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Fuel bed response to vegetation treatments in juniper-invaded sagebrush steppe

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Abstract

Background: Expansion of juniper (*Juniperus* spp. L.) and pinyon (*Pinus* spp. L.) into sagebrush steppe habitats has been occurring for over a century across western United States. Vegetation and fuel treatments, with the goal of increasing landscape diversity and herbaceous productivity, and reducing woody fuels are commonly implemented to mitigate effects of woodland encroachment in sagebrush ecosystems. This study was conducted in conjunction with the Sagebrush Steppe Treatment Evaluation Project (SageSTEP) and was designed to determine the impact of vegetation treatments on fuel variables two years post treatment in sagebrush steppe with an expanding juniper or pinyon –juniper woodland component. Ten locations that characterize common sagebrush steppe sites with an expanding woodland component in the Intermountain West were chosen for analysis. These woodland sites, covering a gradient of juniper development phases, were treated with mechanical (cut and leave) and prescribed fire treatments.

Results: Two years post treatment, prescribed fire increased herbaceous biomass and reduced shrub biomass and down woody debris, but was not as effective in woodlands with higher juniper densities. Mechanical treatments increased herbaceous biomass and were effective in preserving the shrub biomass but increased down woody debris, which could lead to severe fire effects in the future.

Conclusions: We conclude that both prescribed fire and mechanical treatments are important management tools for maintenance and restoration of sagebrush steppe in areas that support juniper woodland expansion, but the differences in effects on shrub biomass and woody debris must be considered. A combination of the two treatments could lead to desirable effects in many areas.

Keywords: *Artemisia*, Fuel treatment, Great Basin, Juniper encroachment, *Juniperus*, *Pinus*, Wildfire

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Resumen

Antecedentes: La expansión de juníperos (*Juniperus* spp. L.) y pinos (*Pinus* spp. L.) en hábitats de la estepa graminosa de artemisia (*sagebrush–grass steppe*) ha venido ocurriendo desde hace más de cien años a través del oeste de los EEUU. Tratamientos de vegetación y combustibles, con el objetivo de incrementar la diversidad a nivel de paisaje y la productividad herbácea y reducir los combustibles leñosos, son comúnmente implementados para mitigar el efecto de la invasión de leñosas en este ecosistema. Este estudio fue conducido en conjunto con el Proyecto de Evaluación del Tratamiento de la Estepa de artemisia (SageSTEP) y fue diseñado para determinar el impacto de tratamientos de vegetación sobre variables de combustibles dos años post tratamiento en áreas de esta estepa que contenían un componente de expansión leñosa de junípero o de pino–junípero. Diez ubicaciones que caracterizan sitios de esta estepa de artemisia, con componentes de expansión de leñosas en el oeste intermontano, fueron elegidas para su análisis. Estos sitios leñosos que cubrían un gradiente de fases de desarrollo de junípero, fueron tratados mecánicamente (corte y dejado en el lugar) y con quemas prescriptas.

Resultados: Dos años luego de los tratamientos, las quemas prescriptas incrementaron la biomasa herbácea y redujeron la biomasa de arbustos y de los residuos leñosos en el suelo, pero no fueron tan efectivas en bosques con mayores densidades de juníperos. Los tratamientos mecánicos incrementaron la biomasa herbácea y fueron efectivos en preservar la biomasa de arbustos, pero incrementaron los residuos leñosos en el suelo, los cuales pueden conducir a efectos severos del fuego en el futuro.

Conclusiones: Concluimos que tanto las quemas prescriptas como los tratamientos mecánicos son importantes herramientas de manejo para el mantenimiento y restauración en áreas que sustentan la expansión de bosques de juníperos, aunque las diferencias en sus efectos en la biomasa de arbustos y residuos leñosos en el suelo deben ser consideradas. Una combinación de los dos tratamientos puede conducir a obtener efectos deseables en muchas áreas.

Background

Sagebrush (*Artemisia* spp. L.) ecosystems in the western United States are contracting due to expansion of juniper (*Juniperus* spp. L.) and pinyon (*Pinus* spp. L.) –juniper woodland expansion at higher elevations, and invasion of annual grasses at lower elevations (Chambers *et al.* 2014). Juniper and pinyon –juniper woodlands and savannas are also native to the western United States, covering more than 30 million ha (West 1999). Hereafter, we will refer to these woodlands as simply juniper woodlands. Over the past 130 to 150 years, there has been an increase in tree density within its historical extent, and an encroachment of juniper woodlands into adjacent vegetation types (Miller *et al.* 2005, Miller *et al.* 2008), primarily into the sagebrush steppe in the Great Basin.

The encroachment process of juniper woodland into sagebrush steppe has been described in three phases (Miller *et al.* 2005, Miller *et al.* 2008). Phase 1 has an open, actively expanding juniper canopy cover of ≤0% with an intact shrub layer; Phase 2 has an actively expanding juniper cover between 10 and 30% and a thinning shrub layer; and Phase 3 has a nearly stabilized juniper cover > 30% with ≥75% shrub mortality. As woodland development progresses, the abundance and richness of sagebrush steppe vegetation decreases, creating large, sparsely vegetated interspaces (Bunting *et al.* 1999, Miller *et al.* 2013). As a consequence of loss in native herbaceous and shrub vegetation, many wildlife species associated with sagebrush steppe habitats have become conservation concerns (Wisdom *et al.* 2005). The expansion of juniper woodlands has also influenced the continuity and availability of wildland fuels (Miller *et al.* 2013, Young *et al.* 2015) and increased accumulation of litter and duff resulting from juniper leaf-fall (Weiner *et al.* 2016). A fuel bed characterized by sparse vegetation, down woody debris, litter, and duff significantly increases fire return interval, but when fires do occur, they tend to be more severe (Miller *et al.* 2013, Strand *et al.* 2013). For clarity, fuel is defined as the live and dead biomass that can contribute to the spread, intensity, and severity of a fire (Rothermel 1983). Fire behavior variables such as rate of spread, potential for crown fire, fire residence time, and fire severity are affected by changes in vegetation (Schoennagel *et al.* 2004, Strand *et al.* 2013, Weiner *et al.* 2016).

Land managers have long recognized the negative impacts of juniper woodland expansion on sagebrush steppe ecosystems, and conduct various treatments to counter their effects (Bates *et al.* 2011, Bates and Davies 2016). Common treatment strategies in woodlands include removing juniper by burning and cutting (Miller *et al.* 2005, Miller *et al.* 2014). Juniper removal treatments are often implemented across hundreds to thousands of hectares and lead to patches of different treatment effectiveness, altered vegetation structure and composition (Miller *et al.* 2014, Roundy *et al.* 2014, Bybee *et al.* 2016), and changed fuel bed characteristics (Young *et al.* 2015), all of which would directly affect fire behavior and fire effects of future wildfires.

The purpose of this study was to quantify the effect of mechanical (cut and leave) and prescribed fire vegetation treatments on the fuel beds in expanding juniper woodlands two years after implementation of treatments. Key fuel bed strata included herbaceous biomass, shrub biomass, and downed woody debris (DWD). In particular, we sought to determine if the treatments resulted in differences in those fuel bed strata. We expected all treatments to reduce shrub and tree abundance and consequently increase herbaceous biomass, at least in the short term. We also expected mechanical treatments to increase downed woody fuel abundance in proportion to the overstory shrub and tree mortality. We expected higher increases in herbaceous biomass and lower levels of DWD in treatments implemented in early phases of woodland development.

Methods

This study was conducted in conjunction with the Sagebrush Steppe Treatment Evaluation Project (SageSTEP; McIver *et al.* 2010). SageSTEP was designed to monitor long-term changes to the ecosystem as a result of different treatment methods in juniper woodland and sagebrush steppe communities of the Intermountain West, USA. The study included data from 10 sites (Fig. 1) located on big sagebrush (*Artemisia tridentata* Nutt.) ecological sites ranging in elevation from 1400 to 2500 m with mean annual precipitation ranging from 230 to 410 mm. Site information details can be found in McIver and Brunson (2014). The 10 sites impacted by the encroachment of juniper into sagebrush steppe were divided into three regions representing western juniper (*J. occidentalis* Hook.; 4 sites), Utah juniper (*J. osteosperma* [Torr.] Little; 4 sites), and a combination of Utah juniper and one-seed pinyon (*Pinus monophylla* Torr. & Frém.; 2 sites). At each site, three treatments were applied across 10 to 30 ha plots and included: 1) untreated control plots, 2) prescribed fire intended to blacken 100% of the plot, and 3) a mechanical treatment using a chainsaw to cut all juniper (and pinyon if present) taller than 0.5 m and leaving the trees where they fell. Fire treatments were hand-ignited broadcast burns conducted between August and October 2006 or 2007. The tree canopy was reduced to less than 5% across all burns. Mechanical treatments were conducted September through November the same years as the prescribed fire treatments. Juniper and pinyon trees were cut with chainsaws and left on the site. See Miller *et al.* (2014) and Roundy *et al.* (2014) for further details about treatments. No seeding was done post treatment and the sites were excluded from livestock grazing.

Sites were sampled two years post treatment. Standard measurement protocols were used across all sites (Bourne and Bunting 2011, McIver and Brunson 2014). Each of the 10 sites used a randomized design to create treatment areas that were varying in size at each site and ranged from 20 to 80 ha, with 14 to 24 permanent 0.1 ha (30 m × 33 m) sampling plots established within each treatment. Each plot was established along a systematic grid with a minimum distance of 50 m between plots. Within plots, seven permanent transects running parallel to the 33 m length were established. Five transects were used to determine species composition utilizing the line-point intercept method (Bonham 1989). The planar intercept method was used to sample all dead woody fuels (Brown *et al.* 1982). Herbaceous fuel loads were determined by destructive sampling (Bonham 1989) within 0.25 m^2 quadrats placed every other meter along the remaining two transects. Shrub composition was estimated by allometric methods specific to big sagebrush utilizing individual plants destructively sampled outside the plots (Tausch 1989). Total shrub biomass was divided into two categories: 1-h (twigs 0 to 0.63 cm in diameter) and 10-h (branches 0.63 to 2.54 cm) (Frandsen 1983). Downed woody debris (DWD) was categorized into standard size classes related to rate of fuel moisture change: 10-h DWD is small branches (0.63 to 2.54 cm diameter), 100-h DWD is medium branches (2.54 to 7.62 cm diameter), and 1000-h DWD is large branches and tree trunks (> 7.62 cm diameter). Fuel variables analyzed included live herbaceous, total shrub biomass, 10-h DWD, 100-h DWD, 1000-h solid DWD, and 1000-h rotten DWD. All fuel variables were summarized and analyzed at the site and plot levels. The plots at each site were divided into groups based on the woodland development phase as described by Miller *et al.* (2005), since we expected that the plot vegetation composition prior to treatment would influence post-treatment response.

Relative change in fuel load was computed for each fuel variable by subtracting the post-treatment value (two years post) from the pre-treatment value and dividing by the pre-treatment value. Relative change was also computed for each fuel type and treatment within woodland development phases.

Statistical software Systat 13.1 (Systat 2009) was used for all statistical analyses. At the site level, relative change was compared between the two treatment types (prescribed fire and mechanical) using a paired student's *t*-test for live herbaceous, total shrub, and 10-h DWD fuels. Treatment differences were also compared for the same fuel types within woodland development phase with a paired student's *t*-test. At the plot level, we used analysis of variance (ANOVA) to determine the effect of treatment (control, prescribed fire, mechanical) on fuel loads for herbaceous biomass, shrub biomass, and downed woody debris two years post treatment within each of the three woodland regions. Pre-treatment fuel loads were included

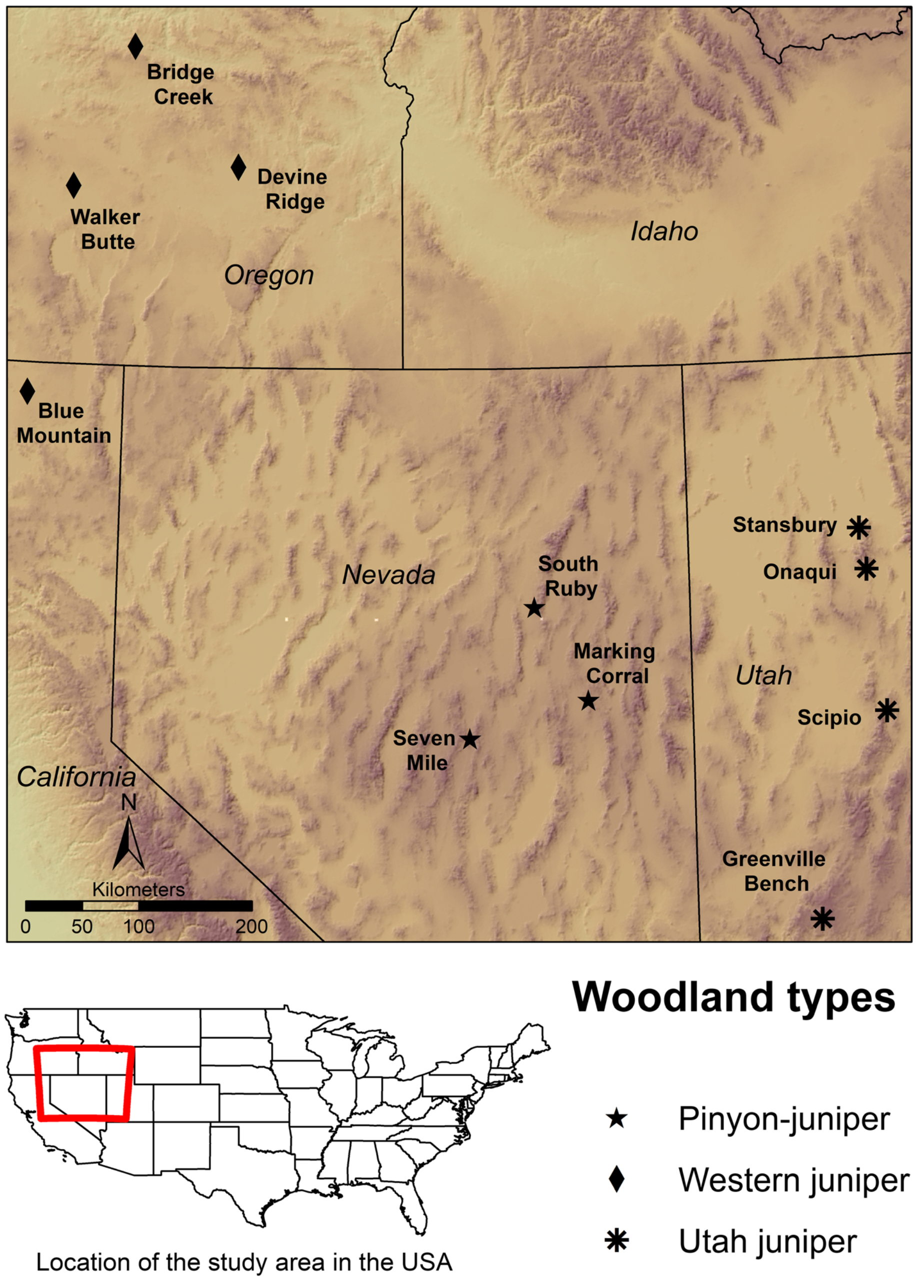

Fig. 1 Map of sites and their names by woodland type that were sampled in this study, located in Oregon, California, Nevada, and Utah, USA

as co-variates in the model to account for differences in vegetation and fuel composition at the plot level. Tukey's post-hoc test was applied to test for significance between individual treatments at the $P = 0.05$ level. The three juniper woodland types were analyzed separately. For each woodland region, fuel types within woodland development phase were analyzed separately, resulting in 9 to 28 samples in each analysis (n is reported with the results in Tables 1, 2 and 3). Following analysis, we reviewed the residual of the fitted value to confirm normality in the data.

Results

Site level analysis

Differences in fuel loading responses at the site level were found between prescribed fire and mechanical treatment (Fig. 2) two years after the treatments. Both prescribed fire and mechanical treatments increased the live herbaceous biomass; however, at the site level, the difference between the two treatment types was not significant. Prescribed fire reduced shrub biomass while the mechanical treatment did not. Downed woody debris (10-h) increased following mechanical treatments

Table 1 Western juniper woodland mean and standard deviation (SD) of fuel load (kg ha^{-1}) by fuel type pre treatment and two years post treatment

Fuel type	Phase	Control (C)							Prescribed burn treatment (Rx)								Mechanical treatment (M)								
		Pre treatment			Post treatment			Change	Pre treatment			Post treatment			Change	C vs. Rx	Pre treatment			Post treatment			Change	C vs. M	Rx vs. M
		n	Mean	SD	*n*	Mean	SD	%	*n*	Mean	SD	*n*	Mean	SD	%	*P* value	*n*	Mean	SD	*n*	Mean	SD	%	*P* value	*P* value
Live herbaceous	1	22	294	98	22	360	212	22	30	257	149	30	820	391	219	**< 0.001**	26	244	93	26	472	194	93	0.391	**< 0.001**
	2	28	197	141	28	225	139	14	18	207	89	18	797	382	284	**< 0.001**	23	166	92	23	393	200	137	**0.027**	**< 0.001**
	3	12	125	64	12	114	41	−9	13	130	88	13	541	240	316	**< 0.001**	12	83	29	12	318	131	283	**0.004**	**0.019**
Shrub biomass	1	7	2945	1902	22	1363	1669	−54	16	3180	1984	30	139	323	−96	**0.062**	9	5572	4769	27	3464	4279	−38	**0.033**	**< 0.001**
	2	15	2322	2185	28	1247	1739	−46	9	2157	1704	18	116	166	− 95	**0.001**	15	2675	2249	23	2082	2401	−22	0.664	**< 0.001**
	3	9	942	1088	12	546	541	−42	7	1042	747	13	483	1047	−54	0.947	7	1006	1388	12	757	1505	−25	0.495	0.714
Shrub 1-h	1	7	1376	918	22	709	770	−48	16	1525	1014	30	97	172	−94	**0.058**	9	2773	2225	27	1871	1997	−33	**0.045**	**0.001**
	2	15	1068	1001	28	582	778	−45	9	1077	903	18	71	91	−93	**0.002**	15	1291	1079	23	1121	1226	−13	0.449	**< 0.001**
	3	9	420	500	12	248	259	−41	7	502	392	13	238	512	−53	0.952	7	462	638	12	377	703	−18	0.438	0.647
Shrub 10-h	1	7	1596	1233	22	606	784	−62	16	1441	1112	30	46	129	−97	0.178	9	2754	2602	27	1541	2061	−44	**0.019**	**< 0.001**
	2	15	1341	1528	28	715	1200	−47	9	903	680	18	37	66	−96	**< 0.001**	15	1417	1432	23	1021	1239	−28	0.931	**< 0.001**
	3	9	540	738	12	286	331	−47	7	512	403	13	304	683	−41	0.590	7	589	866	12	422	880	−28	0.547	0.997
DWD 10-h	1	22	614	297	22	708	308	15	30	784	299	30	323	196	−59	**< 0.001**	27	701	516	27	895	479	28	0.106	**< 0.001**
	2	28	769	434	28	866	450	13	18	718	443	18	446	282	−38	**0.012**	23	724	439	23	1218	581	36	**0.020**	**< 0.001**
	3	12	632	458	12	829	310	31	13	527	310	13	581	429	10	0.842	12	815	753	12	2070	1412	140	**0.005**	**0.001**
DWD 100-h	1	22	1494	1177	22	1033	832	−31	30	2088	1338	30	893	849	−57	0.803	27	1303	1008	27	1769	912	36	**0.011**	**0.001**
	2	28	1843	1203	28	1450	1095	−21	18	1624	1397	18	1225	939	−25	0.892	23	1673	1117	23	4013	1862	140	**< 0.001**	**< 0.001**
	3	12	1278	835	12	965	627	−24	13	1247	1222	13	1680	2141	35	0.721	12	1259	1220	12	6084	3228	383	**< 0.001**	**< 0.001**

Change is reported in percentage (%) and calculated as the pre-treatment value minus the post-treatment value, divided by the pre-treatment value; *n* indicates the number of samples used in the calculations. Treatments include a control (C), prescribed burning (Rx), and mechanical cut-and-leave treatment (M). *P* values from analysis of variance testing for treatment effects two years post treatment are reported. *P* values < 0.05 are in boldface

Table 2 Pinyon –juniper woodland mean and standard deviation (SD) of fuel load (kg ha^{-1}) by fuel type pre treatment and two years post treatment

Fuel type	Phase	Control (C)							Prescribed burn treatment (Rx)								Mechanical treatment (M)								
		Pre treatment			Post treatment			Change	Pre treatment			Post treatment			Change	C vs. Rx	Pre treatment			Post treatment			Change	C vs. M	Rx vs. M
		n	Mean	SD	*n*	Mean	SD	%	*n*	Mean	SD	*n*	Mean	SD	%	*P* value	*n*	Mean	SD	*n*	Mean	SD	%	*P* value	*P* value
Live herbaceous	1	9	288	134	9	549	253	90	10	218	134	10	772	296	254	**0.032**	6	214	73	6	525	285	146	0.857	0.149
	2	9	200	163	9	285	149	43	12	142	54	12	637	431	350	**0.004**	14	111	71	14	352	211	218	0.303	0.074
	3	13	41	32	13	41	21	0	11	8	13	11	153	175	1831	**0.007**	10	48	38	10	134	83	181	0.153	0.359
Shrub biomass	1	9	5449	5238	12	3467	2546	−36	10	5171	3645	13	2950	1514	−43	**0.013**	6	4845	1638	10	4456	1404	−8	0.645	0.004
	2	9	2764	1830	16	2179	1351	−21	12	2950	1514	26	504	1074	−83	**0.024**	14	3244	2385	26	3851	2743	19	0.388	**< 0.001**
	3	13	507	485	18	567	664	12	11	173	326	16	133	194	−23	0.960	10	773	714	13	1279	1537	66	0.965	0.888
Shrub 1-h	1	9	1527	858	12	1420	827	−7	10	1747	1073	13	1184	584	−32	**< 0.001**	6	1888	629	10	1651	444	−13	0.990	0.001
	2	9	1130	845	16	757	453	−33	12	1184	584	26	209	374	−82	**0.025**	14	1093	665	26	1307	816	20	0.268	**< 0.001**
	3	13	193	167	18	193	201	0	11	72	117	16	55	76	−24	1.000	10	310	265	13	472	530	52	0.661	0.721
Shrub 10-h	1	9	1152	1137	12	753	695	−35	10	1211	958	13	777	266	−36	0.061	6	1164	529	10	1876	1458	61	0.201	0.002
	2	9	616	568	16	577	359	−6	12	777	266	26	282	565	−64	**0.016**	14	605	325	26	1207	1262	99	0.431	**< 0.001**
	3	13	103	92	18	146	174	42	11	42	76	16	60	80	43	0.997	10	230	267	13	399	553	74	0.999	0.994
DWD 10-h	1	12	534	390	12	552	307	3	13	983	702	13	887	306	−10	0.197	10	593	360	10	1238	772	109	**0.007**	0.318
	2	16	591	328	16	622	255	5	26	996	663	26	695	226	−30	0.978	26	865	613	26	1716	981	98	**< 0.001**	**< 0.001**
	3	18	565	287	18	982	925	74	16	903	548	16	1063	686	18	0.999	13	896	219	13	3758	2839	320	**< 0.001**	**< 0.001**
DWD 100-h	1	12	1002	719	12	1011	581	1	13	1747	1194	13	1391	475	−20	0.808	10	1235	994	10	1897	944	54	**0.011**	**0.048**
	2	16	958	575	16	772	437	−19	26	1217	559	26	1493	800	23	0.297	26	1531	696	26	3690	1883	141	**< 0.001**	**< 0.001**
	3	18	956	773	18	1103	1265	15	16	979	833	16	2102	784	115	0.488	13	1620	758	13	7219	4479	346	**< 0.001**	**< 0.001**

Change is reported in percentage (%) and calculated as the pre-treatment value minus the post-treatment value, divided by the pre-treatment value; *n* indicates the number of samples used in the calculations. Treatments include a control (C), prescribed burning (Rx), and mechanical cut-and-leave treatment (M). *P* values from analysis of variance testing for treatment effects two years post treatment are reported. *P* values < 0.05 are in boldface

Table 3 Utah juniper woodland mean and standard deviation (SD) of fuel load (kg ha^{-1}) by fuel type pre treatment and two years post treatment

Fuel type	Phase	Control (C)							Prescribed burn treatment (Rx)								Mechanical treatment (M)								
		Pre treatment			Post treatment			Change	Pre treatment			Post treatment			Change	C vs. Rx	Pre treatment			Post treatment			Change	C vs. M	Rx vs. M
		n	Mean	SD	*n*	Mean	SD	%	*n*	Mean	SD	*n*	Mean	SD	%	*P* value	*n*	Mean	SD	*n*	Mean	SD	%	*P* value	*P* value
Live herbaceous	1	19	322	270	19	412	335	28	19	395	312	19	1396	1146	254	**< 0.001**	12	198	209	12	400	303	102	0.632	**0.016**
	2	23	227	240	23	263	269	16	25	226	187	25	749	688	232	**< 0.001**	22	212	169	22	641	420	202	**0.003**	0.731
	3	20	115	123	20	113	128	−1	16	96	87	16	635	706	563	**0.001**	27	133	113	27	805	599	504	**< 0.001**	0.891
Shrub biomass	1	13	8445	5595	19	6232	4812	−26	16	9521	5988	19	180	285	−98	**< 0.001**	8	4893	2839	12	5635	2941	15	0.751	**< 0.001**
	2	15	4858	5501	23	3231	3360	−34	18	5522	6000	26	326	661	−94	**0.002**	16	2679	2039	22	3124	2596	17	0.713	**< 0.001**
	3	16	1164	1183	20	704	480	−39	10	1363	1846	16	112	180	−92	0.246	21	1567	2083	27	1332	1906	−15	0.076	**0.002**
Shrub 1-h	1	13	2869	1160	19	2177	1269	−24	16	3395	1611	19	92	163	−97	**< 0.001**	8	2167	956	12	2208	1165	2	0.705	**< 0.001**
	2	15	1664	1436	23	1254	1109	−25	18	1976	1440	26	145	280	−93	**< 0.001**	16	1257	854	22	1387	989	10	0.538	**< 0.001**
	3	16	517	468	20	413	449	−20	10	487	534	16	62	100	−87	0.068	21	456	558	27	462	595	1	0.493	**0.004**
Shrub 10-h	1	13	3095	1542	19	2436	1472	−21	16	3541	2053	19	41	73	−99	**< 0.001**	8	2176	1262	12	2526	1580	16	0.783	**< 0.001**
	2	15	1843	1741	23	1484	1397	−19	18	1995	1910	26	107	211	−95	**< 0.001**	16	1315	930	22	1449	1111	10	0.683	**< 0.001**
	3	16	526	509	20	363	264	−31	10	528	648	16	55	84	−90	0.120	21	539	711	27	467	686	−13	0.231	**0.003**
DWD 10-h	1	19	722	455	19	645	229	−11	19	651	441	19	397	396	−39	0.086	12	622	354	12	866	405	39	0.201	**0.002**
	2	23	622	316	23	639	240	3	26	629	277	26	626	291	−1	0.995	22	654	376	22	1332	698	104	**< 0.001**	**< 0.001**
	3	20	450	242	20	511	217	14	16	590	283	16	1066	498	81	**0.021**	27	474	271	27	1880	697	297	**< 0.001**	**< 0.001**
DWD 100-h	1	19	987	463	19	1306	827	32	19	1376	1388	19	662	760	−52	0.134	12	1480	1208	12	2077	1414	40	0.096	**0.001**
	2	23	1242	779	23	1304	782	5	26	1111	635	26	1226	800	10	0.979	22	1288	850	22	4922	3008	282	**< 0.001**	**< 0.001**
	3	20	970	695	20	1268	1022	31	16	855	613	16	1813	1118	112	0.651	27	964	793	27	4056	2709	321	**< 0.001**	**0.002**

Change is reported in percentage (%) and calculated as the pre-treatment value minus the post-treatment value, divided by the pre-treatment value; *n* indicates the number of samples used in the calculations. Treatments include a control (C), prescribed burning (Rx), and mechanical cut-and-leave treatment (M). *P* values from analysis of variance testing for treatment effects two years post treatment are reported. *P* values < 0.05 are in boldface

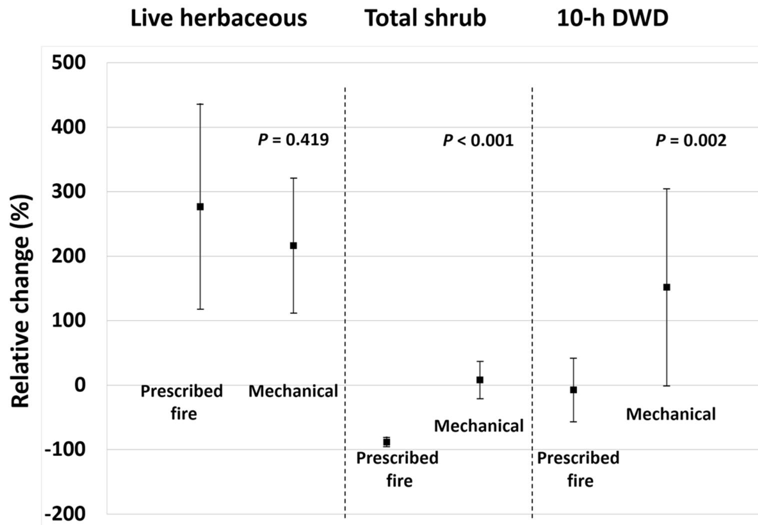

Fig. 2 Relative change in the sagebrush –woodland sites for live herbaceous, total shrub and 10-h DWD fuels two years post treatment for prescribed fire and mechanical treatments. Values are means and error bars are standard deviations of percent change for the 10 sites. Treatment effect (P) comparing prescribed fire and mechanical treatment is reported for each fuel type

but was largely unaffected by the prescribed burn. Treatment resulted in an increase in herbaceous biomass in all woodland development phases; however, no significant difference was observed between fire and mechanical treatments (Fig. 3). Total shrub biomass was significantly lower in prescribed fire compared to mechanical treatment in Phases 1 and 2 of woodland development but not in Phase 3 (Fig. 3). Downed woody debris (10-h) was higher following mechanical compared to prescribed fire treatment in Phases 2 and 3, but not in Phase 1 (Fig. 3).

Young juniper woodlands did not have an abundance of 100-h and 1000-h DWD, and the observations of 1000-h DWD fuel were not normally distributed and were therefore excluded from further statistical analysis. Changes in large down woody debris was highly variable, but generally increased following treatment, particularly in more developed woodlands.

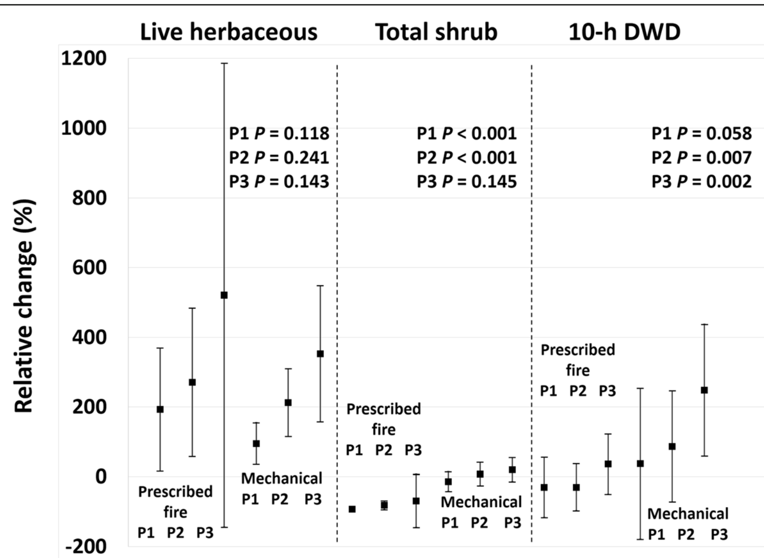

Fig. 3 Relative changes in live herbaceous, total shrub, and 10-h DWD fuels two years post treatment displayed by woodland development phase: Phase 1 (P1), Phase 2 (P2), and Phase3 (P3). Values are means and standard deviations of percent change at the 10 sites. Treatment effect (P) comparing prescribed fire and mechanical treatment is reported for each fuel type and woodland development phase

Prescribed fire

Results from analysis of variance at the plot level are summarized for the three woodland regions in Tables 1, 2 and 3. Prescribed fire resulted in a three-fold to four-fold increase in live herbaceous biomass in Phases 1 and 2 across regions, and even larger increases in Phase 3 (Tables 1, 2 and 3). Although the percent increase in herbaceous biomass was higher in Phase 3, it should be noted that the pre-treatment amount of biomass was less than half in Phase 3 compared to Phases 1 and 2 across regions (Tables 1, 2 and 3). Thus, the absolute amount of biomass increased more in Phases 1 and 2, compared to Phase 3. For example, in the western juniper region, biomass increased from 257 to 820 kg ha^{-1} in Phase 1, from 207 to 797 kg ha^{-1} in Phase 2, and from 130 to 541 kg ha^{-1} in Phase 3 (Table 1). Similar results were observed for pinyon –juniper and Utah juniper regions, although the productivity in those regions were lower (Tables 2 and 3).

Prescribed fire reduced shrub biomass by more than 90% in Phase 1 and Phase 2 in the western juniper and Utah juniper woodland types (Tables 1 and 3), while the reduction was around 40 to 80% in pinyon –juniper woodlands. No effect of prescribed fire treatment was detected for shrub biomass in Phase 3 in any of the woodland regions (Tables 1, 2 and 3). Note that pre-treatment shrub biomass decreased along the woodland development gradient and was 3-fold to 30-fold greater in Phase 1 compared to Phase 3 prior to treatment.

Downed woody debris of the 10-h size class generally decreased in Phase 1 and Phase 2 but increased in Phase 3 following fire (Fig. 3), but results were variable across regions (Tables 1, 2 and 3). Prescribed fire resulted in a decrease in 10-h DWD by 59% in Phase 1 and 38% in Phase 2 in the western juniper region (Table 1), and increased by 81% in Phase 3 in the Utah juniper region (Table 3). Effects on 100-h DWD were highly variable across regions. Although the results were not significant at the $P = 0.05$ level, 100-h DWD generally decreased in Phase 1 and increased in Phase 3 as a result of prescribed fire treatment (Tables 1, 2 and 3).

Mechanical treatment

Mechanical treatments resulted in an increase in live herbaceous biomass in Phases 2 and 3 in the western juniper (Table 1) and Utah juniper (Table 3) regions, but not in the pinyon –juniper region (Table 2). Total shrub biomass was generally not affected by the mechanical treatment except for a 38% decrease in Phase 1 of the western juniper region.

Mechanical treatments resulted in an increase in DWD in older woodland development phases across regions. Changes in 10-h DWD were not detectable in Phase 1 in the western juniper and Utah juniper regions (Tables 1 and 3), while 10-h DWD increased in Phase 2 by 36 to 141% across regions. In Phase 3, 10-h DWD approximately doubled in the western juniper and pinyon –juniper region and increased fourfold in the Utah juniper region. Mechanical treatment resulted in increased 100-h DWD across all regions and phases. In Phase 1, 100-h DWD increased by a factor of 1.5, while the increase was two-fold to four-fold in Phase 2 and four-fold to five-fold in Phase 3. The mechanical treatment converted fuels from the live tree canopy strata to the DWD strata. Thus, there is a logical progression of treatment influence from the minimal DWD increase recorded on Phase 1 to a more pronounced impact in Phase 2 and Phase 3 with their higher abundance and size of juniper on the sites pre treatment.

Discussion

The expansion of juniper woodlands has altered the vegetation composition across the Intermountain West (Bunting *et al.* 1999, Miller *et al.* 2005, Miller *et al.* 2008). The transition from sagebrush steppe to woodland reduces forage quantity and quality for wildlife and domestic animals (Wisdom *et al.* 2000), negatively impacts wildlife habitat for sagebrush obligate species such as the greater sage-grouse (*Centrocercus urophasianus* [Bonaparte, 1827]; Baruch-Mordo *et al.* 2013), disrupts nutrient cycling, increases erosion, and changes the fire frequency of the system (Blackburn and Tueller 1970, Miller and Tausch 2001, Bates *et al.* 2007). To mitigate problems associated with this encroachment, land managers have utilized a wide range of strategies on the landscape, among which are prescribed fire and mechanical treatments. These treatments change the fuel structure of these landscapes, influencing the abundance and continuity of herbaceous biomass, shrub biomass, and downed woody debris, leading to altered expectations for fire behavior and effects associated with a potential future wildfire.

Prescribed fire

The response to prescribed fire was similar across the three juniper woodland regions. Prescribed fire resulted in an increase in live herbaceous biomass in Phases 1, 2, and 3 in western juniper, pinyon –juniper, and Utah juniper sites. An increase in live herbaceous biomass is expected post fire. The removal of competition from shrubs and trees combined with the rapid release of nutrients into the system facilitates regeneration and growth (Everett and Ward 1984, Agee 1993, Rau *et al.* 2008, Miller *et al.* 2014). An increase in herbaceous biomass is expected to continue until available space and resources are expended (Tausch and Tueller 1977, Everett and Ward 1984, Bates *et al.* 2005).

Prescribed fire decreased shrub biomass by about 90% in Phase 1 and Phase 2 woodlands; however, the reduction of shrub biomass in Phase 3 was variable. This variability was unexpected. Big sagebrush is particularly sensitive to fire and experiences stand replacement when consumed (Wambolt and Payne 1986, Bunting *et al.* 1987). Sagebrush biomass is expected to increase given time, but the recruitment process is slow and it may take 35 to 100 years to fully recover to pre-fire conditions (Pieper and Wittie 1990, Wambolt *et al.* 2001). The prescribed fire treatment was designed for 100% of the plots to be blackened; thus, a surviving shrub component indicates an incomplete prescribed fire. This is most likely due to the limited availability of fine fuels to support the flaming front in a Phase 3 woodland.

Downed woody debris had the highest variability in consumption of any fuel variable measured. Generally across sites, DWD decreased in Phases 1 and 2, with the largest reduction in Phase 1. In Phase 3, we generally observed an increase in DWD, particularly in the larger size class (100-h fuels), but the variability was high across sites. This variability was probably due to continuity of fine fuels and their ability to carry fire, and also to the wide variety of fuel moisture and weather conditions for which these treatments were implemented across the woodland sites.

Fuel consumption decreased along the successional gradient from young to older woodlands. Phases 1 and 2 had the highest herbaceous fuel load, which more likely resulted in a continuous flaming front, as was reflected in the greater shrub biomass consumption. Thus, when DWD was consumed, it occurred in those phases. Phase 3 was known for a lack of fuel continuity, making it difficult to burn (Blackburn and Tueller 1970, Pieper and Wittie 1990, Miller and Tausch 2001). Fire treatments are therefore often not recommended for Phase 3 (Bates *et al.* 2000, Miller *et al.* 2005) because it requires more extreme fire conditions that are conducive to a crown fire (Huffman *et al.* 2009), which is generally not desired.

The total fuel load on site decreased in Phases 1 and 2 after prescribed fire treatment. Although there was a sizable increase in the herbaceous biomass, it had not yet compensated for the amount of sagebrush biomass consumed two years post treatment. This difference will likely decrease in the future as herbaceous biomass continues to increase into the open spaces and as shrubs recover from the treatment (Tausch and Tueller 1977, Everett and Ward 1984, Bates *et al.* 2005). Fire severity in these two phases is also expected to decrease, with the exception of that part of Phase 2 that experienced an increase in 1000-h DWD solid fuel. In Phase 3, pinyon–juniper had a herbaceous biomass increase greater than the amount of shrub biomass consumed. This suggests that there is an increase in fuel and fuel continuity across the system, increasing the probability of fire ignition and spread.

Because the young juniper woodlands did not have an abundance of 1000-h DWD and exhibited high variability, the observations of these fuel categories were not normally distributed and were therefore excluded from statistical analysis. These fuels were estimated along five 30 m transects, (i.e., 150 m total transect length per plot) since larger fuels have been shown to vary at broader scales than the fine fuels (Keane *et al.* 2012). For future studies, we recommend longer transects or a different sampling methodology for the 1000-h fuel categories for fuels assessments in sagebrush steppe and juniper woodlands.

Mechanical treatment

Herbaceous biomass response varied by successional phase following mechanical treatment. Mechanical treatments did not significantly increase herbaceous biomass in Phase 1, but increased two-fold to three-fold in Phase 2, and three-fold to six-fold in Phase 3 in western juniper (Table 1) and Utah (Table 3) juniper. Herbaceous biomass in Phase 1 woodland would be expected to be the least effected by juniper woodland encroachment, thus it was not surprising that treatment results were not significant. However, an increase in herbaceous biomass in Phase 2 was found in two of the woodland regions, supporting the notion that, even at lower juniper densities, removal of juniper releases enough resources for a herbaceous vegetation response to be measurable (Bates *et al.* 2005, Miller *et al.* 2005). Other studies were primarily conducted in Phase 2 and Phase 3 juniper woodlands and found that mechanical treatments increased soil nitrogen and water availability, leading to an initial flush of herbaceous biomass in the first two years post treatment (Tausch and Tueller 1977; Bates *et al.* 1998, 2000, 2005). Generally, herbaceous biomass peaked within the first five to ten years, and shrubs eventually increased in abundance (Tausch and Tueller 1977, Skousen *et al.* 1989, Bates *et al.* 2005, Miller *et al.* 2014). Increased herbaceous fuel connectivity may lead to increased probability for a fire to carry across the landscape.

Shrub biomass was generally not affected by mechanical treatment. It was expected that shrub biomass would increase as sagebrush would have benefited from the increase in soil nitrogen and water availability. Previous studies showed that chaining treatments (a type of mechanical treatment that has been used for brush control) caused a vigorous shrub response within the first two years post treatment (Tausch and Tueller 1977, Skousen *et al.* 1989). However, Bates *et al.* (2005) found minimal shrub response 13 years after a mechanical treatment. He cited a lower initial shrub density within his plots as a possible cause of this slower response. This would not be accurate in our study as Phase 2 still had a relatively intact shrub component. Continued long-term study is needed to determine if the shrub layer will respond to the cut-and-leave mechanical treatment.

Changes in DWD varied by successional phase. In Phase 1, we did not observe any increase in 10-h DWD fuels in two of the regions, but a significant increase was recorded in the pinyon –juniper region (Table 2). On Utah juniper and pinyon –juniper sites in Phase 1, we observed an increase in 100-h DWD. The increase in larger fuels indicates that conversion of ≤10% juniper tree cover to surface fuel may be defined by tree trunks and has a minimal influence on the smaller fuels in the fuel bed. Mechanical treatment influences on DWD in Phase 2 and Phase 3 were more pronounced (Tables 1, 2 and 3). The fuel increase was expected and is a function of converting live tree biomass to downed woody debris, demonstrating that juniper canopy cover will remain in the fuel bed two years post treatment.

Mechanical treatments used chainsaws to remove all trees taller than 0.5 m, clearly reducing the probability of a future crown fire. While the potential of a canopy fire has been dramatically reduced by the mechanical treatment, there is a corresponding increase to DWD surface fuels, which can increase the potential for a high-severity surface fire. In these surface DWD fuels, fire-season moisture content is less than in live trees and the fuel is now layered on the surface, which can increase soil heating in the event of a fire, leading to increased mortality of herbaceous vegetation and opening up the landscape for invasion by exotic annual grasses.

The heavier woody fuels (100-h DWD) added to the fuel bed were substantial in our study. For example, pinyon –juniper pre treatment had 1620 kg ha^{-1} 100-h DWD, but post treatment it had over 7200 kg ha^{-1} 100-h DWD. The 100-h DWD and 1000-h fuels can remain in the ecosystem for decades. Decay rates in the sagebrush steppe are variable and slow (Harmon *et al.* 1986) and may be influenced more through abiotic factors than biotic factors (Waichler *et al.* 2001). As the 1000-h fuels decompose and become rotten, they have an increased risk of smoldering and soil heating when burned (Passovoy and Fulé 2006), which may increase fire's effects on soil and vegetation.

Study-wide trends

We focus on three fuel components, including live herbaceous, total shrub, and 10-h DWD, due to their importance in influencing fire intensity and spread as well as fire effects (Rothermel 1983, Ottmar *et al.* 2007). Both prescribed fire and mechanical treatments increased live herbaceous biomass on juniper woodland sites (Fig. 2). The percent increase was greater for fire treatment compared to mechanical treatment. Mechanical treatments understandably increase 10-h DWD the greatest, given that trees were cut and left on the sites. This increase was greatest where woody plant cover was highest —in the Phase 3 woodland. The greater the pre-treatment pinyon and juniper cover, the greater the increase in 10-h DWD post-treatment.

The response of live herbaceous biomass was most variable for Phase 3 woodlands as compared to Phases 1 and 2 (Fig. 3; Tables 1, 2 and 3). Percent increases in live herbaceous biomass were greatest for Phase 3 woodlands for both fire and mechanical treatments, but those sites had low herbaceous biomass prior to treatment (Tables 1, 2 and 3); thus, small absolute increases resulted in large relative increases. Small residual amounts of herbaceous plant populations resulted in erratic responses of those species.

Conclusions

Prescribed burning and mechanical treatments altered fuels, and significant effects were documented two years after implementation across woodland types. Changes in vegetation amounts and structure will likely alter potential fire behavior of the ecosystem in the future. Herbaceous biomass increases resulting from these treatments could increase the likelihood of fire spread if they become ignited. The mechanical treatment effectively reduced live tree biomass at all sites, but converted it to DWD, which may have increased fuel continuity. The greatest increases in DWD were observed on the Phase 3 woodland sites. As the ecosystem recovers from treatment, DWD will persist in the surface fuels, which could increase fire severity.

Prescribed fire's effects were similar within each phase across the woodland regions. The increased post-treatment herbaceous biomass may assist in perpetuating fire spread, making fire effects more consistent. An important difference between the treatments was the highly variable nature of prescribed fire compared to mechanical treatment. Only the fire treatment resulted in significant increases in herbaceous biomass in Phase 1, while both fire and mechanical treatments resulted in increased herbaceous biomass in Phases 2 and 3, suggesting that prescribed fire is the most effective treatment in Phase 1, while fire and mechanical treatments result in similar effects on herbaceous biomass in more developed woodlands. Mechanical treatment had a very uniform effect. Shrub biomass was largely lost in the prescribed fire treatment while it remained unaffected in the mechanical treatments. The potential for crown fire was reduced while there was a corresponding increase in all size classes for DWD surface fuels in Phase 2 and Phase 3. The increase in fuel load may affect the ecosystem for many years due to the arid environmental conditions. The increase in DWD fuel will persist and add to the potential fire severity in future fires, potentially leading to greater soil heating and herbaceous biomass mortality. Thus, mechanical treatment of woodlands may best be used as a restoration strategy as opposed to a fuel mitigation strategy. Mechanical treatments may also be effectively used as an initial treatment prior to a prescribed fire treatments. Of the vegetation treatments studied, only prescribed fire reduced fuel in the ecosystem through the combustion of the shrub and DWD fuel strata. In Phase 3 woodlands, prescribed fire increased the surface fuel load by killing trees and resulting in greater tree fall.

In the future, it is expected that herbaceous biomass will continue to increase on the sites as grass species, in particular, respond to the release from competition from shrubs and trees. Sagebrush will re-establish on the burned sites and contribute to future fuel loading, but it will likely require more than a decade to achieve pre-treatment levels. Large-sized classes of DWD that were created by the treatments will remain on the sites for many decades as decomposition rates occur slowly in cold arid environments.

If management goals for vegetation treatments are to reduce fuel loads, then mechanical and some prescribed fire treatments may not be successful. For these vegetation treatments to be effective as fuel reduction treatments, it may be necessary to add a second treatment, such as mechanical followed by prescribed burning some years later.

Abbreviations
ANOVA: Analysis of variance; DWD: Downed woody debris; P1, P2, P3: Phases 1, 2, and 3 of juniper woodland development; SageSTEP: Sagebrush Steppe Treatment Evaluation Project

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Authors' contributions
CRB analyzed data and drafted the first version of the manuscript. All authors participated in the study conception and design, development of analysis methods, critical review, and final revision of the manuscript. All authors approved the final manuscript version.

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