and relative humidity were high and temperatures cooler, reduced disturbance severity in stump and felled tree zones, which maintained perennial herbaceous understories and prevented or limited the presence of invasive annuals. Burning felled juniper in SEP and APR treatments resulted in moderate to high fire severity in stump and felled tree zones. At two sites, these fires consumed all fuel up to the 1000-h fuel class, largely eliminated herbaceous perennials, and created islands within treatments that enhanced annual grass invasion and dominance. To maintain or boost site resilience and resistance following control of late successional woodlands, reducing piñon-juniper fuels by burning in winter provides managers with a low-impact option for conserving sagebrush steppe.

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1. Introduction

Semi-arid lands occupy 12.2% of the terrestrial world and many have been significantly altered as a result of land use demands, herbivory, altered fire regimes, invasive species, environmental changes, and woodland expansion (FAO, 1989; UNSO/UNDP, 1997). Woodland expansion and infilling in grasslands, shrublands and savannahs are problematic due to reductions in herbage for livestock and wildlife habitat modification, which may be detrimental to wildlife populations and diversity (Brown and Archer, 1989; Burrows et al., 1990; MacDonald and Wissel, 1992; Van Auken, 2000; Davies et al., 2011). In North American, reduced fire frequency has been recognized as a main cause of woodland development (Burkhardt and Tisdale, 1976; Archer et al., 1988; Miller and Wigand, 1994; Miller and Rose, 1995). Prescribed fire and mechanized treatments are used to eliminate trees to maintain or restore grass and shrub ecosystems (Owens et al., 2002; Miller et al., 2005; Teague et al., 2010; Roundy et al., 2014).

Piñon-juniper (*Pinus-Juniperus*) expansion in the western United States has caused widespread conversion of riparian, sagebrush (*Artemisia tridentata* Nutt.) steppe, and other upland communities to conifer woodland (Miller et al., 2005). In the northern Great Basin and Columbia Plateau, western juniper (*Juniperus occidentalis* ssp. *occidentalis* Hook.) woodlands have increased from 0.3 million to nearly 4 million ha the past 120–150 years (Miller et al., 2005; Johnson and Miller, 2008). Potential undesirable effects of woodland development include greater soil erosion and

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reduced water infiltration (Reid et al., 1999; Pierson et al., 2007; Petersen et al., 2009), loss of wildlife habitat (Noson et al., 2006; Reinkensmeyer et al., 2007), and reduced shrub and herbaceous diversity and productivity (Miller et al., 2005; Coultrap et al., 2008; Bates et al., 2005, 2011).

Thus, control of expanding woodlands is an important management action that conserves sagebrush steppe and other plant communities (Davies et al., 2011). Eliminating the influence of piñon-juniper by prescribed fire or mechanical methods is a straightforward task, however, recovery of desirable herbaceous species is influenced by several factors including the woodland successional phase, the method of tree control and treatment of woody fuels, post-treatment floristics, and other site characteristics (e.g. soils, climate) (Miller et al., 2005; Condon et al., 2011; Bates et al., 2013, 2014). Site characteristics are important for forecasting resilience and resistance especially when impacted by disturbances and stressors including fire, drought and invasive species (Chambers et al., 2014a,b). Areas with higher precipitation, cooler temperatures, and intact native plant communities tend to regain their structure and ecological processes (resilience) after disturbance or stressor events, and are better able to retain these attributes (resistance) compared to drier–warmer areas and those with less intact plant communities (Chambers et al., 2015). Severe disturbances can reduce resilience and resistance and may cause a shift from desirable to undesirable plant communities dominated by invasive weeds (Bates et al., 2013). It is vital that managers tailor selection and application of woodland control treatments appropriate to an area to result in successful plant community recovery.

Two objectives in the initial control of piñon-juniper woodlands are; (1) recovery of native perennial herbaceous species to maintain or restore site structure and processes, and resist invasion and dominance by exotic annual grasses, and (2) mitigation of fuel accumulations during or following woodland treatment (Miller et al., 2005; Huffman et al., 2009; O'Connor et al., 2013). Moderating disturbance severity and treating woodlands in earlier successional phases when accumulations of woody biomass are lower are the best means of achieving these objectives (Miller et al., 2005; Baughman et al., 2010; Chambers et al., 2014a, 2015; Bates et al., 2013). In later successional phases use of fire alone to control trees is riskier because the increase in woody biomass generates fires of greater severity than the historic regime and may increase the risk of weed dominance because of high mortalities of native herbaceous perennials (Tausch, 1999; Bates et al., 2006, 2011, 2013; Condon et al., 2011). Therefore, these woodlands are often mechanically cut, anchor chained, or shredded. Downed trees are commonly treated by various fuel reduction methods including dormant season (October–March) and early spring burning and burning of machine or hand piled trees. In the event of wildfire, fuel treatments reduce fire intensities, rate of spread, and scorch heights (Stephens, 1998; O'Connor et al., 2013). Three distinct zones are created from juniper cutting; interspace areas, areas beneath felled trees, and juniper litter mats surrounding the stumps. The arrangement and treatment of woody fuels often results in differing spatial and temporal recovery of vegetation (Vaitkus and Eddleman, 1987; Bates and Svejcar, 2009; Haskins and Gehring, 2004). Dormant season burning of piñon-juniper appears to offer the best combination for reducing woody fuels and maintaining desirable vegetation (Bates and Svejcar, 2009; O'Connor et al., 2013; Bates et al., 2014). However, comparisons of vegetation response to fuel treatments across sites as well as spatial and longer-term herbaceous recovery have been limited in piñon-juniper woodlands.

We evaluated the spatial response of herbaceous life-forms to seasonal burning of mechanically cut western juniper over a 7-year period (2006–2012) in three distinct plant communities in eastern Oregon. Our expectations were that; (1) herbaceous cover would increase in response to cutting and burning trees and (2) the various treatments would result in understory compositional differences among interspace, beneath felled trees, and litter mat zones. We were interested in the temporal dynamics of the response and the potential for treatments to cause a shift from desirable native perennials to invasive annuals.

2. Methods and materials

2.1. Study sites

In 2006, 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 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 15–22%) at 1550 to 1600 m. The plant association was basin big sagebrush/bluebunch wheatgrass-Thurber's needlegrass (*A. tridentata* Nutt. spp. *tridentata* (Rydb.) Beetle/ *Pseudoroegneria spicata* (Pursh) A. Löve – *Achnatherum thurberianum* (Piper) Barkworth). The ecological site is a Droughty Loam 11–13 (280–330 mm) PZ (precipitation zone) (NRCS, 2006, 2010). Prior to treatment, juniper canopy cover averaged 26% and tree density (>1.5 m tall) was 246 trees ha^{-1}. Sagebrush cover was less than 1%. The interspace was 95% bare ground. Perennial bunchgrasses and Sandberg's bluegrass (*Poa secunda* J Pres.) were the main understory species. The criteria developed by Chambers et al. (2014a,b, 2015) indicates that this site has moderate resilience and resistant scores because it is relatively warm and moist, has shallow soils, and the understory, though comprised of perennial grasses, had an evident presence of invasive annual grasses and forbs.

The Fescue site (42°53′25″N, 118°34′18″W) was an east facing slope (20–45%) at 1650–1730 m (Fig. 1). The plant association was mountain big sagebrush/Idaho fescue (*A. tridentata* Nutt. spp. *vaseyana* (Rydb.) Beetle/*Festuca idahoensis* Elmer). The ecological site was a North Slope 12–16 (304–406 mm) PZ. Juniper canopy cover averaged 31% and tree density averaged 289 trees ha^{-1}. Sagebrush cover was less than 2%. The interspace was 60% bare ground and Idaho fescue and perennial forbs were understory dominants. Criteria developed by Chambers et al. (2014a,b, 2015) indicates that this site has high resilience and resistant scores because it is relatively cool and moist, has deep-loamy soils, and an understory mainly comprised of deep-rooted perennial bunchgrasses and forbs.

The NGBER site (43°29′42″N, 119°42′33″W) was on a northeast slope (10–20%) at 1455–1480 m. 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}. Sagebrush cover averaged 3 ± 0.9%. The interspace was 60% bare ground and Idaho fescue and perennial forbs were the main herbaceous species. The criteria developed by Chambers et al. (2014a,b, 2015) indicates this site has high resilience and resistant because it is relatively cool and moderately moist, has moderately deep loamy soils, and the understory was comprised of perennial bunchgrasses and forbs.

Precipitation in the northern Great Basin occurs mostly from late fall into spring. Water year precipitation (1 October–30 September) at the NGBER averaged 284 mm the past 75 years and during the study ranged from 182 to 335 mm. Water year

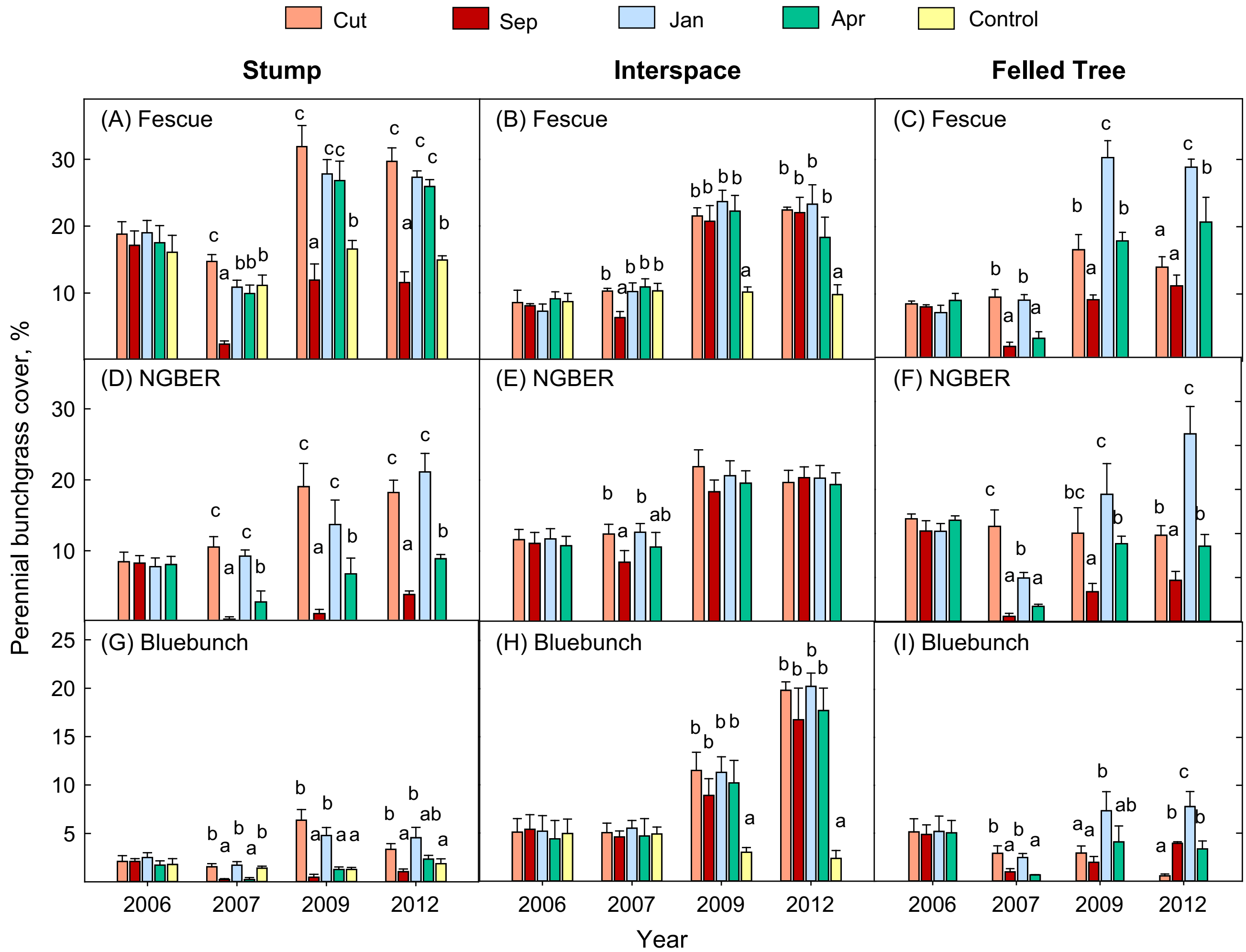

Fig. 1. Perennial bunchgrass cover (%) for the; Fescue site (A) stump, (B) interspace, and (C) felled tree zones; NGBER site (D) stump, (E) interspace, and (F) felled tree zones; and Bluebunch site (G) stump, (H) interspace, and (I) felled tree zones sites, for the western juniper treatments in southeast Oregon, 2006, 2007, 2009, and 2012. Data are means + one standard error. Zonal means sharing a common lower case letter within site and year are not different ($P > 0.05$).

precipitation at the Steens Mountain Bluebunch site averaged 358 mm the past 10 years, ranging from 275 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) years occurred twice at the NGBER site and once at the Bluebunch and Fescue sites after treatment.

2.2. Experimental design and treatment application

The experimental design at each site was a randomized complete block (Peterson, 1985) with 3 cut-and-burn treatments and a cut-and-leave (CUT) treatment. Woodland (control) plots were present at the Bluebunch and Fescue sites. Treatments were designated by the month fire was applied; September (SEP), January (JAN), and April (APR). All trees in the JAN, 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 to kill remaining live trees. Treatment plots ranged from 0.2 to 0.4 ha with 5 replicates at the Bluebunch and Fescue sites and 4 replicates at the NGBER site. The SEP fires (strip head fire) were applied on 24, 25, and 26 September 2006, on the NGBER, Bluebunch and Fescue sites, respectively. JAN fires were applied on 9, 17, and 19 January 2007, at the NGBER, Bluebunch, and Fescue sites, respectively. There was 5–12 cm of snow on the ground when the Fescue and NGBER sites were burned in January. APR fires were applied on 6 April 2007, on the Bluebunch and Fescue sites and on 10 April 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.

2.3. Fire conditions and characteristics

Burning conditions were typical for applications used to fall broadcast burn and reduce fuel loading in winter and spring (Bates et al., 2014). Fine fuels and soils (0 = 4 cm) were drier for SEP and APR treatments than the JAN treatment. Flame lengths, burn duration, area burned, soil temperatures and fuel consumption were lowest in JAN treatments and greatest in SEP treatments (Table 1; Bates et al., 2014). Juniper fuel consumption in canopy and felled tree zones of SEP and APR treatments consumed all 1-h, 10-h and 100-h fuels and partly consumed 1000-h fuels. In interspaces of SEP treatments herbaceous fine fuels were consumed as were any scattered shrubs. Interspace zones in APR treatments did not burn though heat damage was noted for plants in close proximity to burning trees. In JAN treatments, fuel consumption only consumed 1-h fuels in the felled tree zones while stump and interspace zones did not burn. Fire severity was rated moderate to high in SEP treatments, low too high in APR treatments and none too low in the JAN treatments (Bates et al., 2014).

Table 1
Surface and 2 cm deep soil temperatures, plot area burned, and maximum fuel consumption for the prescribed burning treatments at the Bluebunch, Fescue, and NGBER sites, Oregon. All juniper trees (>1.5 m) were cut in July 2006 in the JAN and APR treatments. The SEP treatment was a partial cut (1/3 of trees >1.5 m tall were cut) with fire killing the remaining live trees.[a]

Measurement (units)	SEP (2006)	JAN (2007)	APR (2007)
Surface soil temp. (°C)	878–977	Not detected	704–924
2 cm deep soil temp. (°C)	111–204	Not detected	178–204
Plot area burned (%)	95–100	12–22	20–28
Maximum juniper fuel consumed	100–1000-h[b]	1-h	10–1000-h

[a] Data is summarized from Bates et al. (2014).
[b] 1-h fuels are juniper wood less than 0.64 cm in diameter; 10-h fuels are juniper wood, 0.64–2.54 cm in diameter; 100-h fuels are juniper wood, 2.54–7.62 cm in diameter; 1000-h fuels are juniper wood, 7.62–20.32 cm in diameter. All juniper roundwood, except 1000-h fuels, were collected from the surface up to 10 cm height. The 1000-h juniper roundwood was suspended by branches above ground between 0.5 and 1.5 m above the soil surface.

2.4. Vegetation measurements

Canopy cover of herbaceous species were measured inside 0.2-m^2 (0.4×0.5 m) frames in May 2006 and June 2007–2011. Herbaceous canopy cover was estimated by zone; interspace, litter mats beneath formerly standing trees (stump), and beneath felled trees (felled). Stump zones were measured in the cardinal directions around 8 randomly selected tree stumps in each plot. Frames (4 frames per stump) were placed on the inside edge of the litter area or drip line (1–2.5 m from the stump). For the felled-tree zone, frames were placed under 8 randomly selected felled trees (4 frames per tree). This zone was former interspace now overlain by felled trees and were identical to interspaces in herbaceous cover and density prior to cutting. Stumps and felled trees were marked with metal tags for re-measurement. Interspace zones were randomly sampled in areas between felled trees and stump zones within each plot. On the Bluebunch, Fescue and NGBER sites; interspace zones were 53%, 51%, and 63% of the study areas, stump zones were 27%, 26%, and 21% of study areas, and felled-tree zones were 20%, 23%, and 16% of the study areas, respectively (Bates et al., 2014).

2.5. Analysis

Repeated measures analysis of variance using a mixed model (PROC MIXED, SAS Institute, Cary, North Carolina) for a randomized complete block design tested for year, treatment, zone and interactions for herbaceous cover. The three sites were analyzed separately for herbaceous (species and life form) cover response variables (Bates et al., 2014). Herbaceous life forms and species were grouped as *P. secunda* (shallow rooted grass), perennial bunchgrass (e.g., Idaho fescue), annual grass, perennial forb, and annual forb to simplify presentation of results. An auto regressive order one covariance structure was used because it provided the best model fit (Littell et al., 1996). Data were tested for normality using the Shapiro–Wilk test (Shapiro and Wilk, 1965) and log transformed for analyses when necessary. Because of year by treatment effects, years were analyzed separately using general linearized mixed models (GLMM). Statistical significance for all tests was set at $P < 0.05$.

3. Results

3.1. Perennial bunchgrasses

The cover response of perennial bunchgrasses (PBG) at each site was influenced by year, treatment, and zone (Table 2). Prior to treatment (2006), cover was greater in the stump compared to the other two zones at the Fescue site. At the Bluebunch and NGBER sites cover was greater in the interspace and felled tree zones than the stump.

At the Fescue site, the year following treatment (2007), PBG cover decreased in stump and interspace zones in the SEP treatment and in the felled tree zone cover decreased in the SEP and APR treatments (Fig. 1A–C). Over time, cover increased to 25–30% in the stump zone for CUT, JAN, and APR treatments, which was double the control. Cover in the stump zone for the SEP treatment did not recover to the pre-burn value and was less than the control and other treatments. In the interspace, cover increased in all treatments and was 2–2.5-fold greater than the control in 2009 and 2012. In the felled tree zone, cover of PBG was 2–3-fold greater in the JAN and APR treatments versus the SEP and CUT treatments.

At the NGBER site PBG cover was reduced in stump and felled tree zones for the SEP and APR treatments (Fig. 1D–F). In contrast, cover in the stump zone nearly doubled in JAN and CUT treatments. In the interspace cover declined the first year after fire in the SEP treatment. However, by the end of the study cover had doubled in the interspace and treatments did not differ (Figs. 1E and 2A and B). In 2012, beneath felled trees, cover was nearly 3-fold greater (JAN), remained below (CUT) or recovered (APR) compared to pre-treatment levels (Fig. 1F). In the SEP treatment cover was half the pre-treatment value.

At the Bluebunch site there was decreased PBG cover in the stump zone in the SEP and APR treatments and values did not differ from the control in 2009 and 2012. There were small increases in cover in stump zones of the CUT and JAN treatments, however,

Fig. 2. Interspaces zones at the NGBER site (June 2012), southeast Oregon, for (A) JAN treatment and (B) SEP treatment. Herbaceous covers in interspaces zones did not differ among the treatments at any of the three sites after treatment.

cover remained less than 5%. In the interspace PBG cover increased 5–7-fold in the treatments compared to the control by 2012 (Fig. 1H). Cover in the interspaces of the treatments became increasingly greater over time than their respective values in the stump and felled tree zones. Cover of PBG in the felled tree zone declined in all treatments in 2007 though decreases were greatest for the SEP and APR treatments. In the felled tree zone, cover of PBG increased in the JAN treatment and was 2–8-fold greater than the other treatments. In the CUT-felled tree zone, PBG cover declined below 1% and was less than all other treatments by 2012.

3.2. Perennial Forbs

Prior to treatment (2006), PF cover did not differ among zones at the Fescue site, however, at the NGBER and Bluebunch sites cover was greater in the interspace and felled tree zones compared to the stump zone. Following treatment the cover response of PF at each site was influenced by year, treatment, and zone (Table 2).

At the Fescue site PF cover increased in the stump zone and tended to be greater in the treatments than the control (Fig. 3A). Forb cover increased in all treatments in the interspace but did not differ from the control (Fig. 3B). In the felled tree zone, PF cover increased in all treatments (Fig. 3C). Except for the CUT treatment, PF cover was greater in the felled tree zone than the interspace.

At the NGBER site, PF cover following treatment was 2 to 3-fold greater in the stump zone in the CUT, JAN, and APR treatments compared to the SEP (Fig. 3D). Forb cover initially decreased in the SEP treatment and did not recover to pretreatment levels until 2012. In the interspace, PF cover did not differ among treatments and following a temporary increase in 2007, cover values did not differ from pretreatment values (Fig. 3E). In the felled tree zone PF cover decreased in the SEP treatment and remained at about half of pre-treatment values during the study (Fig. 3F). Cover of PF in treatments of the felled tree zone did not change from pretreatment values and were 2–3-fold greater than the SEP treatment.

At the Bluebunch site temporary differences among treatments were evident depending on zone and year (Fig. 3G–I). In all three zones, treatments and the control did not differ by the conclusion of the study. Perennial forb cover values were below 1–3% and never exceeded 7% of total herbaceous cover.

3.3. Annual grasses

Prior to treatment, AG cover was less than 0.1% at the Fescue and NGBER site and less than 1% at the Bluebunch site across the three zones. Following treatment it took 3–4 years for AG to respond although increases varied by treatment, zone, and site (Table 2).

At the Fescue site, cover of AG increased in the SEP stump zone and was nearly 7-fold greater than the other treatments and control by 2012 (Fig. 4A). AG cover did not increase or differ among treatments in the interspace zone (Fig. 4B). In the felled tree zone, cover increased in the SEP and APR treatments, with increases greater in the SEP treatment (Fig. 4C).

At the NGBER site, there were small to large increases in AG cover in the stump and felled tree zone and no change or treatment differences in the interspace (Fig. 4D–F). In the stump and felled tree zone AG cover was 2–7-fold greater in the SEP and APR treatments than the CUT and JAN treatments (Fig. 5A and B). Cover of AG was also greater in stump and felled tree zones than the interspace, especially the SEP and APR treatments, in 2012.

At the Bluebunch site, AG cover increased in all treatments and zones and were greater than the control. The largest increases were in the SEP and APR treatments in stump and felled tree zones. AG cover tended to be greater in stump and felled tree zones than the interspace, except for the CUT and JAN treatments where cover was less in interspace and felled tree zones than the stump zone.

Table 2
Response variable *P*-values from mixed model analysis for the three western juniper sites on Steens Mountain and the Northern Great Basin Experimental Range, eastern Oregon (2006–2012). Values in bold indicate significant differences for main effects and interactions.

Site and response variable	Treatment (Trt)	Year (Yr)	Zone	Trt * Year	Trt * Zone	Yr * Zone	Trt * Yr * Zone
Bluebunch-Steens Mt							
PBG[a]	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001
Pose	<0.001	<0.001	<0.001	0.002	0.103	0.004	0.050
AG	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001
PF	<0.001	<0.001	<0.001	0.241	0.405	0.157	0.762
AF	<0.001	<0.001	0.007	<0.001	0.006	0.012	<0.001
Herbaceous	<0.001	<0.001	<0.001	<0.001	0.295	<0.001	<0.001
Bare-ground	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	0.002
Litter	<0.001	<0.001	0.032	<0.001	0.015	0.015	<0.001
Bio-crust	0.006	<0.001	<0.001	<0.001	<0.001	<0.001	0.004
Fescue-Steens Mt							
PBG	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	0.268
Pose	<0.001	<0.001	<0.001	0.038	<0.001	<0.001	0.808
AG	<0.001	0.020	0.113	0.139	0.010	0.667	0.824
PF	<0.001	<0.001	<0.001	0.382	0.167	0.016	0.879
AF	<0.001	<0.001	<0.001	<0.001	0.114	0.866	0.778
Herbaceous	<0.001	<0.001	<0.001	<0.001	0.029	<0.001	0.819
Bare-ground	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	0.121
Litter	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001
Bio-crust	<0.001	<0.001	<0.001	0.081	0.413	<0.001	0.841
NGBER							
PBG	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	0.002
Pose	0.321	<0.001	<0.001	0.852	0.418	<0.001	0.894
AG	<0.001	<0.001	<0.001	<0.001	0.010	<0.001	0.003
PF	<0.001	0.022	0.006	0.084	0.024	<0.001	0.804
AF	<0.001	<0.001	0.699	<0.001	0.840	0.002	0.003
Herbaceous	<0.001	<0.001	<0.001	0.006	0.029	<0.001	0.465
Bare-ground	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001
Litter	0.006	<0.001	<0.001	<0.001	<0.001	<0.001	0.003
Bio-crust	<0.001	<0.001	<0.001	0.081	<0.001	0.394	0.867

[a] PBG, perennial bunchgrass; Pose, *Poa secunda*; AG, annual grass, PF, perennial forb; AF, annual forbs; Herbaceous, total herbaceous cover; Bio-crust (moss, lichen, algae).

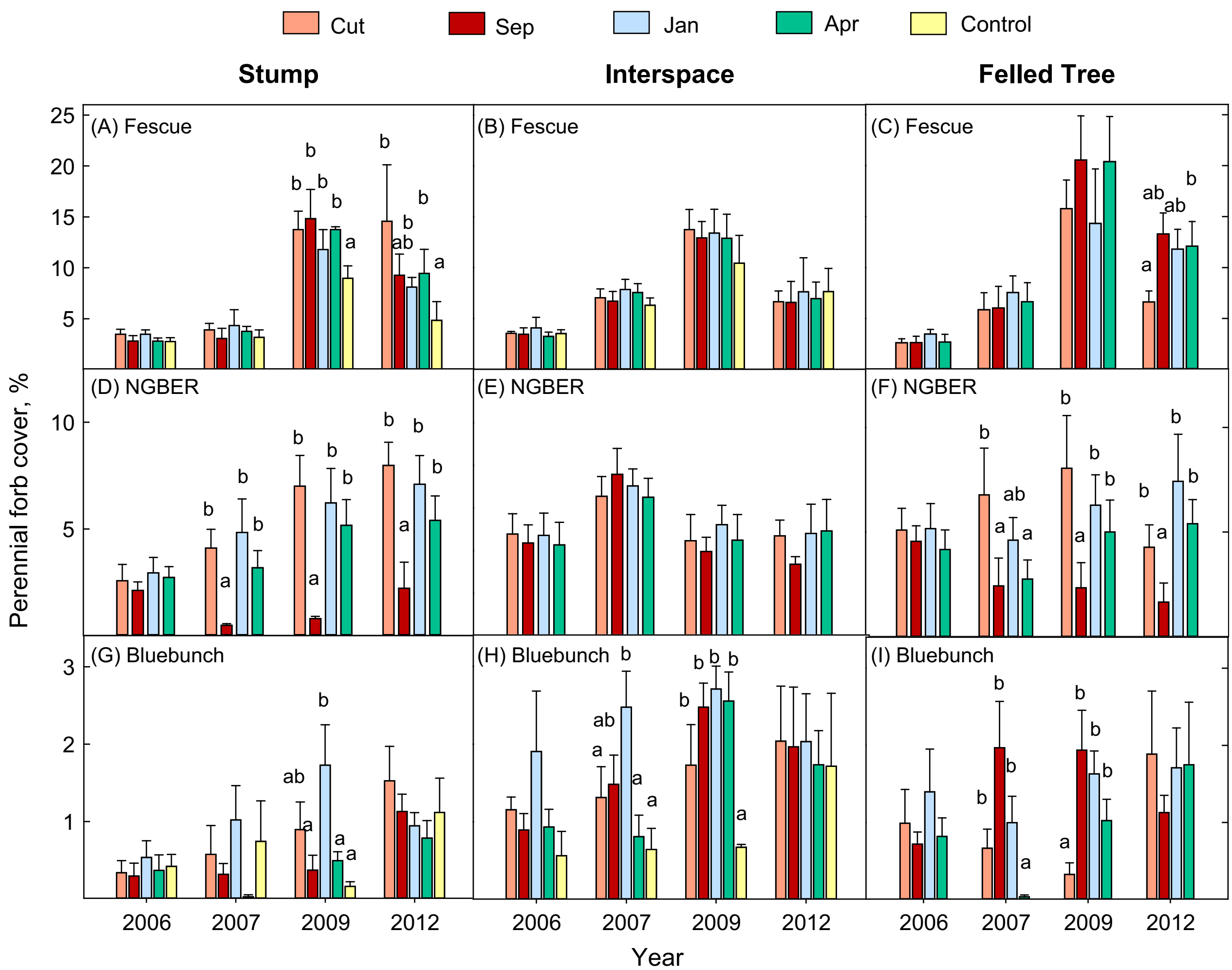

Fig. 3. Perennial forb cover (%) for the; Fescue site (A) stump, (B) interspace, and (C) felled tree zones; NGBER site (D) stump, (E) interspace, and (F) felled tree zones; and Bluebunch site (G) stump, (H) interspace, and (I) felled tree zones sites, for the western juniper treatments in southeast Oregon, 2006, 2007, 2009, and 2012. Data are means + one standard error. Means sharing a common lower case letter within site and year are not significantly different ($P > 0.05$).

3.4. Other cover

The cover response of *P. secunda* at each site was influenced by year, treatment, and zone (Fig. A.1A–I). Prior to treatment (2006), cover was greater in the interspace and felled tree zones than the stump zones at the Fescue and NGBER sites. At the Bluebunch site cover of *P. secunda* was greater in the stump compared to the other two zones. At the Fescue site, cover increased over time in stump and interspace zones (all treatments and control; Fig. A.1A and B) and in the felled-tree zone either decreased (CUT, SEP) or did not change (JAN, APR; Fig. A.1C) from a pre-treatment mean of 3.6%. Cover in the interspace after treatments averaged 5.6 ± 0.4% and was greater than stump and felled tree zones. At the NGBER site cover of *P. secunda* did not change in response to treatment in the stump (0.8 ± 0.3%) and interspace (2.2 ± 0.4%) zones (Fig. A.1D and E). In the felled tree zone cover decreased over time from about 2% in 2006 to less than 0.5% in CUT, SEP, and APR treatments and to 1.0% in the JAN treatment in 2012 (Fig. A.1F). At the Bluebunch site *P. secunda* cover decreased in 2007 in the SEP and APR treatments (stump and felled tree) and CUT treatment (stump). By 2012 cover in all treatment zones was less than the control. In 2012, *P. secunda* cover of the treatments in the interspace was greater than the stump and felled tree zones.

Annual forb cover exhibited similar zone-treatment patterns at the Fescue and NGBER sites, where cover increased, particularity in the SEP treatments stump and felled tree zones, which were 2–7-fold greater than other treatments and the control (Fig. A.2A–F). By 2012 there were no differences across all zones and treatments for annual forb cover at the Fescue and NGBER sites. Annual forbs at the Fescue and NGBER sites consisted exclusively of native species. On the Bluebunch site annual forb cover increased in all treatment zones by 2009 (Fig. A.2G–I). In stump and interspace zones annual forb cover in the treatments were 2–4-fold greater than the control in 2009 and 2012. In the felled tree zone cover in the SEP and APR treatments was 2–3-fold greater, respectively, than the CUT and JAN treatments in 2009; however, by 2012 treatments no longer differed. Annual forbs were mostly represented by two non-native (prickly lettuce [*Lactuca serriola* L.]; desert madwort [*Alyssum desertorum* Stapf.]) and one native species (western tansy mustard [*Descurainia pinnata* (Walter) Britton]).

Prior to treatment bare-ground was 6–8-fold greater in interspace and felled tree zones than the stump at the three sites (Fig. A.3A–I). These differences were altered after tree control especially in SEP and APR treatments. Following treatment the largest increases (8–10-fold) in bare-ground were in the stump zones of the SEP treatment at all sites. Bare-ground in the stump zone of

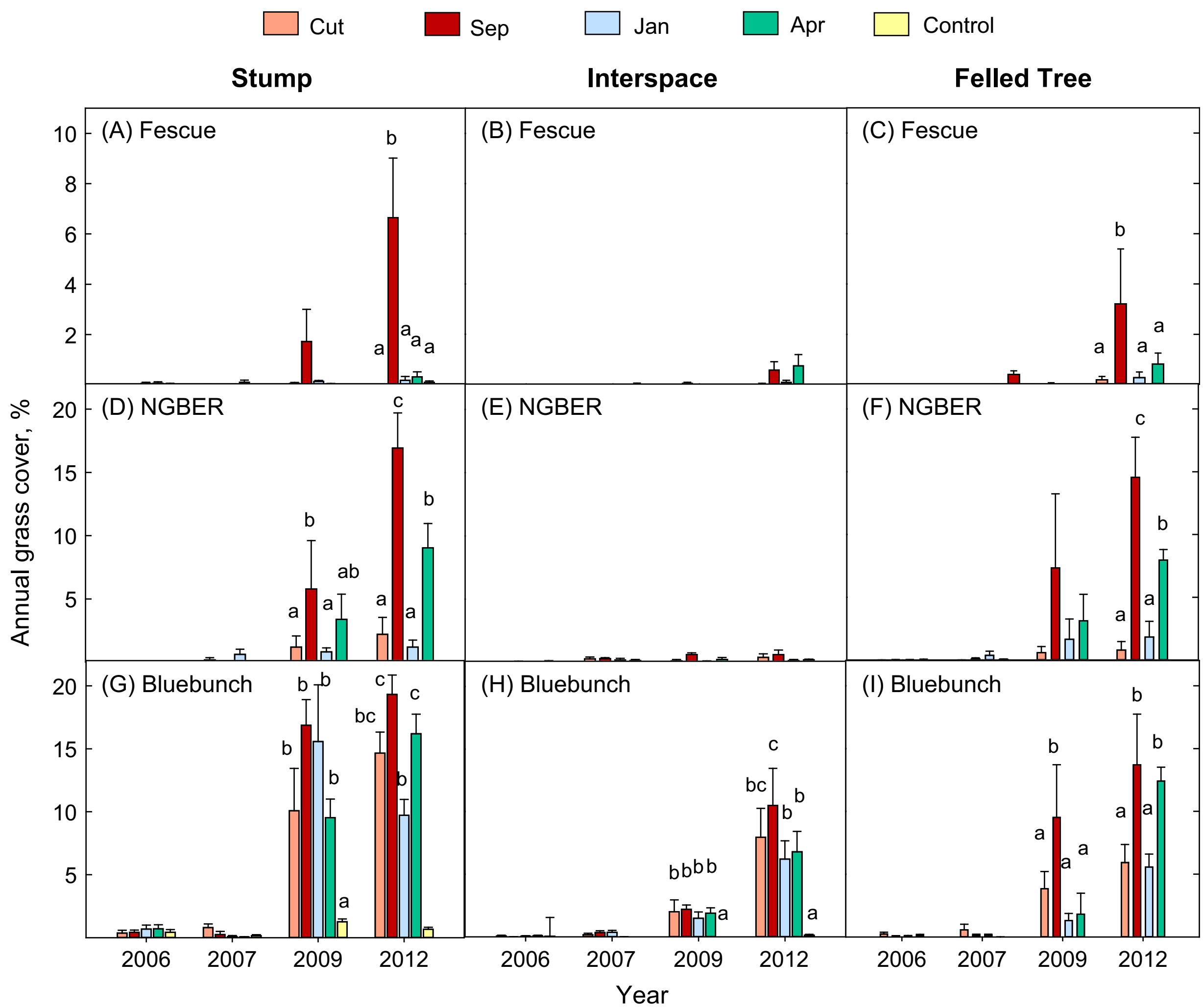

Fig. 4. Annual grass cover (%) for the; Fescue site (A) stump, (B) interspace, and (C) felled tree zones; NGBER site (D) stump, (E) interspace, and (F) felled tree zones; and Bluebunch site (G) stump, (H) interspace, and (I) felled tree zones sites, for the western juniper treatments in southeast Oregon, 2006, 2007, 2009, and 2012. Data are means + one standard error. Means sharing a common lower case letter within site and year are not significantly different ($P > 0.05$).

APR treatments about doubled and were greater than the CUT and JAN treatments and the controls. In the interspace bare-ground decreased overtime in all the treatments at the three sites and were less than the controls. In the felled tree zone of the Fescue and NGBER sites bare-ground decreased in CUT and JAN treatments between 53% and 87%. In the SEP and APR treatments bare-ground decreased less; at the Fescue site by 50% (SEP) and 63% (APR) and at the NGBER by only 8% (APR, SEP). At the Bluebunch site bare-ground decreased by 75% in the CUT and by 40% to 45% in the SEP, APR and JAN treatments.

Litter cover declined in stump zones for all sites and treatments. The greatest decreases were in SEP treatments, where litter declined over 50% (Fig. A.4A–I). Litter cover in stump zones was greater in the controls of the Fescue and Bluebunch sites than the treatments after 2009. Litter in the interspace increased at all sites and treatments. At the Bluebunch site, interspace litter cover was 2-fold greater than the control. In felled tree zones, litter cover increased for all treatments at each site, however, the largest increases were in CUT treatments. Litter in CUT treatments increased from about 10% to 60% (Fescue) and 75% (Bluebunch, NGBER).

Cover of bio-crusts declined in response to treatment in stump (all sites), interspace (Fescue, NGBER) and felled tree zones (Fescue, NGBER) (Fig. A.5A–I). Loss of bio-crust cover occurred within the first year after fire in SEP treatments, especially in stump and felled tree zones. However by 2009 and 2012 there were no differences among treatments for any of the three zones at the three sites. Cover of bio-crusts was greater in the controls in stump (Fescue; Bluebunch) and interspace zones (Fescue) than the treatments after 2006. Cover of bio-crust in interspaces and felled tree zones of the Bluebunch was less than 0.5% before and after treatment, and there were no treatment, zone, or temporal differences.

4. Discussion

The response and recovery of herbaceous and ground cover variables were complex and varied among the juniper treatments and controls, and were affected by site and zone. There were several trends evident across all sites as well as tendencies exclusive to individual sites.

4.1. Interspace zones

In the interspaces at all three sites was fire severity was minimal (JAN, APR, CUT) to high (SEP). At the Fescue and NGBER

Fig. 5. Stump and felled tree zones (June 2012) at the NGBER site, for (A) JAN treatment and (B) SEP treatment, southeast Oregon. These zones of the JAN treatment are dominated by perennial bunchgrasses and in the SEP treatment by the invasive annual cheatgrass.

sites, plant composition in interspaces was resilient following the various juniper treatments, being comprised of perennial herbaceous lifeforms and were dominated by bunchgrasses (Table 3). Consequently, the interspaces at these two sites were resistant to invasion by annual grasses. Cover of annual and perennial forbs, while increasing, were never a dominant portion of herbaceous cover at the Fescue and NGBER sites. Our interspace results are similar to other juniper treatment studies, measured at the whole plot level (all zones considered), that had minimal to moderate fire severity following cutting or winter burning (O'Connor et al., 2013; Bates et al., 2014; Miller et al., 2014).

At the Bluebunch site there was a co-dominance of perennial bunchgrasses and invasive annuals (grasses and forbs), each comprising about 50% of total herbaceous cover for the various treatments (Table 3). These results indicate a moderate level of site resilience, however, resistance is low as annuals were able to increase rapidly after treatment. The increase in annuals was possible because bunchgrass density was only 25% of site potential prior to treatment (Bates et al., 2014). However, in past studies this site has demonstrated the ability to recover despite high annual cover in early succession. After about a decade annual grasses and forbs were only 10–15% of site cover and productivity totals and perennial grasses were the dominant lifeform (Bates et al., 2005; Bates and Svejcar, 2009). In our current study, perennial grass density had increased to 50% of site potential (5–6 plants m^{-2}) six years after treatments were applied (Bates et al., 2014).

4.2. Stump and felled tree zones

Fire severity in stump and felled tree zones ranged from minimal to severe, which influenced herbaceous composition at all three sites (Table 3). At the Fescue and NGBER site, burn severity was a good indicator of herbaceous response. At the Bluebunch site, fire severity was not a good indicator of herbaceous response because invasive annuals increased and dominated stump and felled tree zones regardless of treatment. Thus, response to treatment in stump and felled tree zones is dependent on inherent resiliency of sites and fire severity.

4.2.1. Fescue and NGBER sites

Fires, which consumed 100–1000-h fuel classes, resulted in higher levels of bare ground and mortality of herbaceous perennials (Bates et al., 2014). At the NGBER site, severe fire impacts in stump and felled tree zones of the SEP and APR treatments resulted in reduced resilience and lowered resistance to invasive species. Annual grasses increased in the two zones and 6 years after treatment AG cover was 60–75% of total herbaceous cover in the SEP treatment and exceeded 30% in the APR treatment. At the Fescue site, SEP fire severity was moderate and herbaceous perennial plant mortality low, which resulted in the stump and felled trees zones maintaining relatively high resilience and resistance. Perennial plant composition as a percentage of herbaceous cover at the

Table 3
Summary of dominant followed by sub-dominant lifeforms in stump, debris, and interspace zones for cut-and-leave (CUT), cut and winter burn (JAN), cut and spring burn (APR, and various fire severities 5 years following treatment at the studies cool sites (Fescue-Steens Mt, Northern Great Basin Experimental Range [NGBER]) and warm site (Bluebunch-Steens Mt), south east Oregon, 2006–2012.

Zone and Site	CUT	Treatment		
		JAN	APR	SEP
Stump zone				
Fescue	PBG[a] and PF[a]	PBG and PF	PBG and PF	PBG, PF and AG[a]
NGBER	PBG and PF	PBG and PF	PBG and AG	AG
Bluebunch	AG	PBG and PF	AG	AG
Debris zone				
Fescue	PBG and PF	PBG and PF	PBG and PF	PBG and PF[3]
NGBER	PBG and PF	PBG and PF	PBG, PF and AG	AG
Bluebunch	AG	PBG and AG	AG	AG
Interspace				
Fescue	PBG and PF	PBG and PF	PBG and PF	PBG and PF
NGBER	PBG and PF	PBG and PF	PBG and PF	PBG and PF
Bluebunch	PBG, AG, and IAF[a]	PBG and AG	PBG and AG	PBG and AG

[a] Perennial bunchgrass (PBG), perennial forbs (PF), invasive annual grass (AG), invasive annual forbs (IAF).

Fescue site was 74% in the stump zone and 85% in the felled tree zones. Annual grass did increase on the Fescue-SEP treatments and represented 16% and 7% of total herbaceous cover in stump and felled tree zones, respectively, the last year of measurement. In other woodlands and dry forested systems, decreased herbaceous perennial cover and increased cover of invasive species were associated with greater fuel consumption and fire severity (Armour et al., 1984; Crawford et al., 2001; Griffis et al., 2001; Brockway et al., 2002; Sabo et al., 2009; Kane et al., 2010).

At both sites, treatments with minimal disturbance (CUT) or light to moderate severity fires (JAN, APR) that generally consumed no more than the 1-h to 10-h fuel classes, the mortality of herbaceous perennials was negligible (Table 3). Plant community resilience and resistance for these treatments was maintained as perennials represented 90–98% of total herbaceous cover during the study. Maintaining and increasing perennial bunchgrasses and forbs are key to preventing establishment and dominance by non-native annual grasses (Chambers et al., 2007, 2013), particularly in the early stages following treatment of pinon-juniper woodlands (Bates et al., 2011, 2013, 2014; Miller et al., 2014).

4.2.2. Bluebunch site

On the Bluebunch site annual grasses became the dominant component of the understory in stump and felled tree zones for all treatments except the felled tree zone of the JAN treatment (Table 3). In the JAN-felled tree zone, perennial and invasive annual composition as percentages of total herbaceous cover were 50% and 48%, respectively. Thus, there was a benefit in applying the JAN treatment as annual grass cover was lower and perennial bunchgrass cover higher than the other treatments. In the other treatment zones, invasive annual cover increased and ranged between 60% and 96% of herbaceous totals between the third and sixth year after treatment. The large invasive annual response results from site and vegetation characteristics, as well as the treatments. Invasiveness of annual grasses in the Great Basin is enhanced on sites with warmer temperatures, higher soil water variability, and lower 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). These characteristics apply to the Bluebunch site and are one reason that even in minimally disturbed stump zones (JAN, CUT) annuals established dominance. Resilience and resistance were then lowered by severe

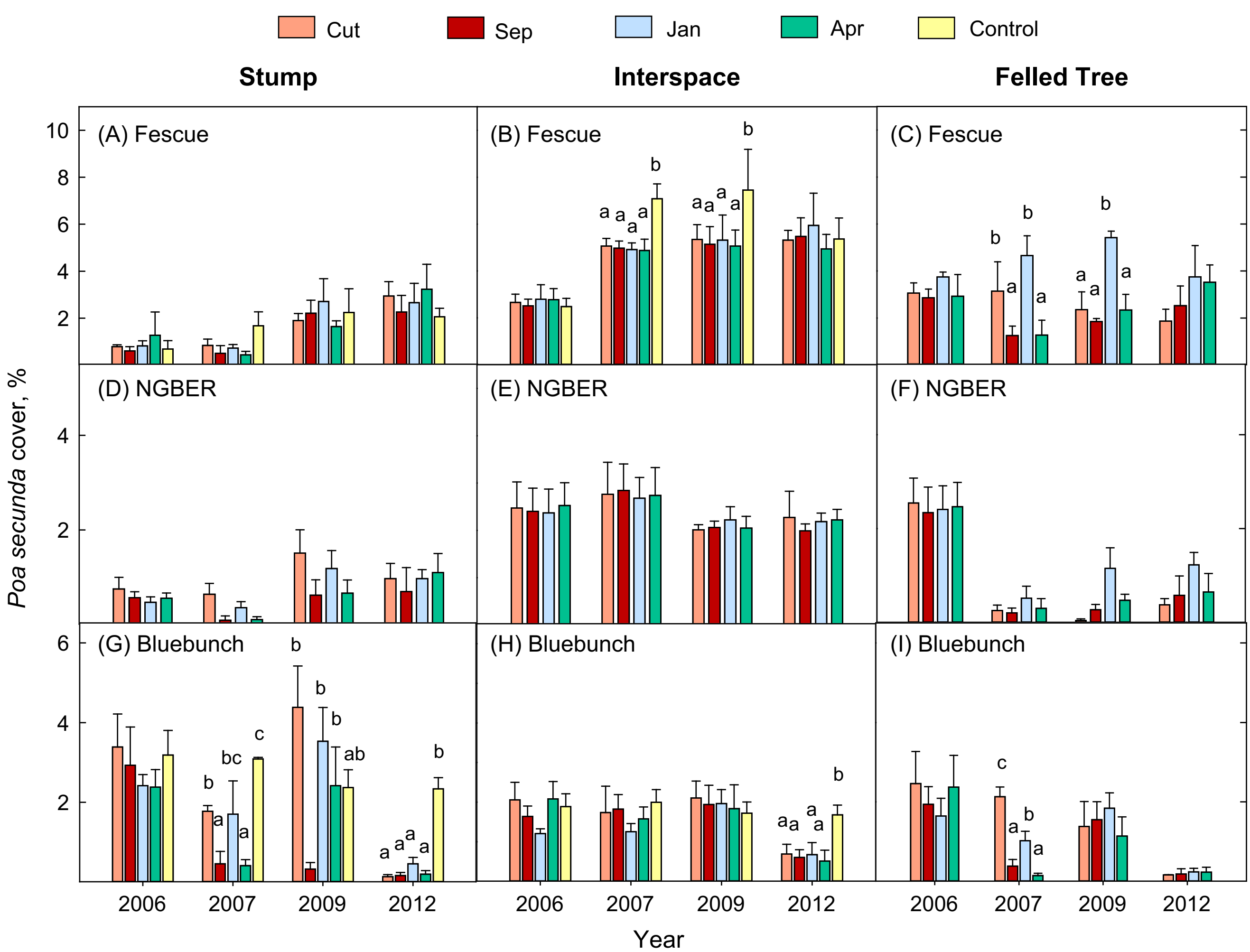

Fig. A.1. *Poa secunda* cover (%) for the; Fescue site (A) stump, (B) interspace, and (C) felled tree zones; NGBER site (D) stump, (E) interspace, and (F) felled tree zones; and Bluebunch site (G) stump, (H) interspace, and (I) felled tree zones sites, for the western juniper treatments in southeast Oregon, 2006, 2007, 2009, and 2012. Data are means + one standard error. Zonal means sharing a common lower case letter within site and year are not significantly different ($P > 0.05$).

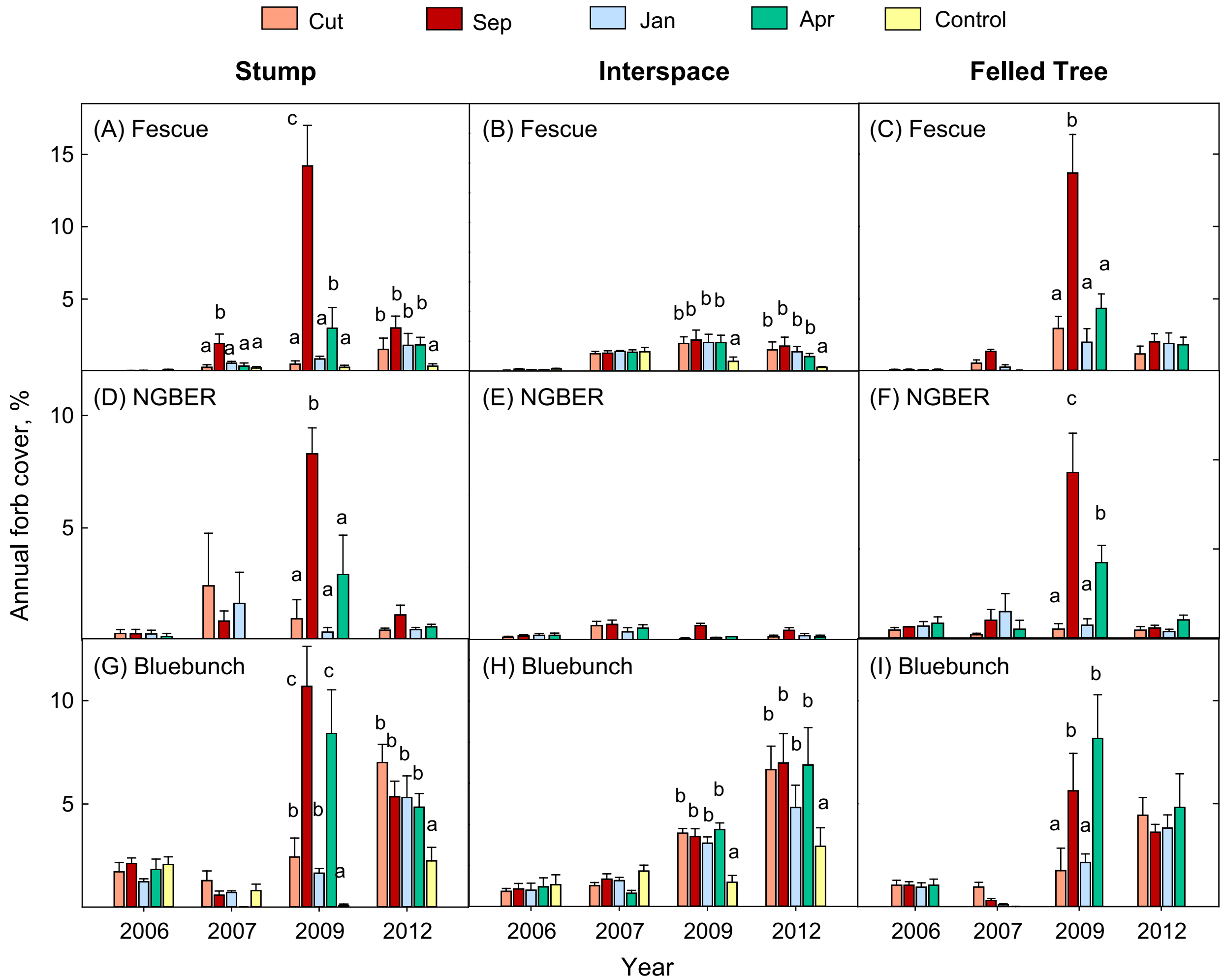

Fig. A.2. Annual forb cover (%) for the; Fescue site (A) stump, (B) interspace, and (C) felled tree zones; NGBER site (D) stump, (E) interspace, and (F) felled tree zones; and Bluebunch site (G) stump, (H) interspace, and (I) felled tree zones sites, for the western juniper treatments in southeast Oregon, 2006, 2007, 2009, and 2012. Data are means + one standard error. Means sharing a common lower case letter within site and year are not significantly different ($P > 0.05$).

fire effects in the SEP and APR treatments because perennial herbaceous species were largely eliminated; consequently, invasive annual cover became an even greater component of the herb layer.

Cutting and leaving trees (CUT) also reduced resilience and resistance beneath felled trees as perennial composition decreased and annuals increased (Table 3). The declines of the main perennial bunchgrasses (Thurber's needlegrass, bluebunch wheatgrass) and *P. secunda* are likely a result of smothering and shading by felled trees. An equivalent response by these species after juniper cutting has been reported by Bates et al. (2005) and Bates and Svejcar (2009). Although resilience and resistance were not affected, perennial bunchgrasses (mainly Idaho fescue) beneath felled trees of CUT treatments in the NGBER and Fescue sites were not able to increase above pre-treatment values, indicating that felled trees were hindering recovery.

4.3. Other trends

The lack of response or decline of *P. secunda* reflect a consistent pattern reported in other juniper treatments (Bates et al., 2005, 2011, 2013). This suggests that *P. secunda* is not able to take advantage of greater availability of soil water and nutrients as other life forms following juniper treatments. On the Bluebunch site *P. secunda* was being gradually eliminated as a result of mortality and lack of recruitment as perennial bunchgrasses or invasive annuals increased.

The decline of bio-crust was a result of fire treatments and possibly change in zonal microenvironments or increased herbaceous cover. Star moss (*Tortula ruralis* (Hedw.) G. Gaertn., B. Mey. & Scherb) dominated the bio-crust layer. Once treatments were burned or exposed to direct sunlight, star moss and other bio-crust were immediately (SEP treatment) or gradually lost (other treatments). Declines in bio-crust have been measured after cutting or burning of other juniper woodlands and sagebrush steppe (Bates et al., 2005, 2013; Davies et al., 2007; O'Connor et al., 2013).

4.4. Implications

Piñon-juniper control and fuel treatments commonly result in greater herbaceous cover and productivity (Miller et al., 2005, 2014; Roundy et al., 2014). The composition of herbaceous response is a major management concern and influenced by site characteristics, woodland phase, treatment method and post-fire management. An immediate goal following pinon-juniper control treatments is to maintain or increase herbaceous perennials because their abundance is key to preventing establishment and dominance of non-native annual grasses (Miller et al., 2005; Chambers et al., 2007). Results from our study mainly apply to

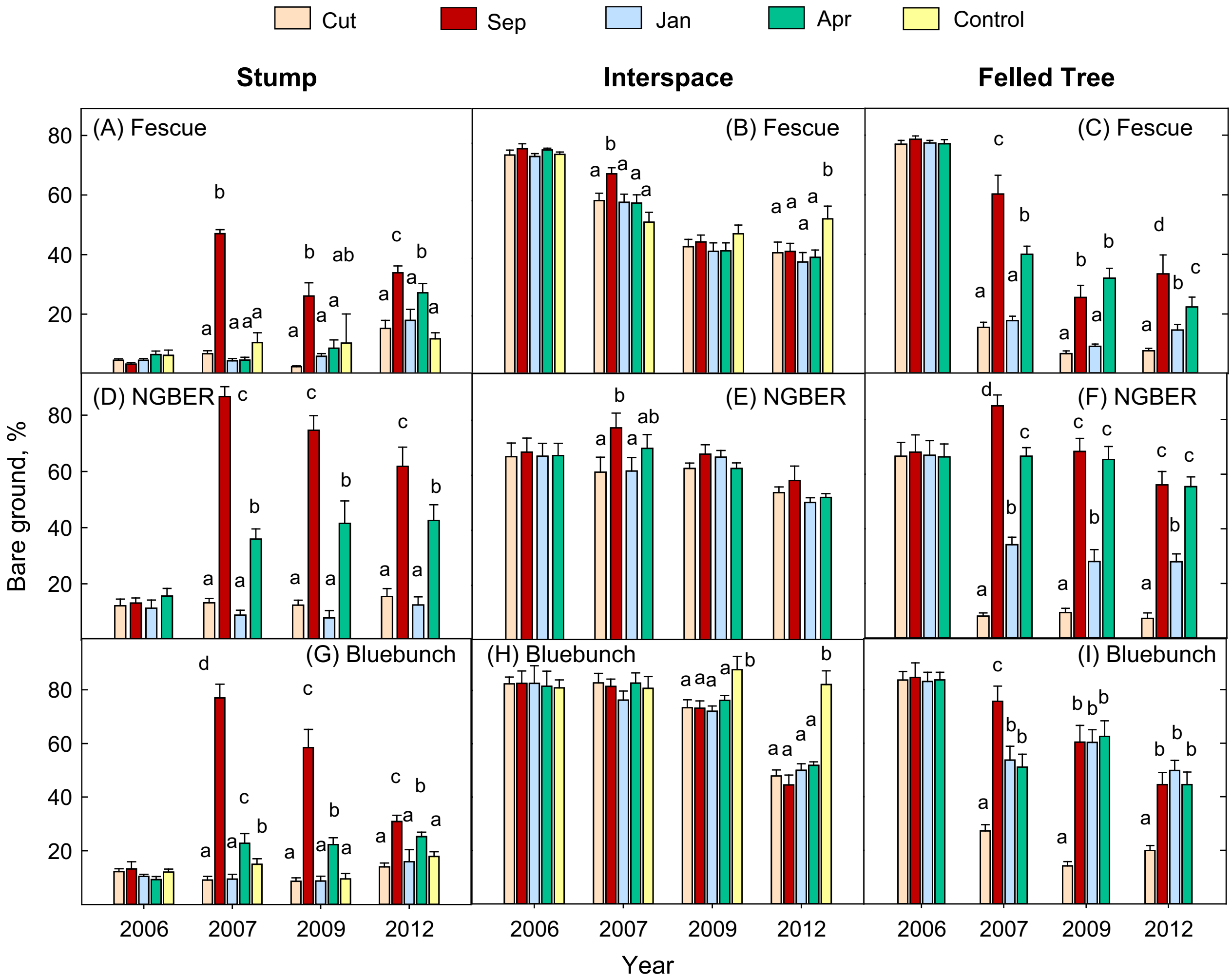

Fig. A.3. Bare ground (%) for the; Fescue site (A) stump, (B) interspace, and (C) felled tree zones; NGBER site (D) stump, (E) interspace, and (F) felled tree zones; and Bluebunch site (G) stump, (H) interspace, and (I) felled tree zones sites, for the western juniper treatments in southeast Oregon, 2006, 2007, 2009, and 2012. Data are means + one standard error. Means sharing a common lower case letter within site and year are not significantly different ($P > 0.05$).

later successional woodlands that have expanded into sagebrush steppe the past 80–150 years. Herbaceous response following treatment of early and mid-successional woodlands with intact native understories is fairly predictable, with recovery generally dominated by perennials (Davies et al., 2011; Bates et al., 2013; Roundy et al., 2014). Herbaceous response when controlling trees in late successional woodlands is often less predictable because of depleted understories and the potential for greater mortality of native vegetation when treatments include fire, potentially promoting weed dominance (Bates et al., 2006, 2013; Condon et al., 2011). Results from our study indicate mechanical cutting followed by dormant season (late-fall and winter) burning of felled juniper reduces or eliminates the chance for invasive weeds to dominate and post fire recovery is mainly comprised of herbaceous perennials.

Winter burning and pile burning of cut trees have several advantages over early fall broadcast burning including; disrupting fuel continuity after cutting, localizing the fire disturbance to small areas, and may have fewer weather or logistical constraints when implementing the fire portion of the treatments (Bates et al., 2006; Bates and Svejcar, 2009; O'Connor et al., 2013). Tradeoffs of cutting and leaving trees (CUT) or burning felled trees from late fall to early spring are that small junipers remain and fuels reductions often only consume, at most, 1- and 10-h fuel types (Bates et al., 2006, 2014; Bates and Svejcar, 2009). Advantages to burning in the early fall (SEP) are that burning is effective at consuming fuel sizes up to 1000-h fuels, smaller junipers are killed, and costs per acre are less (Miller et al., 2005; Bates et al., 2014). Spring burning (APR) was also effective at removing fuel sizes up to 1000-h fuels, however, lack of fire spread mean that juniper seedlings and saplings are not controlled (Bates et al., 2014).

In our earlier evaluation of these treatments at the whole plot scale, we concluded that western juniper control resulted in recovery (Fescue, NGBER sites) or a potential path to recovery (Bluebunch) of native herba-ceous understories within 5 years post-treat-ment (Bates et al., 2014). This judgment remains unchanged; however, by evaluating response in the three zones it is evident that treatments targeting high woody fuel consumption (SEP, APR) can eliminate or reduce perennials in stump and felled tree zones and create islands of invasive annuals. These weed islands represented between 10% and 45% of total plot area on SEP and APR treatments (Bates et al., 2014). These annual islands are potentially problematic if they are able to persist and expand into adjacent areas. This is a concern, for even in forested systems of the western United States, cheatgrass and other invasive annuals have expanded and dominated understories following fuel reduction and tree thinning treatments (Dodson and Fiedler, 2006; Youngblood et al., 2006; Collins et al., 2007; McGlone et al., 2009).

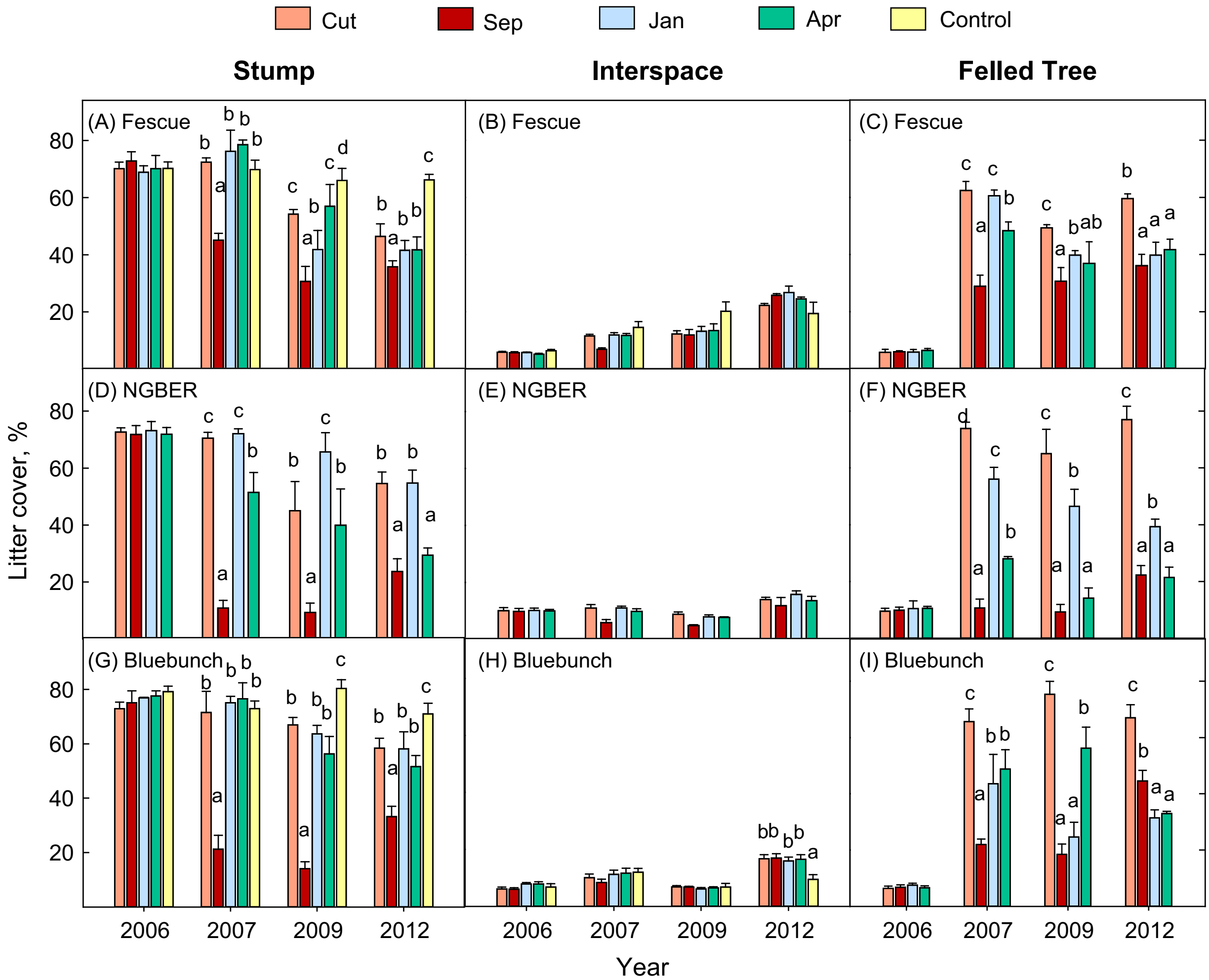

Fig. A.4. Litter cover (%) for the; Fescue site (A) stump, (B) interspace, and (C) felled tree zones; NGBER site (D) stump, (E) interspace, and (F) felled tree zones; and Bluebunch site (G) stump, (H) interspace, and (I) felled tree zones sites, for the various western juniper treatments in southeast Oregon, 2006, 2007, 2009, and 2012. Data are means + one standard error. Zonal means sharing a common lower case letter within site and year are not significantly different ($P > 0.05$).

5. Conclusions

Because pinon-juniper woodlands continue to expand and infill, shrub and herbaceous components are displaced and there is increased risk that large, high severity wildfires could potentially stimulate replacement of sagebrush steppe communities by annual grasslands. Thus development of management approaches that conserve the sagebrush steppe while mitigating wildland fire hazards are needed. Maintaining or increasing resilience and resistance of sagebrush communities is key to conserving the sagebrush steppe. Our results indicate there are tradeoffs in reducing juniper fuels by seasonal burning. Burning felled juniper in the late-fall and winter when fuel moisture and relative humidity are high and temperatures are cooler reduces fire severity which maintains perennial herbaceous understories and limits development of invasive annuals. High fire severity areas produced by burning where juniper fuels are concentrated in early fall and spring, and in some cases cutting and leaving trees, can eliminate desirable perennials and create islands within treatments that enhance weedy annual encroachment and dominance. In light of this result, further work is needed to assess long-term vegetation dynamics in response to pinon-juniper fuel treatments in order to assess the potential for desirable perennials to reoccupy fire created weed islands or whether or not invasive species are able to expand into areas dominated by herbaceous perennials. Continued study will assist development of appropriate woodland treatments that managers may select from to conserve the sagebrush steppe ecosystem.

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Appendix A

See Figs. A.1–A.5.

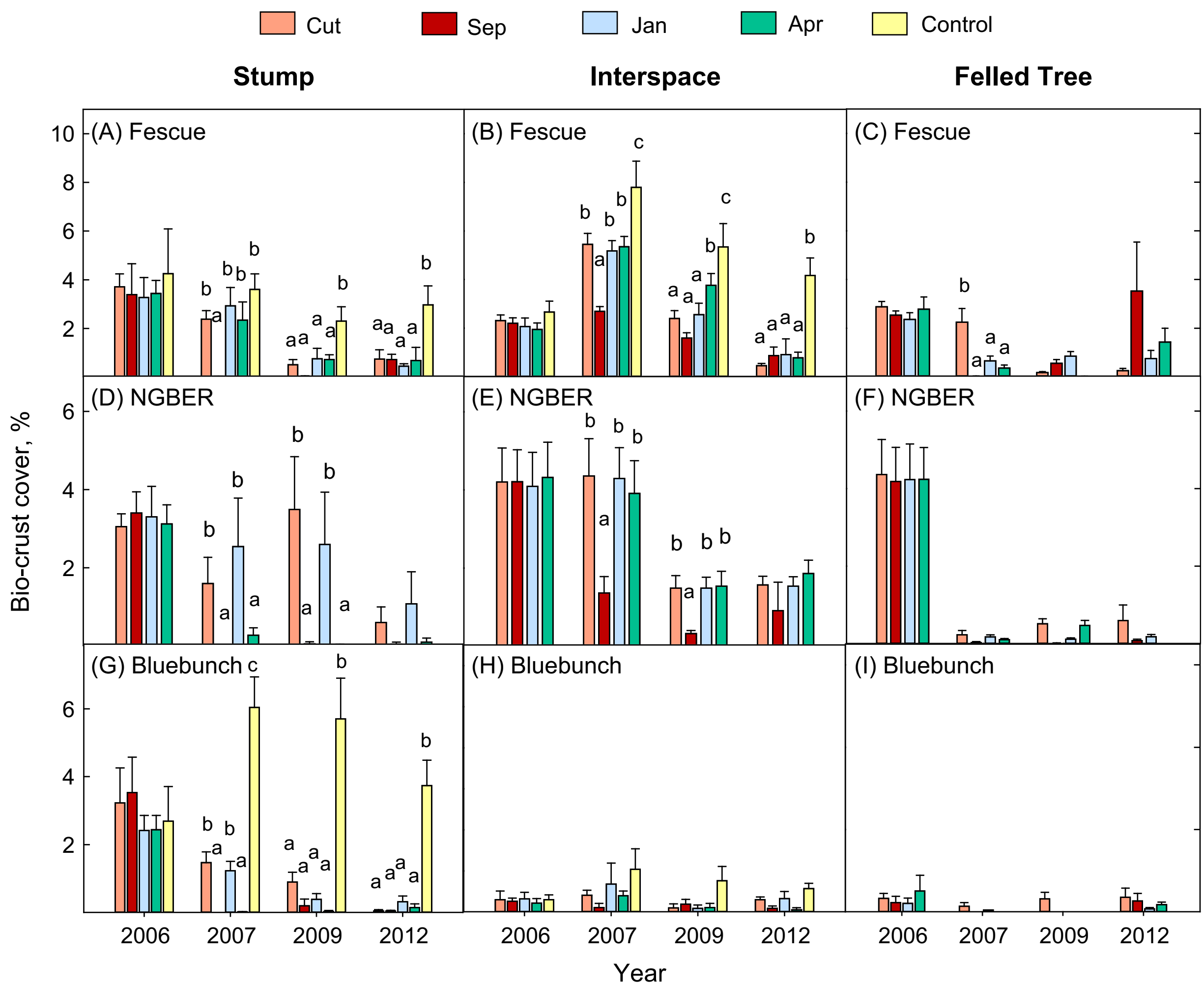

Fig. A.5. Bio-crust cover (%) for the; Fescue site (A) stump, (B) interspace, and (C) felled tree zones; NGBER site (D) stump, (E) interspace, and (F) felled tree zones; and Bluebunch site (G) stump, (H) interspace, and (I) felled tree zones sites, for the various western juniper treatments in southeast Oregon, 2006, 2007, 2009, and 2012. Data are means + one standard error. Zonal means sharing a common lower case letter within site and year are not significantly different ($P > 0.05$).

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