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Tree reduction and debris from mastication of Utah juniper alter the soil climate in sagebrush steppe ☆

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ABSTRACT

Juniper (*Juniperus* spp.) trees are masticated to reduce canopy fuel loads and the potential for crown fire. We determined the effects of tree reduction and soil cover in the forms of tree mounds and masticated debris on hourly soil water potential and soil temperature at 1–30 cm soil depth. Measurements were made in masticated and untreated areas at three sites in the western Utah portion of the Great Basin. Cumulative seasonal-response variables included wet days (>−1.5 MPa), degree days (>0 °C), and wet degree days (>−1.5 MPa and >0 °C). Masticated areas had 27 more wet days ($P < 0.001$), 32 more degree days ($P = 0.007$), and 311 more wet degree days ($P < 0.001$) than untreated areas across soil depths and seasons. Soil cover had less influence on these soil climate variables than tree reduction. Most importantly, tree reduction increased wet days ($P < 0.001$) by an average of 44.5 days during the spring and summer growing seasons at depths of 13–30 cm. Managers are advised to masticate trees while desired understory cover remains high in order to minimize water available to weeds.

1. Introduction

Desertification with increased woody plants, reduced perennial grasses, and increased heterogenization of soil resources is one of the most significant changes on rangelands globally in the last 150 years (Schlesinger et al., 1990; Archer et al., 2011). The shift from herbaceous to woody plants in these dryland systems often alters habitat and ecosystem trophic structure (Archer et al., 2011), reduces primary production (Knapp et al., 2008), and increases erosion (Wainwright et al., 2000; Gillette and Pitchford, 2004; Breshears et al., 2009). In the semiarid western United States, juniper trees (*Juniperus* spp.) have encroached on millions of hectares of sagebrush (*Artemisia tridentata* Nutt.) steppe and commonly reduced understory plant cover (Johnsen, 1962; West, 1984; Miller and Wigand, 1994; Miller and Rose, 1999; Miller et al., 2000, 2005). Juniper trees reduce the pre-encroachment plant community through competition for and redistribution of resources (Breshears et al., 1997a; Roundy et al., in press b; Ryel et al., 2010). For example, juniper trees begin transpiration in early spring reducing soil water remaining for understory plants (Angell and Miller, 1994); shallow juniper roots use resources from the same soil depth as grass roots (Emerson, 1932); juniper roots hydraulically move water deeper into the soil profile; and soil water repellant layers below juniper trees funnel water to greater depths away from shallow rooted species and the evaporation zone (Leffler et al., 2002; Robinson et al., 2010).

Reduced fire frequency in the sagebrush steppe during the past 100–150 yr has led to dense juniper encroachment (Miller et al., 2000) and increased woody fuel loads. Increased fuel loads following years of fire suppression and property development in fire prone areas led to extensive wildfire damage during the 2000 fire season (PIC, 2002). This prompted the National Fire Plan that appropriated millions of dollars to hazardous fuels reduction across the United States (PIC, 2002). Mechanical reduction of encroaching woodlands is one such fuel reduction method that has been applied on thousands of hectares in the western US. Mechanical mastication of dense juniper woodlands is often used to convert canopy and bole fuels to surface fuels before prescribed fire can safely reduce fuel loads without the risk of crown fires escaping and damaging neighboring communities. Juniper tree reduction has also helped pre-encroachment plant communities recover by increasing resources available for residual plants (Miller et al., in press; Roundy et al., in press a).

Sagebrush steppe communities depend on resources available in resource growth pools when soil water potentials are >−1.5 MPa within the top 0.3–0.5 m of soil for major plant growth and diffusion of nutrients to roots in spring and early summer (Leffler and Ryel, 2012; Roundy et al., in press b; Ryel et al.,

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2010). The stability of resource pools is especially important to plant community assembly because unusually large increases in resources due to disturbance can lead to increased weedy species dominance (Leffler and Ryel, 2012). Wet and wet degree days are important metrics of resource growth pools because they relate these pools to plant growth by quantifying the amount of time resources are adequate (soil water potential >−1.5 MPa) for rapid growth during each season. The resources remaining after plant growth make up the maintenance pool down to 1–1.5 m that enables perennial plants like sagebrush to survive summer drought (Leffler and Ryel, 2012). The accurate use of wet, degree, and wet degree day summations to predict specific plant growth responses depends on adequately modeling the linearity or curvilinearity and temperature thresholds of the response (Bonhomme, 2000), as well as accounting for limiting factors besides soil temperature and water availability (Idso et al., 1978; Wang, 1960). In ecosystems where plant response is highly dependent on short periods of soil water availability when soil and air temperatures are warm enough for growth, these metrics indicate soil microenvironmental conditions that support plant establishment and growth.

Our major objective was to determine the effects of juniper tree mastication on wet, degree, and wet degree days to indicate favorable growing conditions for plants. The effects of juniper tree mastication can be summarized in two categories. The first category is tree reduction associated with reduced juniper resource uptake and canopy shade. The second category is soil cover associated with preexisting tree mounds and newly added masticated-juniper debris. We sought to determine the effects of tree reduction separate from soil cover on wet, degree, and wet degree days. With recent work evaluating harvesting of juniper trees for biofuel energy (Jaeger et al., 2007; Skog et al., 2009) and the potential for this to become an important driver of juniper tree reduction, it was also important to evaluate the effects of tree reduction in areas without masticated-juniper debris cover. We hypothesized that: (1) the reduction of juniper resource uptake and shade with juniper tree mastication will increase wet, degree, and wet degree days compared to untreated areas with live juniper trees remaining; (2) soil cover will reduce degree days during warm periods, increase degree days during cool periods, and increase wet days and wet degree days throughout the year compared to uncovered soil; and (3) wet days will increase with soil depth throughout the year, degree days will decrease with soil depth during warm periods and increase with soil depth during cool periods, and wet degree days will increase with soil depth during cool periods.

2. Materials and methods

2.1. Study locations

We studied the three Sagebrush Steppe Treatment and Evaluation Project (SageSTEP) research locations of Greenville, Onaqui, and Stansbury in the western Utah portion of the Great Basin (McIver et al., 2010; www.sagestep.org). We measured soil water and temperature in Phase III woodland encroachment (*sensu* Miller et al., 2005) of sagebrush-bunchgrass communities. Communities are considered to be at Phase III encroachment when tree cover >67% of the total relative perennial plant cover. High densities of Utah juniper trees or mixed piñon-juniper trees have depleted the previous sagebrush (*Artemisia* spp.) and bunchgrass plant communities. Maximum absolute and relative tree cover before mastication were 31% and 89% at Onaqui, 54% and 97% at Greenville, and 65% and 93% at Stansbury. Maximum tree density (>0.5-m tall) prior to mastication was 586 trees ha^{-1} at Greenville, 444 trees ha^{-1} at Onaqui, and 1030 trees ha^{-1} at Stansbury. Before juniper tree mastication, shrub cover was <5% across study locations and perennial grass cover was <10% at Greenville and Onaqui and <20% at Stansbury.

The average elevation at these locations is 1700–1900 m. Annual average temperatures at these locations are 9–10 °C with minimum average temperatures of 0–3 °C and maximum average temperatures of 16–19 °C. Annual average precipitation ranged between 193 and 389 mm. Most precipitation comes as snow during winter and rain in spring and fall but summers are mostly dry. Greenville (38°12′N, 112°48′W) in Beaver County is on the north side of the Black Mountains with soils classified as loamy-skeletal, carbonatic, mesic Typic Calcixerepts (Rau et al., 2011). The dominant vegetation includes Utah juniper trees, two-needle piñon trees (*Pinus edulis* Engelm.), Wyoming big sagebrush (*Artemisia tridentata* Nutt. ssp. *wyomingensis* Beetle & Young), rabbitbrush [*Chrysothamnus viscidiflorus* (Hook.) Nutt.], bluebunch wheatgrass [*Pseudoroegneria spicata* (Pursh) A. Löve], needle-and-thread [*Hesperostipa comata* (Trin. & Rupr.) Barkworth], and Indian ricegrass [*Achnatherum hymenoides* (Roem. & Schult.) Barkworth]. Onaqui (40°13′N, 112°28′W) in Tooele County is on the east side of the Onaqui Mountains with soils identified as loamy-skeletal, carbonatic, mesic, shallow Petrocalcic Palexerolls (Rau et al., 2011). The dominant vegetation includes Utah juniper trees, Wyoming big sagebrush, bluebunch wheatgrass, Sandberg bluegrass (*Poa secunda* J. Presl), and Indian ricegrass. Stansbury (40°35′N, 112°39′W) in Tooele County is on the west side of the Stansbury Mountains with soils identified as loamy-skeletal, mixed, active, frigid Pachic Haploxerolls (Rau et al., 2011). The dominant vegetation includes Utah juniper trees, Wyoming big sagebrush, antelope bitterbrush [*Purshia tridentata* (Pursh) DC.], bluebunch wheatgrass, Sandberg bluegrass, and cheatgrass (*Bromus tectorum* L.).

2.2. Treatment implementation

A Tigercat® M726E Mulcher (Tigercat Industries, Inc., Brantford, Ontario) with Fecon® Bull Hog® (Fecon, Inc., Lebanon, OH) attachment masticated Utah juniper trees at Onaqui in the fall of 2006 and at Stansbury in the fall of 2007. A skid steer loader with Fecon® Bull Hog® attachment masticated Utah juniper and two-needle piñon trees at Greenville in the fall of 2007. Greenville and Onaqui had 20-ha treatment areas while Stansbury had 5-ha areas. Most of the masticated-juniper debris had diameters <2.54 cm and nearly all of the debris had diameters <7.62 cm with lengths varying widely from less than a centimeter to a couple meters. We did not measure residual plant cover or seed banks in this study but removed volunteer plants from microsites where soil climate was measured. Plant growth did not appear to change in untreated areas during our study. Herbaceous plants appeared to increase at Stansbury 1 yr after juniper tree mastication and 2–3 yr after mastication at Greenville and Onaqui. Across the Great Basin, Miller et al. (in press) and Roundy et al. (in press a) found that invasive annual and native perennial herbaceous cover increased 2–3 yr after mechanical reduction of trees at moderate to high levels of juniper-piñon encroachment.

2.3. Study design and field measurements

We paired masticated and untreated control areas with similar soils and pretreatment vegetation at each location to test the effects of reduced juniper tree resource uptake and shade on wet, degree, and wet degree days. We installed a randomized complete block design within each masticated and untreated area. Sixteen juniper trees in masticated areas and eight juniper trees in untreated areas were grouped into four replicate blocks. We selected trees with at least a 2-m diameter tree mound to allow room for soil climate measurements. One tree per block was selected for soil water and temperature measurements in this study.

We sectioned juniper inter- and subcanopy areas into pie shaped microsites to isolate the effects of the different soil cover types and uncovered soil on wet, degree, and wet degree days (Figs. 1 and 2). Juniper trees in untreated areas had three microsite types that included: tree mounds with intact tree litter composed of fallen leaf scales, twigs, and berries; tree mounds with tree litter removed down to the soil surface; and bare interspaces between tree canopies with little understory vegetation remaining. Juniper trees in masticated areas had five microsite types that included: (1) tree mounds with intact litter; (2) tree mounds with tree litter removed; (3) bare interspaces between tree canopies; (4) bare interspaces covered with masticated-juniper debris mostly composed of wood pieces, bark, and leaf scales; and (5) tree mounds with intact tree litter covered with masticated-juniper debris. The number of microsite experimental units per research location was 32 derived from 4 untreated blocks * 3 microsite types plus 4 masticated blocks * 5 microsite types.

We buried copper-constantan thermocouples (Omega Engineering, Inc., Stamford, CT) to measure soil temperature and gypsum blocks (Delmhorst Instrument Co., Towaco, NJ) to measure soil water potential at Onaqui in October 2007 and at Greenville and Stansbury in July 2008. One of each sensor was buried at 1–3, 13–15, and 28–30 cm soil depths in each microsite of one randomly selected tree per block. We buried sensors at these depths because the effects of tree reduction and soil cover type on the soil climate were expected to change with soil depth and these depths relate to the resource growth pool (see Section 1; Leffler and Ryel, 2012; Roundy et al., In Press b; Ryel et al., 2010). The difference in rooting depth among species, seasons, solar radiation, evaporation, and hydrophobic layers are also among the several factors that influence the soil climate at different intensities depending on soil depth. Soil water potential and temperature were recorded at Greenville from September 2008 through February 2011; Onaqui from December 2007 through February 2011; and Stansbury from September 2008 through June 2009. We converted electrical resistance as measured by gypsum blocks to soil water potential using a standard calibration curve (Campbell Scientific, Inc., 1983). CR10X data loggers and AM16/32 multiplexers (Campbell Scientific, Inc., Logan, UT) recorded hourly-average soil water potential and soil temperature using 1-min interval measurements. Onsite air temperature was recorded hourly using a thermistor in a gill shield. Precipitation was measured using an electronic tipping-bucket rain gauge at each research location to tract annual climate variability throughout the study.

2.4. Data analysis

Soil water and temperature were analyzed as the seasonal summations of wet days (summation of hours 24^{-1} when hourly soil matric potential >−1.5 MPa), degree days (summation of hours 24^{-1} when hourly soil temperature >0 °C), and wet degree days (summation of hours 24^{-1} when hourly soil matric potential>–1.5 MPa and hourly soil temperatures >0 °C) separately using Proc Mixed (SAS v9.2, SAS Institute, Inc., Cary, NC). The four seasons included spring: 1 March to 30 June; summer: 1 July to 31 August; fall: 1 September to 30 November; and winter: 1 December to 28 February to account for seasonal weather patterns and plant growth. Analysis of variance data requirements were met without transformation of response variables based on evaluation of residuals plots. Seasons, treatment areas, microsite types, and soil depths were fixed effects, and years, locations, blocks, and trees were random effects in mixed-model analysis of variance. Fixed effects were evaluated with *F*-tests from maximum likelihood estimation. Microsites as experimental units were nested in trees and trees were nested in years, locations, and blocks. This analysis structure accounted for potential microsite spatial correlation. Season was crossed with years because seasons were the same period of time each year. Season was included as a repeated measures variable to account for potential temporal correlation.

A full factorial analysis was not appropriate because masticated areas had more types of microsites than untreated areas, a result of untreated areas not having masticated-juniper debris. We assigned each treatment by microsite type combination to be one of eight levels of the treatment-microsite main effect. These eight levels were the three untreated and five masticated microsite types. We used linear contrasts to test the overall treatment (tree reduction) effects on soil climate by comparing the three microsite types in untreated areas with the five microsite types in masticated areas. We also used linear contrasts within treatments to test soil cover type effects and across treatments to test tree reduction

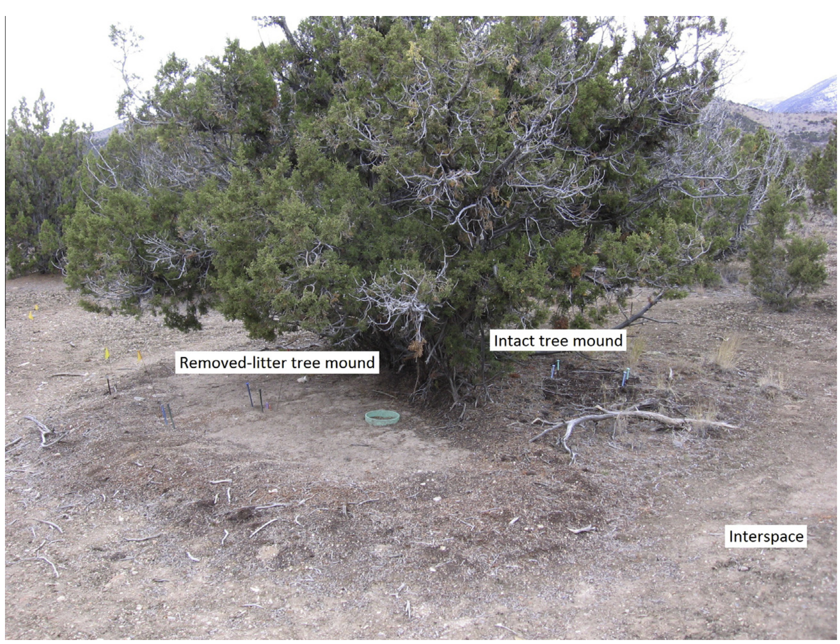

Fig. 1. Untreated control area identifying microsite types.

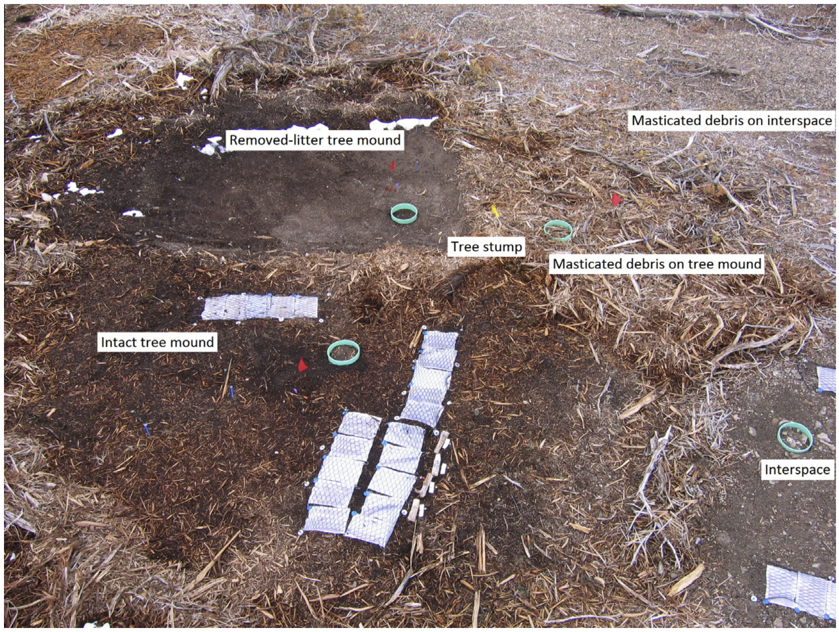

Fig. 2. Masticated area identifying microsite types.

effects on an individual microsite type basis. We adjusted for false positives from multiple comparisons by using pseudo-Bonferroni with a critical alpha level of 0.001 for individual microsite and soil depth comparisons. Each response variable had 3628 observations for analysis.

3. Results

3.1. Climate

Climate provides the background upon which the effects of mechanical mastication of juniper influence wet, degree, and wet degree days. Annual-average air temperatures were consistent across years but annual precipitation totals varied greatly across years and were generally lower than long-term averages. Greenville and Onaqui had onsite annual-average air temperatures of 9–10 °C with minimum temperatures of 0–2 °C and maximum temperatures of 17–19 °C. Onsite annual air temperature and precipitation data are not available for Stansbury. The long-term annual averages from 1970 to 2007 at Greenville, Onaqui, and Stansbury for minimum air temperature were 0, 2, and 3 °C and for maximum air temperature were 17, 17, and 16 °C, respectively (PRISM, 2008). Greenville had annual precipitation totals of 193 mm in 2009 and 387 mm in 2010. Onaqui had annual precipitation totals of 259 mm in 2008, 287 mm in 2009, and 370 mm in 2010. The long-term annual precipitation totals for 1970–2007 at Greenville, Onaqui, and Stansbury were 334, 311, and 389 mm, respectively (PRISM, 2008).

3.2. Tree reduction – reduced juniper tree resource uptake and shade

The treatment-microsite, soil depth, and season main effects and their interactions always influenced wet, degree, and wet degree days ($P < 0.001$) except the treatment-microsite by soil depth interaction did not alter degree days ($P > 0.05$, Table 1). Reduced juniper resource uptake and shade with mastication increased wet days, wet degree days, and sometimes degree days compared to untreated areas and these differences increased with soil depth ($P < 0.001$, Figs. 3 and 4). The five microsite types in masticated areas collectively had 27 more wet days ($P < 0.001$), 32 more degree days ($P = 0.007$), and 311 more wet degree days ($P < 0.001$) than the three microsite types in untreated areas across soil depths and seasons (Table 2). Importantly, masticated areas during the critical spring-summer growth period averaged 44.5 more wet days than untreated areas across the lower soil depths ($P < 0.001$, Fig. 3).

Mastication of juniper trees affected tree mound degree days and wet days differently than adjacent interspaces. Reduced juniper canopy shade with mastication increased intact and removed-litter tree mound degree days during spring and summer by 127–309 but increased interspace degree days only during fall by 98–118 at all soil depths ($P < 0.001$; Table 3). Reduced juniper resource uptake increased intact and removed-litter tree mound wet days at most soil depths by 21–63 during fall-spring but increased interspace wet days only at the lowest soil depth by 27–54 throughout the year ($P < 0.001$, Fig. 3). However, the combined effects of reduced juniper resource uptake and shade resulted in both increased tree mound and interspace wet degree days at most soil depths by 282–966 during spring-fall ($P < 0.001$, Fig. 4).

3.3. Soil cover types

Soil cover influenced degree days to greater soil depths than wet days. Soil cover in masticated and untreated areas whether intact litter on tree mounds or masticated-juniper debris on interspaces decreased degree days at most soil depths by 55–265 during spring and summer but increased wet days only at the 1–3 cm soil depth by 24–31 during spring ($P < 0.001$, Tables 3 and 4). Additionally, soil cover increased masticated wet degree days only at the 1–3 cm soil depth for intact litter on tree mounds by 328–394 during spring and summer and for masticated-juniper debris by 340 during spring ($\underline{P} < 0.001$, Table 4). An important thermal difference between soil cover types appeared to be due to color of the soil cover. Dark-colored, intact litter on tree mounds had more degree days by 87–187 than light-colored, masticated-juniper debris during spring and summer at most soil depths ($P < 0.001$, Table 3).

Table 1
Mixed-model analysis of variance and type III *F*-tests from maximum likelihood estimation for the response variables of wet, degree, and wet degree days. We assigned each treatment (trt) by microsite combination as one of eight levels of the combined main effect of trt-microsite. Denominator degrees of freedom (df) = 3204.

Effect	Numerator df	*P*-value		
		Wet days	Degree days	Wet degree days
Trt-microsite (T-M)	7	<0.001	<0.001	<0.001
Depth (D)	2	<0.001	<0.001	<0.001
Season (S)	5	<0.001	<0.001	<0.001
T-M*D	14	<0.001	0.25	<0.001
T-M*S	35	<0.001	<0.001	<0.001
D*S	10	<0.001	<0.001	<0.001
T-M*D*S	70	<0.001	<0.001	<0.001

3.4. Soil depth

Most microsite degree days decreased with soil depth during spring and summer by 139–233 but increased with soil depth during fall and winter by 103–174 regardless of juniper mastication ($P < 0.001$, Table 3). Untreated wet days had seasonal trends opposite that of degree days. Untreated, removed-litter tree mound and interspace wet days increased with soil depth during spring by 19–31 and wet degree days also increased with soil depth during spring by 268–418 but wet days decreased with soil depth during fall by 19–24 ($P < 0.001$, Table 4, Figs. 3 and 4). Whereas masticated, intact and removed-litter tree mound and interspace wet days usually increased with depth by 25–40 and wet degree days usually increased with depth by 401–914 during spring-fall ($P < 0.001$, Table 4, Figs. 3 and 4).

4. Discussion

4.1. Tree reduction – reduced juniper tree resource uptake and shade

Juniper tree encroachment is expected to continue in the sagebrush steppe without treatment. Juniper trees increase dominance by competing with other plants for resources and redistributing soil water and nutrients away from surrounding vegetation to directly below its canopy, which contributes to desertification (Leffler et al., 2002; Newman et al., 2010; Ryel et al., 2010; Archer et al., 2011). Because soil water is often the most limiting resource for plant growth in these juniper encroached sagebrush-bunchgrass communities (Young et al., 2013) increased resource availability with juniper tree mastication translates into better growing conditions (Young, 2012). The greater number of wet, degree, and wet degree days and greater soil N availability (Young, 2012) after juniper tree mastication explain the increased bluebunch and cheatgrass aboveground biomass, tillers, and cheatgrass spikelets found in a related study conducted on the same sites (Young et al., 2013). This indicates that our wet, degree, and wet degree day metrics are good indicators of favorable growing conditions.

The plant species that benefit most from increased resource availability after tree reduction are those that survive juniper encroachment, have high propagule pressure, lack enemies, or have the morphological and physiological capabilities to quickly take advantage of the increased resource growth pool (Leffler and Ryel, 2012). The use of water from the resource growth pool by one plant can limit the size of the growth pool available to other plants and thereby interfere with their growth (Leffler and Ryel, 2012). This link between plant species performance and resource

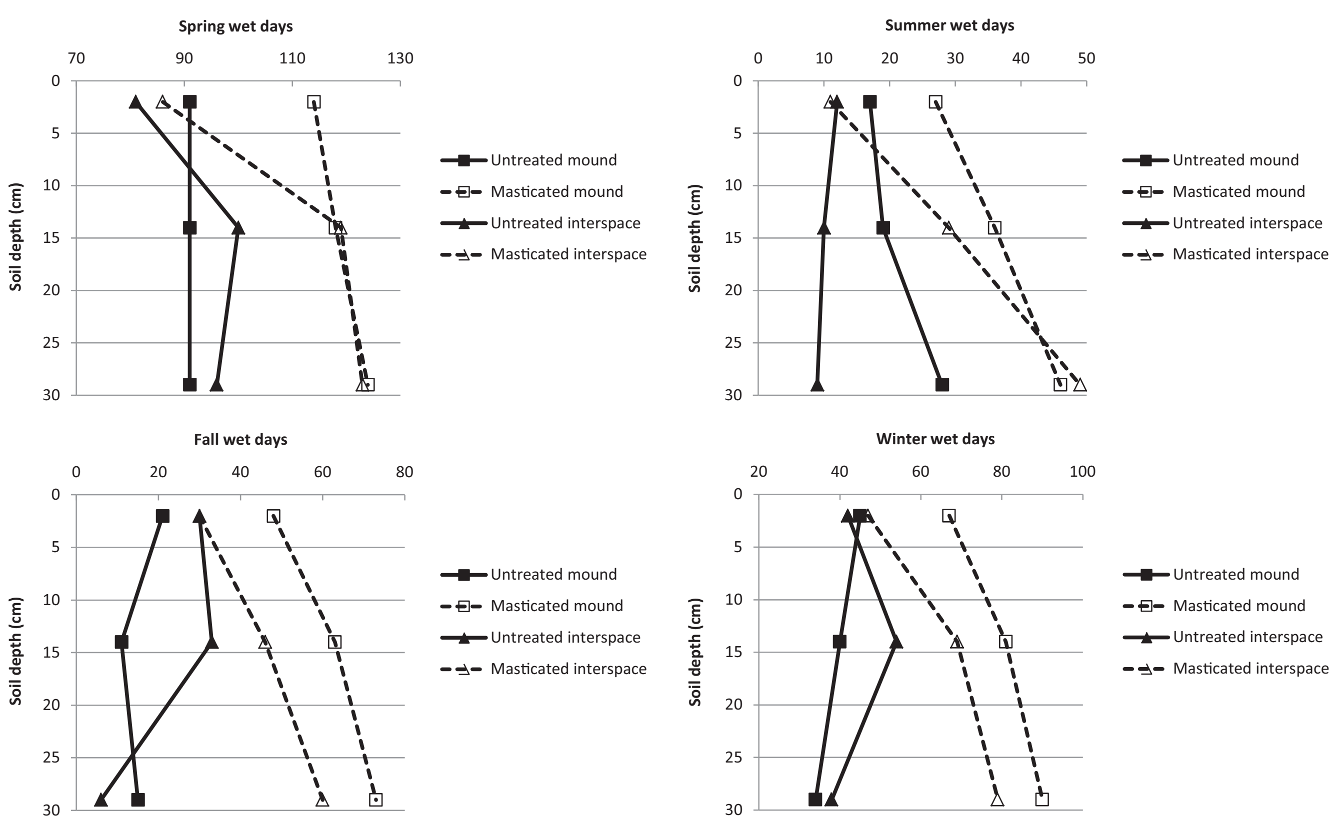

Fig. 3. Wet day comparisons between untreated and masticated areas. For intact juniper tree mounds, masticated was greater than untreated during fall, winter, and spring ($P < 0.001$). For interspaces, masticated was greater than untreated for the lower two soil depths during spring and the lowest soil depth during other seasons. Note: different scales for different seasons.

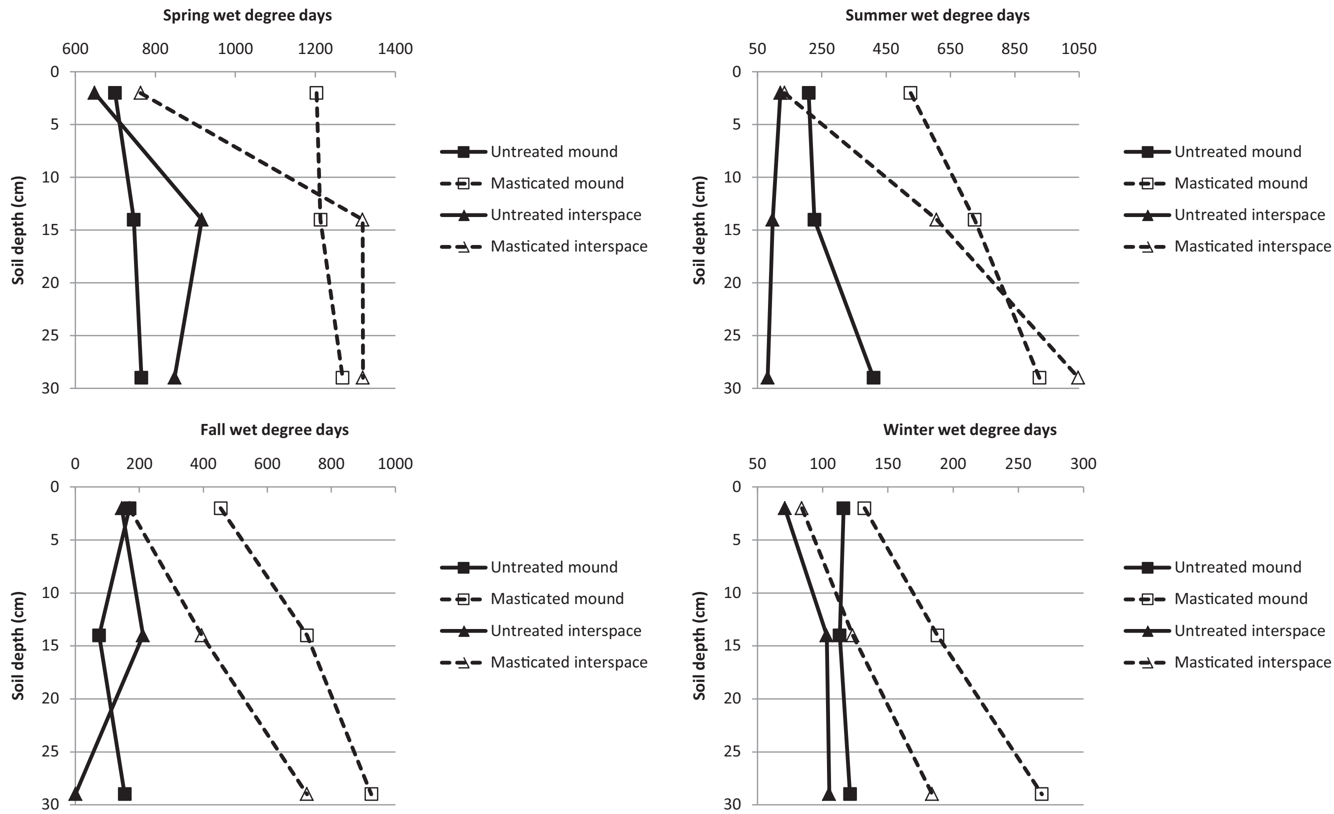

Fig. 4. Wet degree day comparisons between untreated and masticated areas. For intact juniper tree mounds, masticated was greater than untreated during all seasons except winter ($P < 0.001$). For interspaces, masticated was greater than untreated for the lower two soil depths during spring and summer and for the lowest soil depth in fall ($P < 0.001$). Note: different scales for different seasons.

availability provides land managers with means to modify plant community composition by modifying resource availability with management treatments (Leffler and Ryel, 2012) like mechanical mastication.

With the understory plant community often reduced by juniper encroachment (Roundy et al., in press a), the amount of resources made available by juniper reduction increases with the density and cover of juniper trees treated (Roundy et al., in press b). A concern with treatment at an advanced phase of tree encroachment is that the few remaining desired perennials may not be sufficient to take up the increase in resource availability. This could leave unused resources available for invasive weedy species like cheatgrass to alter the plant community, reduce ecosystem goods and services, and reduce ecosystem resistance to invasion (D'Antonio et al., 2009). For example, following juniper tree mastication, cheatgrass cover increased more at higher phases of juniper tree encroachment than at lower phases (Roundy et al., in press a). This suggests that juniper tree encroachment should be controlled early before desired perennials are reduced in order to minimize the availability of resources for weedy species and to maximize ecosystem resistance to weeds (D'Antonio et al., 2009). Early control of juniper encroachment will also reduce treatment costs because the \$50–500 ac^{-1} to masticate juniper trees depends on tree density and tree maturity as well as roughness of terrain and remoteness of the treatment site (SageSTEP, 2011).

Table 2
Overall treatment comparisons between masticated and untreated areas across microsite types, soil depths, and seasons using maximum-likelihood estimates (degrees of freedom = 3204).

Response	SE	*t*-value	Masticated	Untreated	*p*-value
Wet days	1.58	17.3	70	42	<0.001
Degree days	11.93	2.68	1009	977	0.007
Wet degree days	18.70	16.61	627	316	<0.001

4.2. Soil cover types

Intact tree mounds and masticated-juniper debris had less of an effect on soil water and temperature than tree reduction but still increased surface wet and wet degree days during spring in masticated areas. Intact tree mounds also increased surface wet degree days during summer in masticated areas. The organic, intact tree mounds and masticated-juniper debris conserved soil water by reducing evaporation in multiple ways. Organic cover has low heat capacity and conductivity (Hillel, 2004) that allows it to intercept and reduce incident solar energy available to evaporate soil water, as well as maintain cooler soil temperatures during the growing season (Facelli and Pickett, 1991). Organic cover also lowers evaporation by reducing the vapor pressure deficit between the soil and atmosphere (Facelli and Pickett, 1991) and increases infiltration rates (Cline et al., 2010). These longer periods of available water near the soil surface should favor germination (Roundy et al., 2007) and seedling emergence. However, intact tree mounds and masticated-juniper debris did not increase and sometimes decreased bluebunch wheatgrass and cheatgrass emergence (Young et al., 2013) compared to uncovered soil. This suggests that the soil cover physically restricted seedling emergence (Facelli and Pickett, 1991) or that the environmental requirements for seedling establishment were met in covered and uncovered areas.

Soil cover also influences plant phenology by altering soil temperatures because warmer temperatures can increase germination and seedling growth rates (Chambers et al., 2007; Rawlins et al.,

Table 3
Tree reduction and soil cover type effects on degree days. Estimates in paired columns at the same soil depth with the same letter are not significantly different ($P < 0.001$).

	Depth (cm)	Spring		Summer		Fall		Winter	
Mastication effects		Untreated	Masticated	Untreated	Masticated	Untreated	Masticated	Untreated	Masticated
Intact tree mound	1–3	1118b	1427a	1306b	1557a	1068a	1132a	96a	83a
	13–15	1090b	1354a	1259b	1463a	1125a	1191a	140a	137a
	28–30	1085b	1274a	1237b	1387a	1197a	1255a	231a	221a
Interspace	1–3	1509a	1505a	1678a	1645a	947b	1045a	27a	50a
	13–15	1440a	1447a	1562a	1551a	1014b	1132a	61a	84a
	28–30	1370a	1356a	1494a	1481a	1119b	1219a	144a	161a
Tree mound effects		Intact	Removed	Intact	Removed	Intact	Removed	Intact	Removed
Untreated	1–3	1118b	1355a	1306b	1516a	1068a	1099a	96a	80a
	13–15	1090b	1250a	1259b	1385a	1125a	1158a	140a	103a
	28–30	1085b	1202a	1237a	1316a	1197a	1225a	231a	183a
Masticated	1–3	1427b	1529a	1557b	1676a	1132a	1071a	83a	46a
	13–15	1354a	1410a	1463a	1522a	1191a	1124a	137a	80a
	28–30	1274a	1329a	1387a	1443a	1255a	1208a	221a	173a
Masticated debris effects		Debris	No debris	Debris	No debris	Debris	No debris	Debris	No debris
Intact tree mound	1–3	1165b	1427a	1327b	1557a	1098a	1132a	125a	83a
	13–15	1139b	1354a	1295b	1463a	1157a	1191a	170a	137a
	28–30	1088b	1274a	1246b	1387a	1223a	1255a	241a	221a
Interspace	1–3	1240b	1505a	1434b	1645a	1051a	1045a	87a	50a
	13–15	1201b	1447a	1376b	1551a	1125a	1132a	146a	84a
	28–30	1139b	1356a	1314b	1481a	1192a	1219a	214a	161a

2012; Roundy et al., 2007). This indicates that the cooler soil temperatures under intact tree mounds and masticated-juniper debris during spring could delay seedling establishment while the lack of soil cover and associated warmer soil temperatures in interspaces could hasten spring seedling emergence. In untreated areas, the minimal effect of soil cover on wet days and wet degree days was associated living trees. Untreated trees still used soil water, shaded subcanopy areas and diurnally shaded some interspaces, and redistributed precipitation and soil water through canopy interception, hydraulic flow through roots, and water repellant layers below litter mounds funneling soil water deeper into the soil away from shallow-rooted plants (Breshears et al., 1997a, 1997b; Lebron et al., 2007; Newman et al., 2010; Young et al., 1984).

4.3. Soil depth

Degree days frequently decreased with soil depth during spring and summer but increased with soil depth during fall and winter as

Table 4
Soil cover type effects on wet and wet degree days. Estimates in paired columns at the same soil depth with the same letters are not significantly different ($P < 0.001$).

	Depth (cm)	Spring		Summer		Fall		Winter	
Wet days									
Tree mound effects		Intact	Removed	Intact	Removed	Intact	Removed	Intact	Removed
Untreated	1–3	91a	67b	17a	15a	21a	23a	45a	52a
	13–15	91a	101a	19a	24a	11a	17a	40a	44a
	28–30	91a	98a	28a	37a	15a	4a	34a	30a
Masticated	1–3	114a	86b	27a	14a	48a	38a	67a	56a
	13–15	118a	122a	36a	29a	63a	56a	81a	78a
	28–30	124a	126a	46a	49a	73a	67a	90a	90a
Masticated debris effects		Debris	No debris	Debris	No debris	Debris	No debris	Debris	No debris
Intact tree mound	1–3	121a	114a	28a	27a	45a	48a	76a	67a
	13–15	122a	118a	33a	36a	51a	63a	82a	81a
	28–30	125a	124a	38a	46a	63a	73a	91a	90a
Interspace	1–3	117a	86b	18a	11a	43a	30a	71a	47b
	13–15	126a	119a	36a	29a	51a	46a	80a	69a
	28–30	128a	123a	42a	49a	59a	60a	82a	79a
Wet degree days									
Tree mound effects		Intact	Removed	Intact	Removed	Intact	Removed	Intact	Removed
Untreated	1–3	699a	527a	209a	178a	169a	143a	116a	131a
	13–15	746a	924a	227a	356a	74a	162a	113a	107a
	28–30	765a	945a	411a	657a	154a	16a	121a	85a
Masticated	1–3	1203a	809b	526a	198b	454a	241a	132a	97a
	13–15	1213a	1346a	725a	596a	724a	563a	188a	130a
	28–30	1268a	1357a	927a	1035a	925a	827a	268a	209a
Masticated debris effects		Debris	No debris	Debris	No debris	Debris	No debris	Debris	No debris
Intact tree mound	1–3	1091a	1203a	478a	526a	401a	454a	171a	132a
	13–15	1092a	1213a	581a	725a	573a	724a	209a	188a
	28–30	1097a	1268a	674a	927a	782a	925a	285a	268a
Interspace	1–3	1103a	763b	284a	134a	282a	169a	146a	84a
	13–15	1215a	1318a	676a	607a	499a	395a	197a	123a
	28–30	1198a	1319a	781b	1048a	709a	724a	250a	184a

expected (Table 3). In spring and summer, more direct solar radiation at northern latitudes results in greater warming of surface than subsurface soils (Brady and Weil, 1999). Conversely, in fall and winter, less direct solar radiation results in cooler surface than subsurface soils (Brady and Weil, 1999). These temperature gradients across soil depths can alter invasive-annual seedling establishment relative to native-perennials (Harris, 1967). Rapid root elongation after fall germination of invasive annuals like cheatgrass allows their roots to penetrate deeper into the soil profile where soil temperatures are warmer, thereby supporting winter growth (Harris, 1967). This gives cheatgrass a resource acquisition advantage in early spring over native perennial seedlings like bluebunch wheatgrass whose roots grow slower at cool temperatures (Harris, 1967).

The ratio of herbaceous to woody plant biomass is dependent on the ratio of shallow to deep soil water (Breshears et al., 1997b). The thick juniper stands in untreated areas frequently decreased soil water with soil depth during fall even though soil water often increased with soil depth during spring in untreated areas and throughout the year in masticated areas. This indicates that live juniper trees deplete much of the plant available soil water by the end of summer before the return of fall rains (Fig. 3). The reduction in soil water with soil depth likely explains the common reduction of shrub cover with juniper encroachment. These results show that the historic sagebrush steppe community will not return to dominance until juniper encroachment is reduced.

5. Conclusions

Without juniper tree reduction or crown fire, juniper trees are expected to continue dominating sagebrush-bunchgrass communities because they access deeper soil water, compete for and manipulate resources, and decrease understory plant cover (Breshears et al., 2009; Leffler et al., 2002; Miller and Wigand, 1994; Newman et al., 2010; Ryel et al., 2010). The metrics of wet, degree, and wet degree days are useful tools for evaluating the effects of woody species control on resource availability and subsequent plant performance. Mastication of juniper trees increased the time of plant available soil water when temperatures were warm during spring and summer, a critical time for seedling establishment and plant growth (Hardegree et al., 2003; Roundy et al., 2007). Even when Greenville precipitation in 2009 was only 50% of 2010 and 58% of the long-term average, juniper tree mastication increased soil water availability. The increased resource availability is expected to benefit both surviving desirable and weedy plant species adapted to site conditions (Miller et al., in press). However, to best manage for weed resistance, juniper trees should be controlled well before desirable perennial plant cover is lost to limit resources available to invasive plants. In the future, the metrics of wet, degree, and wet degree days should be evaluated for their potential to monitor the effects of climate change on the soil climate and associated changes in plant community composition.

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References

Angell, R.F., Miller, R.F., 1994. Simulation of leaf conductance and transpiration in *Juniperus occidentalis*. Forest. Sci. 40, 5–17.

Archer, S.R., Davies, K.W., Fulbright, T.E., McDaniel, K.C., Wilcox, B.P., Predick, K.I., 2011. Brush management as a rangeland conservation strategy: a critical evaluation. In: Briske, D.D. (Ed.), Conservation Benefits of rangeland practices: ASSESSMENT, recommendations, and knowledge gaps. USDA, NRCS, pp. 105–170.

Bonhomme, R., 2000. Bases and limits to using 'degree day' units. Eur. J. Agron. 13, 1–10.

Brady, N.C., Weil, R.R., 1999. The Nature and Properties of Soils. Prentice-Hall Inc., Upper Saddle River, NJ.

Breshears, D.D., Myers, O.B., Johnson, S.R., Meyer, C.W., Martens, S.N., 1997a. Differential use of spatially heterogeneous soil moisture by two semiarid woody species: *Pinus edulis* and *Juniperus monosperma*. J. Ecol. 85, 289–299.

Breshears, D.D., Rich, P.M., Barnes, F.J., Campbell, K., 1997b. Overstory-imposed heterogeneity in solar radiation and soil moisture in a semiarid woodland. Ecol. Appl. 7, 1201–1215.

Breshears, D.D., Myers, O.B., Barnes, F.J., 2009. Horizontal heterogeneity in the frequency of plant-available water with woodland intercanopy-canopy vegetation patch type rivals that occurring vertically by soil depth. Ecohydrology 2, 503–519.

Campbell.Scientific, Inc., 1983. Model 227 Delmhorst Cylindrical Soil Moisture Block Instruction Manual. Campbell Scientific, Logan, UT.

Chambers, J.C., Meyer, S.E., Whittaker, A., Roundy, B.A., Blank, R.R., 2007. What makes Great Basin sagebrush ecosystems invasible by *Bromus tectorum*? Ecol. Monogr. 77, 117–145.

Cline, N.L., Kormos, P., Williams, C.J., Roundy, B.A., Pierson, F.B., 2010. Hydrologic response to mechanical shredding in a juniper woodland. Rangeland Ecol. Manage. 63, 467–477.

D'Antonio, C.M., Chambers, J.C., Loh, R., Tunison, J.T., 2009. Applying ecological concepts to the management of widespread grass invasions. In: Inderjit, R.L. (Ed.), Management of Invasive Weeds. Springer, Dordrecht, Netherlands, pp. 123–149.

Emerson, F.W., 1932. The tension zone between the grama grass and piñon-juniper associations in northeastern New Mexico. Ecology 13, 347–358.

Facelli, J.M., Pickett, S.T., 1991. Plant litter: Its dynamics and effects on plant community structure. Bot. Rev. 57, 1–32.

Gillette, D.A., Pitchford, A.M., 2004. Sand flux in the northern Chihuahuan desert, New Mexico, USA, and the influence of mesquite-dominated landscapes. J. Geophys. Res. Earth. 109. http://dx.doi.org/10.1029/2003JF000031.

Hardegree, S.P., Flerchinger, G.N., van Vactor, S.S., 2003. Hydrothermal germination response and the development of probabilistic germination profiles. Ecol. Model. 167, 305–322.

Harris, G.A., 1967. Some competitive relationships between *Agropyron spicatum* and *Bromus tectorum*. Ecol. Monogr. 37, 89–111.

Hillel, D., 2004. Introduction to Environmental Soil Physics. Academic Press, San Diego, CA.

Idso, S.B., Jackson, R.D., Reginato, R.J., 1978. Extending the "degree day" concept of plant phenological development to include water stress effects. Ecology 59, 431–433.

Jaeger, W.K., Cross, R., Egelkraut, T.M., 2007. Biofuel potential in Oregon: Background and evaluation of options. Special Report 1078. Oregon State Univer. Ext. Serv., Corvallis, OR.

Johnsen, T.N., 1962. One-seed juniper invasion of northern Arizona grasslands. Ecol. Monogr. 32, 187–207.

Knapp, A.K., Briggs, J.M., Collins, S.L., Archer, S.R., Bret-Harte, M.S., Ewers, B.E., Peters, D.P., Young, D.R., Shaver, G.R., Pendall, E., Cleary, M.B., 2008. Shrub encroachment in North American grasslands: shifts in growth form dominance rapidly alters control of ecosystem carbon inputs. Glob. Change Biol. 14, 615–623.

Lebron, I., Madsen, M.D., Chandler, D.G., Robinson, D.A., Wendroth, O., Belnap, J., 2007. Ecohydrological controls on soil moisture and hydraulic conductivity within a pinyon-juniper woodland. Water Resour. Res. 43, 1–15.

Leffler, A.J., Ryel, R.J., 2012. Resource pool dynamics: Conditions that regulate species interactions and dominance. In: Monaco, T.A., Sheley, R.L. (Eds.), Invasive Plant Ecology and Management: Linking Processes to Practice. CABI, Cambridge, MA, pp. 57–78.

Leffler, A.J., Ryel, R.J., Hipps, L., Ivans, S., Caldwell, M.M., 2002. Carbon acquisition and water use in a northern Utah *Juniperus osteosperma* (Utah juniper) population. Tree Physiol. 22, 1221–1230.

McIver, J.D., Brunson, M., Bunting, S.C., 2010. The Sagebrush Steppe Treatment Evaluation Project (SageSTEP): A test of state-and-transition theory. Gen. Tech. Rep. RMRS-GTR-237, US For. Serv. Rocky Mountain Res. Stn., Fort Collins CO.

Miller, R.F., Rose, J.R., 1999. Fire history and western juniper encroachment in sagebrush steppe. J. Range Manage. 52, 550–559.

Miller, R.F., Wigand, P.E., 1994. Holocene changes in semiarid pinyon-juniper woodlands: Responses to climate, fire, and human activities in the U.S. Great Basin. Bioscience 44, 465–474.

Miller, R.F., Svejcar, T.J., Rose, J.R., 2000. Impacts of western juniper on plant community composition and structure. J. Range Manage. 53, 574–585.

Miller, R.F., Bates, J.D., Svejcar, T.J., Pierson, F.B., Eddleman, L.E., 2005. Biology, Ecology, and management of western juniper. Tech. Bull. 152, Agric. Exp. Stn., Oregon State Univer., Corvallis, OR.

Miller, R.F., Ratchford, J., Roundy, B.A., Tausch, R.J., Pereia, C., Hulet, A., Chambers, J.C., in press. Response of conifer encroached shrublands in the Great Basin to prescribed fire and mechanical treatments. Rangeland Ecol. Manage.

Newman, B.D., Gard, M.O., Breshears, D.D., 2010. Evapotranspiration partitioning in a semiarid woodland: Ecohydrologic heterogeneity and connectivity of vegetation patches. Vadose Zone J. 9, 561–572.

Pinchot Institute for Conservation., 2002. An introduction to the national fire plan: history, structure, and relevance to communities. <http://www.pinchot.org>. (accessed Jun. 2013).

PRISM Climate Group, 2008. Parameter-elevation regression on independent slopes model. <http://prism.oregonstate.edu>. (accessed 2.2008.

Rau, B.M., Johnson, D.W., Blank, R.R., Tausch, R.J., Roundy, B.A., Miller, R.F., Caldwell, T.G., Lucchesi, A., 2011. Woodland expansion's influence on belowground carbon and nitrogen in the Great Basin U.S. J. Arid Environ. 75, 827–835.

Rawlins, J.K., Roundy, B.A., Egget, D., Cline, N., 2012. Predicting germination in semi-arid wildland seedbeds II. Field validation of wet thermal-time models. Environ. Exp. Bot. 76, 68–73.

Robinson, D.A., Lebron, I., Ryel, R.J., Jones, S.B., 2010. Soil water repellency: A method of soil moisture sequestration in pinyon-juniper woodland. Soil Sci. Soc. Am. J. 74, 624–634.

Roundy, B.A., Whittaker, A., Chambers, J.C., Hardegree, S.P., 2007. Prediction of cheatgrass field germination potential using wet thermal accumulation. Rangeland Ecol. Manage. 60, 613–623.

Roundy, B.A., Miller, R.F., Tausch, R.J., Young, K.R., Hulet, A., Rau, B., Jessop, B., Chambers, J.C., Eggett, D., in press a. Understory cover responses to piñon-juniper treatments across tree cover gradients in the Great Basin. Rangeland Ecol. Manage.

Roundy, B.A., Young, K.R., Cline, N., Hulet, A., Miller, R.F., Tausch, R.J., Chambers, J.C., Rau, B., in pressb. Piñon-juniper reduction effects on soil temperature and water availability of the resource growth pool. Rangeland Ecol. Manage.

Ryel, R.J., Leffler, A.J., Ivans, C., Peek, M.S., Caldwell, M.M., 2010. Functional differences in water-use patterns of contrasting life forms in Great Basin Steppelands. Vadose Zone J. 9, 1–13.

Sagebrush Steppe Treatment Evaluation Project., 2011. Guide to vegetation treatment costs for land management in the Great Basin. URL: <http://www.sagestep.org>. (accessed: 25-06-2013).

Schlesinger, W.H., Reynolds, J.F., Cunningham, G.L., Huenneke, L.F., Jarrell, W.M., Virginia, R.A., Whitford, W.G., 1990. Biological feedbacks in global desertification. Science 247, 1043–1048.

Skog, K.E., Rummer, R., Jenkins, B., Parker, N., Tittmann, P., Hart, Q., Nelson, R., Gray, E., Schmidt, A., Patton-Mallory, M., Gordon, G., 2009. A strategic assessment of biofuels development in the western states. In: McWilliams, W., Moisen, G., Czaplewski, R., (Eds.). In: Forest Inventory and Analysis (FIA) Symposium 2008. RMRS-P-56CD. US For. Serv. Rocky Mountain Res. Stn., Fort Collins, CO.

Wainwright, J., Parsons, A.J., Abrahams, A.D., 2000. Plot-scale studies of vegetation, overland flow and erosion interactions: case studies from Arizona and New Mexico. Hydrol. Process. 14, 2921–2943.

Wang, J.Y., 1960. A critique of the heat unit approach to plant response studies. Ecology 41, 785–790.

West, N.E., 1984. Successional patterns and productivity of pinyon-juniper ecosystems. In: Committee on Developing Strategies for Rangeland Management (Ed.), Developing Strategies for Range Management. Westview Press, Boulder CO, pp. 1301–1332.

Young, K.R., 2012. Plant establishment and soil microenvironments in Utah juniper masticated woodlands. [dissertation]. Brigham Young Univer., Provo, UT.

Young, J.A., Easi, D.A., Evans, R.A., 1984. Stem flow on western juniper (*Juniperus occidentalis*) trees. Weed Sci. 32, 320–327.

Young, K.R., Roundy, B.A., Eggett, D.L., 2013. Plant establishment in masticated Utah juniper woodlands. Rangeland Ecol. Manage. 66, 597–607.