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Original Research

Response of Soil Moisture to Infrequent Heavy Defoliation of Chemically Thinned Juniper Woodland ☆

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ABSTRACT

In semiarid regions of the western United States, there is heightened interest in tree removal to increase water availability for other uses such as forage growth and groundwater recharge. This study was conducted in central New Mexico to determine the effects of heavy infrequent defoliation of chemically thinned juniper woodland *(Juniperus monosperma)* on soil moisture. Each of three cattle-grazing exclosures (CD, FG, and KI) was instrumented: 1) beneath trees with a set of three soil moisture probes (0–25, 25–50, and 50–75 cm depth) and one soil temperature probe under live trees (control) and dead trees (herbicide-treated); and 2) between trees with one soil moisture and one soil temperature probe in control and herbicide-treated intercanopy plots. Each plot had three clipped and three unclipped subplots. Mean daily maximum surface soil temperature was highest (17.19°C) in intercanopy, intermediate (16.13°C) under herbicide-treated, and lowest (14.90°C) under control trees. Topsoil moisture (0–25 cm depth) was different among treatment combinations from late July to early September 2006. Thus, the control unclipped combination had the highest topsoil moisture while the herbicide-treated unclipped combination had the lowest topsoil moisture. Comparing other depths, control unclipped plots had higher soil moisture in the middle layer (25–50 cm) and bottom layer (50–75 cm) than at the top from late August to early November 2006. Results imply that clipping on chemically thinned juniper woodlands does not increase soil moisture at any depth, yet macropore flow and water absorption on deep soil layers, underneath live trees, might help to store soil moisture for longer periods in water-limited environments.

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Introduction

Woody vegetation has expanded and triggered changes in terms of structure and ecosystem function on a global scale over the past century (Archer et al. 2017). Juniper encroachment has expanded rapidly in the western United States (Miller et al. 2008). Overgrazing, climate change, and reduction of fine fuels are the main factors responsible for such encroachment (Gerardi and Sala 2015; OĆonnor et al. 2020). According to long-term studies, woody plant encroachment has a rate of < 0.5% cover yr^{-1} in hot and cold deserts of North America (Barger et al. 2011). On the other hand, Pacala et al. (2001) estimated a woody-plant encroachment cover of 335 million ha in the United States.

Junipers are evergreen small to medium trees with dense canopy cover and lateral shallow and deep root systems, which make areas dominated by these species vulnerable to soil erosion (Ansley et al. 2006). Their dense foliage structure can intercept significant amounts of precipitation and prevent solar radiation from reaching the soil surface (Breshears et al. 1998). Juniper influences the distribution of nutrients and moisture in the soil, reduces understory plant cover and species diversity, decreases herbaceous forage available for livestock grazing (Bates 2005; Abdallah et al. 2021), increases runoff (Wood and Javed 2001), and alters catch-

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ment hydrological function (Zou et al. 2014; Abdallah et al. 2020; Mata-González et al. 2021). Dense woody overstory canopy cover is one of the main factors affecting potential soil water recharge in juniper ecosystems (Owens et al. 2006; Peterson and Stringham 2008) and reduces understory biomass due to competition for water, light, and nutrients (Pieper 1990; Pelaez et al. 1994; Koukoura and Kyriazopoulos 2007; Macdonald and Fenniak 2007). For instance, juniper cover, as low as 10–20%, can significantly limit forage growth by canopy interception (Ansley et al. 2006).

Clearing juniper woodlands began after 1945 to increase forage and improve watershed conditions and big game habitat (Aro 1975; Dwyer 1975; Terrel and Spillett 1975; Miller et al. 2019). The main mechanical method used to remove trees was chaining (Aro 1975) and more recently, since 2000, shredding and cutting (Miller et al. 2019). These mechanical treatments (i.e., shredding and cutting) increased soil water availability (more days) and increased plant cover (Roundy et al. 2014a). Herbicide treatment has been applied to mature woodlands along with the mechanical approach (Miller et al. 2019). In 1975, herbicides were used on grazing lands in the United States (Evans 1975). Some of the results with the herbicide treatment were increased cheatgrass biomass (*Bromus tectorum,* Young and Evans 1976) and increased annual invasive grasses (Roundy et al. 2014b).

Targeted livestock grazing is an emerging tool used to manipulate vegetation (e.g., woody species) to accomplish landscape management goals (Bailey et al. 2019). Usually, targeted grazing is used as an herbicide and/or fire surrogate. Its efficacy in controlling one-seed juniper has been extensively tested (Estell et al. 2018). The use of livestock to target other undesirable rangeland plants have been shown to suppress species such as cheatgrass (*Bromus tectorum,* Diamond et al. 2009), yellow starthistle (Centaurea solstitialis, Goehring et al. 2010), and white locoweed (*Oxytropis sericea,* Goodman et al. 2014). Targeted grazing treatments often involve using high animal densities for short periods (Utsumi et al. 2010; Goodman et al. 2014), which usually result in heavy defoliation of nontarget herbaceous vegetation (Bailey et al. 2019). This side effect of targeted grazing programs could conceivably free up soil moisture and create windows of opportunity for seed germination that may well result in recruitment events of the nondesired woody species. Nonetheless, the impact that nontarget vegetation defoliation exerts on soil moisture in juniper-encroached rangelands is uncertain since the defoliation (i.e., hand clipped) has not shown any effect on the superficial soil moisture (Garduño et al. 2010).

Most of the soil moisture studies in pinyon-juniper woodlands have taken place in the western United States (Breshears et al. 1997a; Breshears et al. 2008; Roundy et al. 2014a; Ray et al. 2019). However, the effect of heavy defoliation on soil moisture in cleared juniper woodlands has not been explored in detail. The overall goal of this study was to determine whether infrequent heavy defoliation could influence soil moisture status. Specifically, this study was designed to assess the long-term effects of heavy defoliation of chemically thinned juniper woodland on soil moisture. On the basis of previous results (Garduño et al. 2010), we hypothesized that removing understory vegetation (i.e., clipping) would not lead to higher soil moisture at any depth in the herbicide-treated or control plots.

Methods

Description of the study site

The study was conducted at the Corona Range and Livestock Research Center of New Mexico State University located in central New Mexico (lat 34°15′36″N, long 105°24′36″W). The topography consists of rolling hills to flat areas with an elevation ranging from 1 737 to 2 048 m. The parent material consists of limestone and sandstone with soils classified as sandy loams and sandy clay loams. The average annual (1990–2006) precipitation is 325 mm, mostly received as convective storms from July through September (Torrell unpublished). The mean annual temperature is 12.3°C (NMCC 2020).

Overstory vegetation is dominated by one-seed juniper *(Juniperus monosperma)* and Pinyon pine *(Pinus edullis).* Understory herbaceous vegetation includes blue grama *(Bouteloua gracilis),* sideoats grama *(Bouteloua curtipendula),* black grama *(Bouteloua eripoda),* sand dropseed *(Sporobolus cryptandrus),* spike dropseed *(Sporobolus contractus)* poverty threeawn *(Aristida divaricata),* and wolftail *(Lycurus setosus).* Other common understory plants are broom snakeweed *(Gutierrezia sarothrae)* and cholla (*Opuntia cylindrical,* Garduño et al. 2010).

In 1995 at the Corona Range and Livestock Research Center, 960 ha of juniper woodland were sprayed aerially with the herbicide Tebuthiuron (EPA 1994, Fig. 1) encompassing three pastures. Before chemical treatment, three randomly selected cattle grazing exclosures (i.e., CD, FG, and KI) were installed and half the area of each exclosure was sprayed, leaving half of the area with live trees (hereafter control) and half of the area with interspersed dead tree snags (hereafter herbicide treated). Although pastures were excluded to cattle grazing, it is possible that mule deer and rodents had access to exclosures for feeding. In spring 2005, thirty-six plots (i.e., 12 plots per exclosure) were established under control trees (i.e., six plots per exclosure) and under herbicide trees (i.e., six plots per exclosure), killed by the herbicide treatment in 1995. Each plot varied in size from 4 to 10 m^2 due to vertical tree canopy projection. In spring 2006, we installed 24 intercanopy plots (4 m^2 each) within the same cattle grazing exclosures; four plots between two or three control trees and four plots between herbicide-treated tree snags were installed in each exclosure. To reduce potential variation of soil, undercanopy and intercanopy plots were deployed in a relatively small area of 120 m^2.

In spring 2005 and 2006, understory herbaceous vegetation (grasses and forbs) was clipped in three randomly selected plots under herbicide-treated tree snags and three plots under control trees (three clipped and three unclipped under each) in every exclosure. In spring 2006, we clipped four additional plots, two in herbicide treated interspaces, and two in control interspaces in each exclosure.

Field data collection

Volumetric soil water content (Θ) was measured with CS616 (Campbell Scientific Inc., Logan, UT) probes. Soil moisture probes were randomly assigned to install below the canopy drip line (at a 67-degree angle) at two or three sampling depths (0–25 cm, 25–50 cm, and 50–75 cm) depending on the presence of petrocalcic (caliche) horizon ($CaCO_3$). Thus, if the caliche layer was found at the deepest layer, only two soil moisture probes were installed. In 2005, eight undercanopy plots (four herbicide-treated and four control trees) were instrumented with soil moisture probes at the drip line in each exclosure (Table 1). In 2006, four intercanopy plots (two between control and two between herbicide-treated trees) were instrumented with one soil moisture probe per plot at 25-cm depth (see Table 1). Soil moisture probes were installed on the south side of each plot.

Each exclosure was instrumented with three temperature probes 107-L (Campbell Scientific Inc.) installed at 20-cm depth near the soil moisture probes (see Table 1). In addition, one tipping bucket rain gauge TE525WS-L (Campbell Scientific Inc.) was installed in each exclosure, between herbicide treated and control plots in the open area to avoid canopy influence, to record rainfall. Soil moisture, soil temperature, and rainfall data were recorded



Fig. 1. Juniper woodland at Corona Range and Livestock Research Center, control trees (left side), and herbicide-treated trees (right side).

Table 1
Probe setup in a juniper woodland at Corona Range and Livestock Research Center.

Soil moisture probes								
	Undercanopy				Intercanopy			
	Herbicide-treated		Control		Herbicide-treated		Control	
Exclosure	Clipped	Unclipped	Clipped	Unclipped	Clipped	Unclipped	Clipped	Unclipped
CD	2	2	3	1	1	1	1	1
FG	2	2	2	2	1	1	1	1
KI	2	2	3	1	1	1	1	1
Soil temperature probes								
CD	1	–	1	–	1	–	–	–
FG	1	–	1	–	–	–	1	–
KI	1	–	1	–	1	–	–	–

hourly in one data logger CR10X (Campbell Scientific Inc.) per exclosure. Recorded data included daily maximum and minimum soil temperatures.

Statistical data analyses

The weekly average of topsoil moisture content (0–25 cm depth) was analyzed as a split-plot type design with repeated measures. Whole plots corresponded to the herbicide treatment (herbicide treated and control) and were laid out in three complete blocks (exclosures). The split-plot treatment levels corresponded to the two-way structure defined by the canopy (under and inter) and defoliation treatment (hereafter clipped and unclipped) and were replicated within each whole plot. Week, from 25 June 2006 to 18 July 2008 (1–104) was the repeated factor. All interactions for herbicide, canopy, clipping, and week were included in the fixed effects. Additionally, block and block by week were included in the fixed effects.

Maximum and minimum daily soil temperature weekly averages were analyzed as a randomized complete block design with repeated measures. Soil temperature measurements started on 1 July 2006 and ended on 18 July 2008. Model factors included block (i.e., exclosures), a three-level treatment variable (herbicide-treated undercanopy, control undercanopy, and intercanopy), and week. Both block-by-week and treatment-by-week interactions were included in the fixed effects.

Statistical analyses were developed to accommodate soil moisture data that were unbalanced relative to sample number by depth due to the caliche layer. At some undercanopy sites, soil moisture probes were installed at 0–25 cm (top), 25–50 cm (middle), and bottom (50–75 cm) soil depths. For each hour and probe site, top-middle (0–25 vs. 25–50 cm), top-bottom (0–25 vs. 50–75 cm), and middle-bottom (25–50 vs. 50–75 cm) soil moisture differences were computed, and weekly difference averages were obtained. This method ensured that only complete pairs were used, allowed using simpler models, and accommodated un-

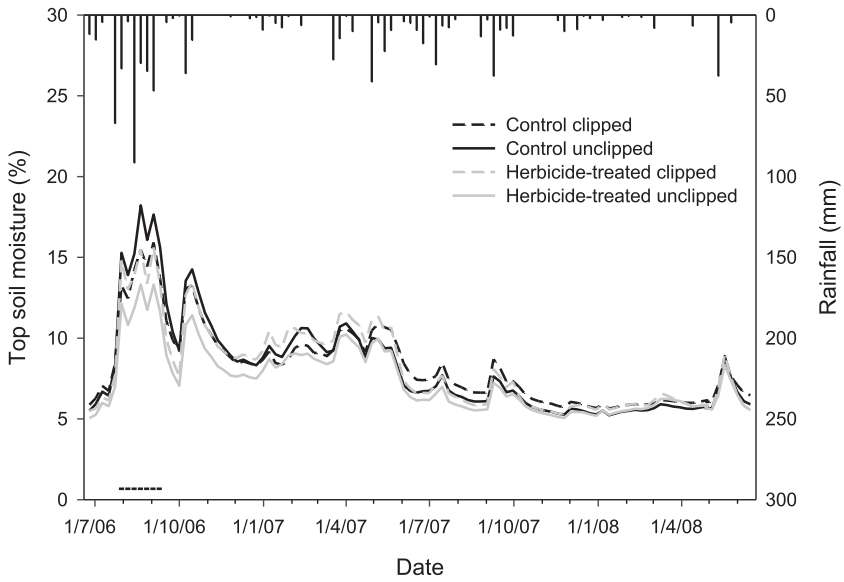


Fig. 2. Topsoil moisture (land surface model). Minus symbol along the X-axis represents statistical significance.

balance present in the soil moisture data due to the caliche layer. Differences were analyzed using a mixed model with fixed effects for herbicide treatment, clipping, week, and all their interactions. Due to using differences and because blocks were incomplete, blocking was accounted for with a random block by week effect.

For all models, serial correlation was accounted for using a repeated statement that specified week as the repeated factor, the plot or probe as the subject, and an AR (1) correlation structure. To further explore significant interactions involving treatment factors and week, simple effects were assessed by slicing on week. Follow-up comparisons corresponding to significant slices included pairwise comparisons and comparisons of soil moisture depth difference estimates to 0. SAS PROC MIXED (version 9.1.3) software was used to analyze all response variables (SAS Institute 2004). Least square means, standard error means (SEM), and two-tailed P values are reported with a significance of $P \leq 0.05$.

Results

Rainfall

Rainfall patterns were similar among the exclosures. The average weekly total rainfall was 8.09 mm (CD), 7.97 mm (FG), and 7.93 mm (KI) sites during the study. Exclosures experienced relatively high rainfall in wk 8 (13–19 August 2006) with a maximum rainfall of 113.8 mm at the FG exclosure, 79.24 mm at the CD exclosure, and 81.53 mm at the KI exclosure.

Topsoil moisture

For topsoil (0–25 cm) moisture content, there were differences among the treatment combinations during wk 6–12 (30 July to 10 September 2006). During this 7-wk period, rainfall was relatively high. The herbicide-treated unclipped plots tended to have the lowest Θ, while the control unclipped plots tended to have the highest top Θ (Fig. 2). On the other hand, there were inconclusive but suggestive of possible differences in intercanopy and undercanopy plots with top Θ patterns ($P = 0.0667$). Contrary to undercanopy (Fig. 3A), intercanopy estimates for control clipped and herbicide-treated unclipped were numerically similar throughout the study even during wk 7–11 (6 August to 9 September 2006; see Fig. 3B).

Top-middle soil moisture

For top-middle (0–25 vs. 25–50 cm) soil moisture content, there were significant differences among the four herbicide–clipping treatment combinations in wk 8–15 (13 August to 1 October 2006) and 17–21 (15 October to 12 November 2006) (Fig. 4). Averaged across weeks ($P < 0.0001$), estimated top-middle Θ differences were 1.88 (SEM 1.30%), −2.88 (SEM 1.46%), −0.22 (SEM 1.46%), and −0.42 (SEM 1.30%) for control clipped, control unclipped, herbicide-treated clipped, and herbicide-treated unclipped, respectively.

Top-bottom soil moisture

For top-bottom (0–25 vs. 50–75 cm) soil moisture content, there were significant differences. The control unclipped plots, in wk 9–20 (20 August to 5 November 2006), the bottom Θ was higher than the top Θ with the top-bottom difference ranging from −11.15 to −16.02 SEM 4.10%. For control clipped plots, in wk 9 and 11 (20 August and 3 September 2006) top Θ was higher than the bottom Θ (9.05 and 9.17 SEM 4.10%, respectively) (Fig. 5). Averaged top-bottom Θ differences were 3.77 (SEM 3.19%), −7.38 (SEM 3.19 %), −1.87 (SEM 3.91 %), and −0.63 (SEM 3.19 %) for control clipped, control unclipped, herbicide-treated clipped, and herbicide-treated unclipped, respectively.

Middle-bottom soil moisture

For middle-bottom (25–50 vs. 50–75 cm) soil moisture content, there were significant differences between the herbicide treatments in wk 12–15 (10 September to 1 October 2006) and control plots had higher bottom Θ than middle Θ with estimated middle-bottom differences ranging from −5.14 to −5.38 SEM 1.38 (Fig. 6). Averaged across weeks ($P = 0.0182$), estimated middle-bottom Θ differences were −0.27 (SEM 1.14%), −5.05 (SEM 1.14%), −1.78 (SEM 1.40%), and −0.03 (SEM 1.14%) for control clipped, control unclipped, herbicide-treated clipped, and herbicide-treated unclipped, respectively. Overall, for control unclipped, bottom soil moisture was higher than middle soil moisture.

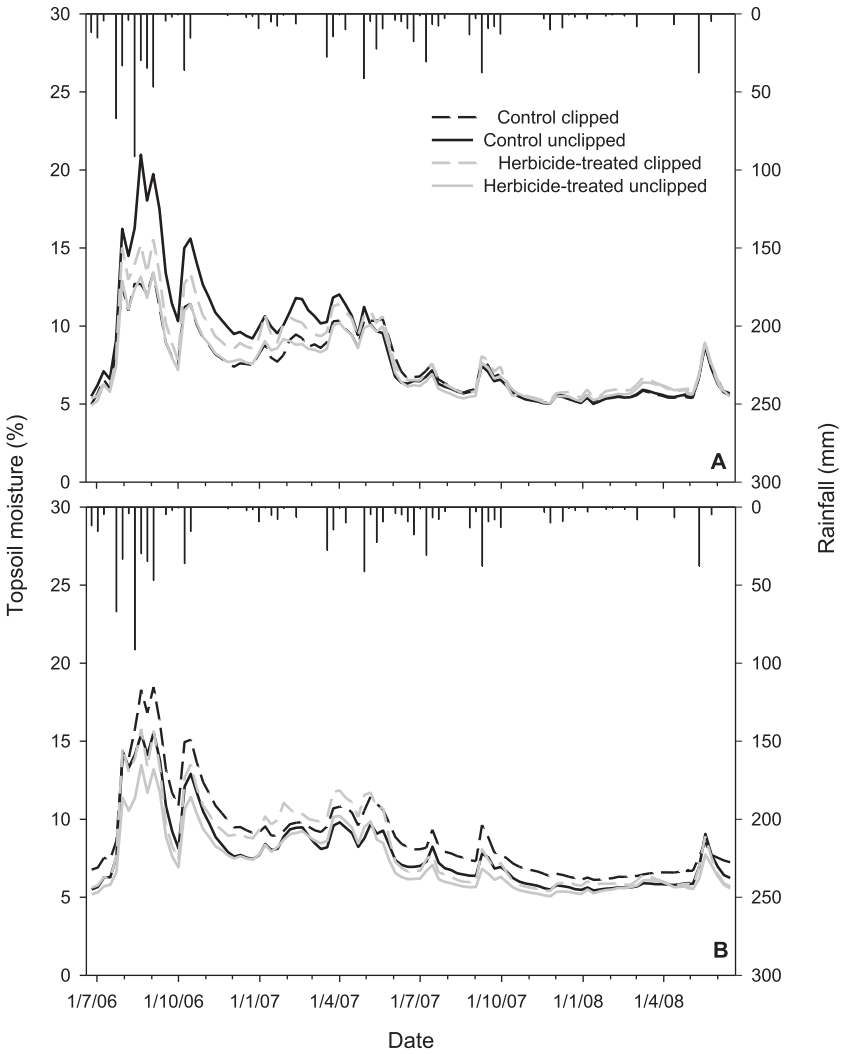


Fig. 3. Topsoil moisture (land surface model) at **A,** intercanopy and **B,** undercanopy plots.

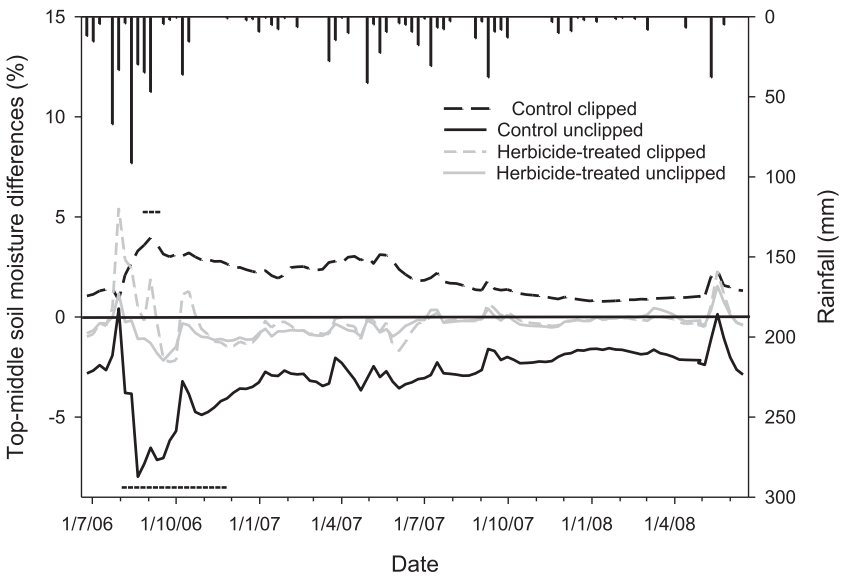


Fig. 4. Top-middle soil moisture differences (land surface model). Minus symbol along the X-axis represents statistical significance.

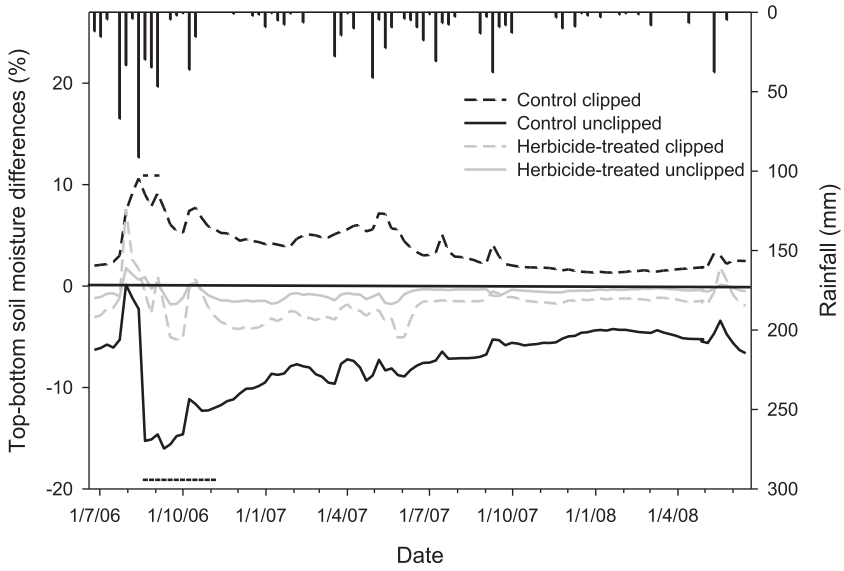


Fig. 5. Top-bottom soil moisture differences (land surface model). Minus symbol along the X-axis represents statistical significance.

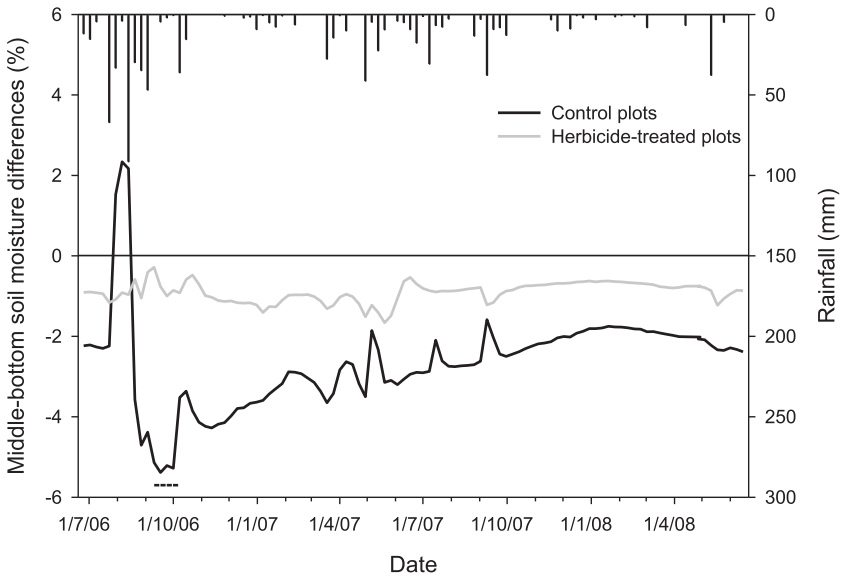


Fig. 6. Middle-bottom soil moisture differences (land surface model). Minus symbol along the X-axis represents statistical significance.

Soil temperature

For maximum soil temperature, averaged across weeks ($P = 0.0297$), the mean daily maximum soil temperature was higher for intercanopy (17.19, SEM 0.37°C) than control undercanopy plots (14.90, SEM 0.37°C, Fig. 7A). The mean daily maximum soil temperature for herbicide undercanopy plots (16.13, SEM 0.37°C) was intermediate and did not differ significantly from either the intercanopy mean or the control undercanopy plots. Differences among herbicide and control (undercanopy) and intercanopy plots varied from week to week ($P = 0.0050$) and were significant in wk 2–7, 9–19, 33, 35–71, and 86–104 (2 July to 12 August 2006, 20 August to 28 October 2006, 4–10 February 2007, 18 February to 3 September 2007, and 10 February to 21 June 2008, respectively; see Fig. 7A). During these weeks, intercanopy plots had the highest soil temperature and control plots had the lowest soil temperature.

Minimum daily soil temperature did not differ among herbicide treatments, and there was no evidence of a significant herbicide treatment by week interaction, either ($P > 0.05$, see Fig. 7B). Minimum daily temperature estimates were similar for intercanopy (12.85 SEM 0.23°C) and herbicide undercanopy plots (12.70 SEM 0.23°C), but untreated undercanopy plots were estimated to have a minimum daily temperature of 11.90 (SEM 0.23°C).

Discussion

The effect of treatment level (i.e., herbicide-treated and control plots) and defoliation level (clipped vs. unclipped plots) on top Θ (0–25 cm depth) during the study period (2006–2008) was evident during 7 wk of 2006. The herbicide-treated plots lacked canopy cover that protects the soil surface from solar radiation. This condition might have resulted in lower top Θ compared with control plots. Similar to our results, Lin et al. (1992) reported that in open spaces within a pinyon-juniper woodland, soil moisture tended to be lower, likely by evaporation, particularly during the summer when temperatures are high. In contrast, although differ-

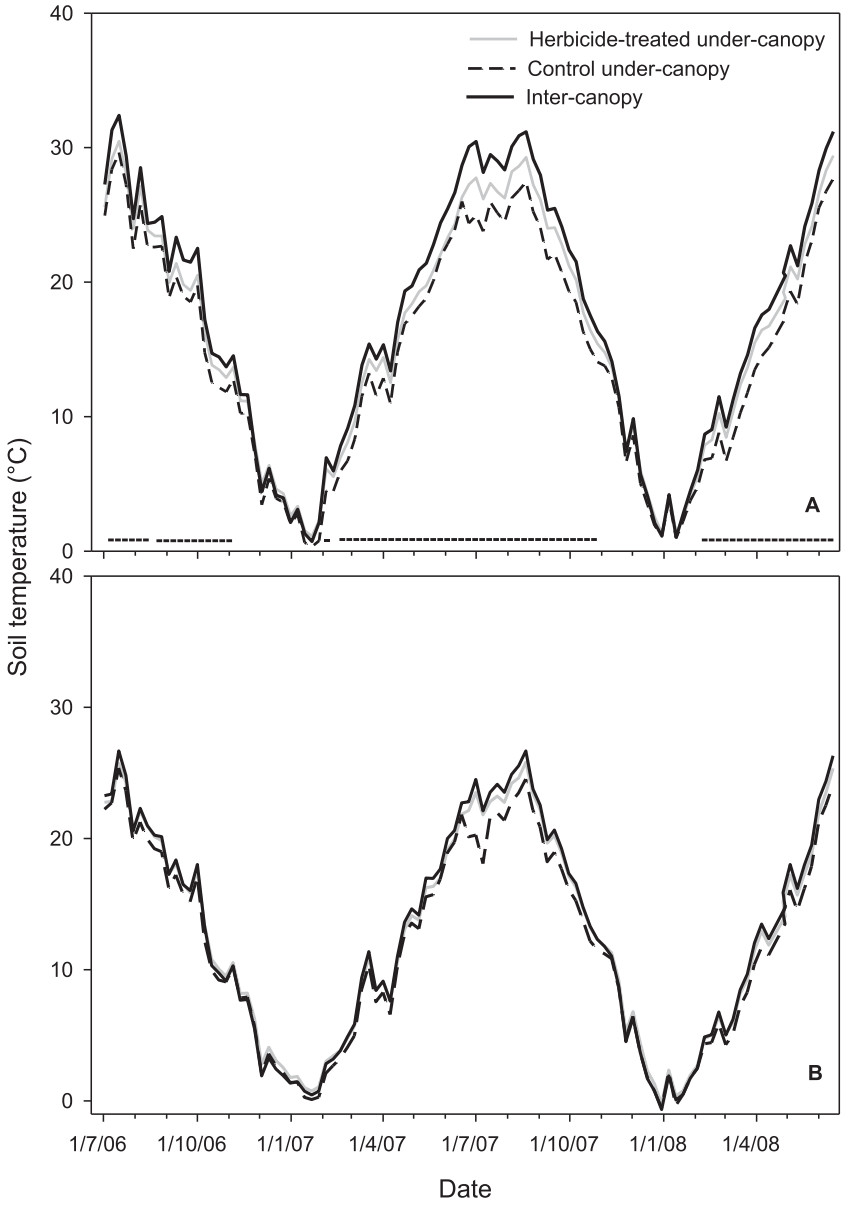


Fig. 7. A, Maximum and **B,** minimum soil temperature (land surface model). Minus symbol along the X-axis represents statistical significance.

ent in scale, Ray et al. (2019) reported higher top Θ (12 cm) in the treated watershed (1–3%) versus control watershed.

On the other hand, the control unclipped plots had higher top Θ on 20–26 August 2006. Overstory dictates predictable solar radiation and soil moisture by creating microclimate zones (Breshears et al. 1997b). Although soil temperature did not differ statistically between undercanopy herbicide-treated versus control plots, over the study period the daily maximum temperature average was 1.23°C lower in the control plots. Canopy cover contributed to cooler temperatures that aimed to sustain greater soil moisture over the 1-wk period. According to our results, Breshears et al. (2009) reported higher plant available water at 20 cm depth in undercanopy patches during the rainy months in Northern New Mexico piñon-juniper woodland.

Study results showed different undercanopy soil moisture responses at different depths to treatment (herbicide and control) and defoliation mainly influenced by rainfall from June (last wk) to October (second wk) 2006 with a total of 399 mm. For top-middle Θ (0–25 vs. 25–50 cm), the control clipped plots (27 August to 10 September 2006) had higher top than the middle Θ depth. After this period, top Θ decreased, likely as a response to understory vegetation growth. The clipping treatment was carried out in March 2006. The understory biomass was mainly composed of perennial grasses (spp.), herbaceous, and *B. gracilis* (Garduño et al. 2010). Perennial grasses flower by July or August depending on rainfall (Stubbendieck et al. 1997) and are able to deplete soil moisture within the root zone (Culman et al. 2013) or even from the 15-cm depth in ambient conditions or up to 55-cm depth during drought or warm periods (Grossiord et al. 2018).

On the other hand, the middle was higher than top Θ in control unclipped plots from 6 August to 26 November 2006 (17-wk period). Juniper species such as western juniper *(Juniperus occidentalis)* and one-seed juniper (*J. monosperma*) compete for water resource with understory vegetation above the 60-cm depth (Leffler et al. 2002; Mollnau et al. 2014; Grossiord et al. 2016; Grossiord et al. 2018). However, one-seed juniper did not influence soil moisture at the middle depth due to soil water extraction from inter-canopy plots due to the extensive lateral roots (Breshears et al. 1997a). The 17-wk period was marked by a total of 268 mm that kept soil moisture high in the middle compared with the top layer

at the undercanopy unclipped control plots. During this same period, the soil moisture in undercanopy clipped control plots tended to be higher at the top likely by the lower biomass recorded. According to our results, Niemeyer et al. (2017) reported higher soil moisture at the undercanopy (western juniper trees) at 60-cm compared with 15-cm depth. It is likely that animal burrows or "macropores" might influence middle Θ since burrows were only observed under control plots. Votrubova et al (2017) reported high infiltration rates in a forest attributed to animal burrows that served as macropore flow.

For top-bottom (0–25 vs. 50–75 cm) soil moisture, untreated clipped plots had higher top Θ than bottom Θ. The difference in soil moisture was similar to top-middle, although this difference lasted a 2-wk period (20–26 August, and 3–9 September 2006). Before 20 August, it rained 228 mm in an 8-wk period (from 25 June to 19 August 2006). This period might have helped the growing stage of herbaceous and perennial grasses, which was reflected in a slow decline in top Θ. Although different in comparison (i.e., water uptake by grass vs. tree), Mazzacavallo and Kulmatiski (2015) reported that water uptake by grasses (i.e., warm-season grasses) occurred within the 30-cm depth. Furthermore, canopy cover might influence top Θ by intercepting solar radiation and creating cooler soil temperatures (average of 1.06°C cooler than herbicide-treated plots) during the 2-wk period.

On the other hand, untreated unclipped plots had higher bottom Θ than top Θ. The difference was over an 11-wk period (from 20 August to 5 November 2006). Before 20 August 2006, it rained 228 mm and 171 mm during the 11-wk period. Higher bottom Θ was likely due to the lack of water uptake by junipers. This might be explained by the fact that one-seed juniper has half of its root mass up to 32-cm depth and diminishes up to 13% of its total root mass below 80-cm depth (Schwinning et al. 2020). Consistent with our results but with different vegetation (i.e., mesquite woodland), soil moisture was greater at 70-cm depth versus shallow depth (Potts et al. 2010). Another condition that might result in the higher bottom Θ is the indurated petrocalcic layer ($CaCO_3$) found below 50-cm depth in 40% of experimental plots. The petrocalcic or caliche layer may restrict water movement (Stuart and Dixon 1973; Hennessy et al. 1983) and can store water that might be used for plants (Zwieniecki and Newton 1996). Although indurated caliche layer absorbs water, most of the absorbed water is slowly released (Hennessy et al. 1983). Similar to our results, the presence of caliche nodules increased soil water content at deep layers (30–40 cm) and held water that might be used for plants (Gong et al. 2019). Another cause of high bottom Θ is the macropore flow caused by animal burrows that aimed to infiltrate water deeper.

For middle-bottom Θ (25–50 vs. 50–75 cm), control plots had higher bottom Θ than middle Θ. The difference lasted a 4-wk period (from 10 September to 1 October 2006). In addition, control unclipped plots had higher bottom Θ than middle Θ. Some conditions might have resulted in high bottom Θ: 1) Junipers did not tap water at the deepest layer measured. Thus, one-seed juniper has a rooting depth average of 243 cm (Foxx and Tierney 1987). However, the presence of roots at deep layers does not necessarily mean root activity (Prieto et al. 2015), and root mass distribution and length do not correspond to resource uptake (Lehmann 2003; Jobbagy and Jackson 2004); 2) Caliche layer underlies at 50 cm depth and below. This layer stores soil moisture for longer periods and releases water slowly for plant growth; and 3) Animal burrows enhance infiltration via macropore flow.

Our results document clear trends in maximum daily soil temperature (Tm) in response to the canopy level (undercanopy and intercanopy). Intercanopy plots had higher Tm compared with undercanopy plots. As we expected, higher Tm was recorded on intercanopy plots due to the absence of canopy cover, and cooler Tm was recorded under control trees due to canopy interception influence. Consistent with our results, Royer et al. (2012) reported that undercanopy patches (e.g., live trees) had cooler Tm versus intercanopy patches due to canopy cover influence (i.e., canopy intercepts solar radiation). Maximum soil temperature differences were more pronounced, during the study period, from mid-February to late October likely from the short-wave variations depending on the earth-to-sun's closeness (Lal and Shukla 2004). According to our results, Breshears et al. (1997b) and Krämer and Green (2000) reported that soil temperature differed temporally (i.e., from February through October) mainly by spatial position in a pinyon-juniper woodland and a semiarid woodland.

Conclusions and Implications

Tree removal has been used to eliminate undesirable vegetation to free up water for native grasses and water percolation. We assessed the effect of infrequent heavy defoliation (targeted grazing) of chemically thinned juniper woodland on soil moisture and found no increase in soil moisture at any measured depth. Although macropore flow and water absorption on deep soil layers, underneath junipers, increase soil moisture with increasing depth, the stored water would be used by the junipers themselves. To reduce the risk of water loss via evapotranspiration and to increase the likelihood of water percolation, we argue for the tree removal to create buffers of native grasses to store soil moisture for longer periods.

Declaration of Competing Interest

None.

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References

Abdallah, M. A. B., Mata-González, R., Noller, J. S., and Ochoa, C. G. 2021. Effects of western juniper *(Juniperus occidentalis)* control on ecosystem nitrogen stocks in central Oregon, USA. *Journal of Plant Ecology*

Abdallah, M.A.B., Durfee, N., Mata-González, R., Ochoa, C.G., Noller, J.S., 2020. Water use and soil moisture relationships on western juniper trees at different growth stages. Water 12, 1596.

Ansley, R.J., Wiedemann, H.T., Castellano, M.J., Slosser, J.E, 2006. Herbaceous restoration of juniper dominated grasslands with chaining and fire. Rangeland Ecology & Management 59, 171–178.

Archer, S.R., Andersen, E.M., Predick, K.I., Schwinning, S., Steidl, R.J., Woods, S.R., 2017. Woody plant encroachment: causes and consequences. In: Briske, D.D (Ed.), Rangeland systems: processes, management and challenges. Springer International Publishing, Cham, Switzerland, pp. 25–84.

Aro, R.S., 1975. Pinyon-juniper woodland manipulation. In: Gifford, G.F., Busby, F.E. (Eds.), The pinyon-juniper ecosystem: a symposium. Utah State University, College of Natural Resources, Agricultural Experiment Station, Logan, UT, USA, pp. 67–75.

Bailey, D.W., Mosley, J.C., Estell, R.E., Cibils, A.F., Horney, M., Hendrickson, J.R., Burritt, E.A., 2019. Synthesis paper: targeted livestock grazing: prescription for healthy rangelands. Rangeland Ecology & Management 72, 865–877.

Barger, N.N., Archer, S.R., Campbell, J.L., Huang, C.Y., Morton, J.A., Knapp, A.K., 2011. Woody plant proliferation in North American drylands: a synthesis of impacts on ecosystem carbon balance. Journal of Geophysical Research 116.

Bates, J.D., 2005. Herbaceous response to cattle grazing following juniper cutting in Oregon. Rangeland Ecology & Management 58, 225–233.

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

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*. Journal of Ecology 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. Ecological Applications 7, 1201–1215.
Breshears, D.D., Nyhan, J.W., Heil, C.E., 1998. Effects of woody plants on microclimate in a semiarid woodland: soil temperature and evaporation in canopy and inter-canopy patches. International Journal of Plant Science 159, 1010–1017.
Breshears, D.D., McDowell, N.G., Goddard, K.L., 2008. Foliar absorption of intercepted rainfall improves woody plant water status most during drought. Ecology 89, 41–47.
Culman, S. W., Snapp, S. S., Ollenburger, M., Basso, B., and DeHaan, L. R. 2013. Soil and water quality rapidly responds to the perennial grain kernza wheatgrass. *Agronomy, Soils and Environmental Quality*105:735–744.
Diamond, J.M., Call, C., Devoe, N., 2009. Effects of targeted cattle grazing on fire behavior of cheatgrass-dominated rangeland in the northern Great Basin, USA. International Journal of Wildland Fire 18, 944–950.
Dwyer, D.D., 1975. Response of livestock forage to manipulation of the pinyon-juniper ecosystem. In: Gifford, G.F., Busby, F.E. (Eds.), Proceedings: pinyon and juniper ecosystem. Utah State University, College of Natural Resources, Agricultural Experiment Station, Logan, UT, USA, pp. 97–102.
Environmental Protection Agency. 1994. R.E.D. Facts. EPA-738-F-94-006.
Estell, R. E., Cibils, A. F., Utsumi, S. A., Stricklan, D., Butler, E., Fish, A., and Ganguli, A. 2018. Controlling one-seed juniper saplings with small ruminants: what we have learned. *Rangelands*40:129–135.
Evans, R.A., 1975. The role of herbicides in management of pinyon-juniper woodlands. In: Gifford, G.F., Busby, F.E. (Eds.), Proceedings: pinyon and juniper ecosystem. Utah State University, College of Natural Resources, Agricultural Experiment Station, Logan, UT, USA, pp. 83–89.
Foxx, T.S., Tierney, G.D., 1987. Rooting patterns in the pinyon–juniper woodland. In: Everett, R.L. (Ed.), Proceedings: pinyon–juniper conference. US Department of Agriculture, Forest Service, Intermountain Research Station, Reno, Nevada, USA, pp. 69–79.
Garduño, H.R., Fernald, A.G., Cibils, A.F., VanLeeuwen, D.M., 2010. Response of understory vegetation and soil moisture to infrequent heavy defoliation of chemically thinned juniper woodland. Journal of Arid Environments 74, 291–297.
Gerardi, L.A., Sala, O.E., 2015. Enhanced precipitation variability decreases grass-and decreases shrub-productivity. PNAS 112, 12735–12740.
Goehring, B.J., Launchbaugh, K.L., Wilson, L.M., 2010. Late-season targeted grazing of yellow starthistle *(Centaurea solstitialis)* with goats in Idaho. Invasive Plant Science and Management 3, 148–154.
Goodman, L.E., Cibils, A.F., Lopez, S.C., Steiner, R.L., Graham, J.D., McDaniel, K.C., Abbott, L.B., Stegelmeyer, B.L., Hallford, D.M., 2014. Targeted grazing of white locoweed: short term effects of herbivory regime on vegetation and sheep. Rangeland Ecology & Management 67, 680–692.
Gong, T., Zhu, Y., Wang, Y., Hu, W., and Shao, M. 2019. Effect of caliche nodules on soil water storage in the northern Loess Plateau of China. *Clean–Soil, Air, Water* doi:10.1002/clen.201800385.
Grossiord, C., Sevanto, S., Dawson, T.E., Adams, H.D., Collins, A.D., Dickman, L.T., Newman, B.D., Stockton, E.A., McDowell, N.G., 2016. Warming combined with more extreme precipitation regimes modifies the water sources used by trees. New Phytology 213, 584–596.
Grossiord, C., Sevanto, S., Bonal, D., Borrego, I., Dawson, T.E., Ryan, M., Wang, W., McDowell, N.G., 2018. Prolonged warming and drought modify belowground interactions for water among coexisting plants. Tree Physiology 39, 55–63.
Hennessy, J.T., Gibbens, R.P., Tromble, J.M., Cardenas, M., 1983. Water properties of caliche. Rangeland Ecology & Management 36, 723–726.
Jobbagy, E.G., Jackson, R.B, 2004. The uplift of soil nutrients by plants: Biogeochemical consequences across scales. Ecology 85, 2380–2389.
Koukoura, Z., Kyriazopoulos, A., 2007. Adaptation of herbaceous plant species in the understorey of *Pinus brutia*. Agroforestry Systems 70, 11–16.
Krämer, S., Green, D.M., 2000. Acid and alkaline phosphatase dynamics and their relationships to soil microclimate in a semiarid woodland. Soil Biology and Biochemistry 32, 179–188.
Lal, R., Shukla, M.K., 2004. Principles of soil physics. Marcel Dekker Inc, New York, NY, USA, p. 716.
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 Physiology 22, 1221–1230.
Lehmann, J., 2003. Subsoil root activity in tree-based cropping systems. Plant and Soil 255, 319–331.
Lin, T., Rich, P.M., Heisler, D.A., Barnes, F.J., 1992. Influences of canopy geometry on near-ground solar radiation and water balances of pinyon-juniper and ponderosa pine woodlands. Annual meeting of American Society for Photogrammetry and Remote Sensing; … 1992 285–294 Albuquerque, NM, USA.
MacDonald, S.E., Fenniak, T.E., 2007. Understory plant communities of boreal mixed wood forests in western Canada: natural patterns and response to variable-retention harvesting. Forest Ecology and Management 242, 34–48.
Mata-González, R., Abdallah, M.A.B., Ochoa, C.G., 2021. Water use by mature and sapling western juniper *(Juniperus occidentalis)* trees. Rangeland Ecology & Management 74, 110–113.
Mazzacavallo, M.G., Kulmatiski, A., 2015. Modelling water uptake provides a new perspective on grass and tree coexistence. PLoS ONE 10 (12), e0144300.
Miller, R.F., Tausch, R.J., McArthur, E.D., 2008. Age structure and expansion of piñon-juniper woodlands: a regional perspective in the Intermountain West. US Department of Agriculture, Forest Service, Rocky Mountain Research Station, Fort Collins, CO, USA, p. 15 Res. Pap. RMRS-RP-69.
Miller, R.F., Chambers, J.C., Evers, L., Williams, C., Snyder, J., Keirith, A., Roundy, B.A., Pierson, F.B, 2019. The ecology, history, ecohydrology, and management of pinyon and juniper woodlands in the Great Basin and Northern Colorado Plateau of the western United States. US Department of Agriculture, Forest Service, Rocky Mountain Research Station, Fort Collins, CO, USA, p. 284 Gen. Tech. Rep. RMRS-GTR-403.
Mollnau, C., Newton, M., Stringham, T., 2014. Soil water dynamics and water use in a western juniper *(Juniperus occidentalis)* woodland. Journal of Arid Environment 102, 117–126.
New Mexico Climate Center, 2020. New Mexico weather Available at:.
Niemeyer, R.J., Heinse, R., Link, T.E., Seyfried, M.S., Klos, P.Z., Williams, C.J., Nielson, T., 2017. Spatiotemporal soil and saprolite moisture dynamics across a semi-arid woody plant gradient. Journal of Hydrology 544, 21–35.
OĆonnor, R.C., Taylor, J.H., Nippert, J.B., 2020. Browsing and fire decreases dominance of a resprouting shrub in woody encroach grassland. Ecology 101, 1–11.
Owens, M.K., Lyons, R.K., Alejandro, C.L, 2006. Rainfall partitioning within semiarid juniper communities: effects of event size and canopy cover. Hydrological Processes 20, 3179–3189.
Pacala, S. W., Hurtt, G. C., Baker, D., Peylin, P., Houghton, R. A., Birdsey, R. A., Heath, L., Sundquist, E. T., Stallard, R. F., Ciais, P., Moorcroft, P., Caspersen, J. P., Shevliakova, E., Moore, B., Kohlmaier, G., Holland, E., Gloor, M., Harmon, M. E., Fan, S. M., Sarmiento, J. L., Goodale, C. L., Schimel, D., and Field, C. B. 2001. Consistent land- and atmosphere-based U.S. carbon sink estimates. *Science*22:2316–20.
Pelaez, D.V., Distel, R.A., Bóo, R.M., Elia, O.R., Mayor, M.D., 1994. Water relations between shrubs and grasses in semi-arid Argentina. Journal of Arid Environments 27, 71–78.
Petersen, S.L., Stringham, T.K., 2008. Infiltration, runoff, and sediment yield in response to Western juniper encroachment in Southeast Oregon. Rangeland Ecology & Management 61, 74–81.
Pieper, R., 1990. Overstory-understory relations in pinyon-juniper woodlands in New Mexico. Journal of Range Management 4, 413–415.
Potts, D.L., Scott, R.L., Bayram, S., Carbonara, J., 2010. Woody plants modulate the temporal dynamics of soil moisture in a semi-arid mesquite savanna. Ecohydrology: Ecosystems, Land and Water Process Interactions, Ecohydrogeomorphology 3, 20–27.
Prieto, I., Roumet, C., Cardinael, R., Dupraz, C., Jourdan, C., Kim, J.H., Maeght, J.L., Mao, Z., Pierret, A., Portillo, N., Roupsard, O., Thammahacksa, C., Stokes, A., 2015. Root functional parameters along a land-use gradient: evidence of a community-level economics spectrum. Journal of Ecology 103, 361–373.
Ray, G., Ochoa, C.G., Deboodt, T., Mata-Gonzalez, R., 2019. Overstory–understory vegetation cover and soil water content observations in western juniper woodlands: a paired watershed study in Central Oregon, USA. Forests 10 (2), 151.
Roundy, B.A., Young, K., Cline, N., 2014a. Piñon-juniper reduction increases soil water availability of the resource growth pool. Rangeland Ecology & Management 67, 495–505.
Roundy, B.A., Miller, R.F., Tausch, R.J., 2014b. Understory cover responses to piñon–juniper treatments across tree dominance gradients in the Great Basin. Rangeland Ecology & Management 67, 482–494.
Royer, P.D., Breshears, D.D., Zou, C.B., Villegas, J.C., Cobb, N.S., Kurc, S.A., 2012. Density-dependent ecohydrological effects of piñon–juniper woody canopy cover on soil microclimate and potential soil evaporation. Rangeland Ecology & Management 65, 11–20.
Institute, SAS, 2004. SAS/STAT9.1 user's guide. Version 9.1.3. Cary. SAS Institute, Inc, NC, USA.
Schwinning, S., Litvak, M.E., Pockman, W.T., Pangle, R.E., Fox, A.M., Huang, C.W., McIntire, C.D., 2020. A 3-dimensional model of *Pinus edulis* and *Juniperus monosperma* root distributions in New Mexico: implications for soil water dynamics. Plant and Soil 450, 337–355.
Stuart, D.M., Dixon, R.M., 1973. Water movement and caliche formation in layered arid and semiarid soils. Soil Science Society of America Journal 37, 323–324.
Stubbendieck, J., Hatch, S.L., Butterfield, C.H., 1997. North American range plants, 5th ed.. University of Nebraska Press, Lincoln, NE, USA, p. 501.
Terrel, T.L., Spillett, J.J., 1975. Pinyon-juniper conversion: its impact on mule deer and others wildlife. In: Gifford, G.F., Busby, F.E. (Eds.), Proceedings—pinyon and juniper ecosystem. Utah State University, College of Natural Resources, Agricultural Experiment Station, Logan, UT, USA, pp. 105–119.
Utsumi, S.A., Cibils, A.F., Estell, R.E., Baker, T.T., Walker, J.H., 2010. One-seed juniper sapling use by goats in relation to stocking density and mixed grazing with sheep. Rangeland Ecology & Management 63, 373–386.
Votrubova, J., Dohnal, M., Vogel, T., Tesar, M., Jelinkova, V., Cislerova, M., 2017. Ponded infiltration in a grid of permanent single-ring infiltrometers: spatial versus temporal variability. Journal of Hydrology and Hydromechanics 65, 244–253.
Wood, M.K., Javed, N., 2001. Hydrologic and vegetal responses to fuelwood harvest and slash disposal in a pinyon pine and juniper dominated grassland. New Mexico Water Resources Research Institute, Las Cruces, NM, USA Miscellaneous Report M27.
Young, J.A., Evans, R.A., 1976. Control of pinyon saplings with picloram or karbutilate. Journal of Range Management 29, 144–147.
Zou, C.B., Turton, D.J., Will, R.E., Engle, D.M., Fuhlendorf, S.D., 2014. Alteration of hydrological processes and streamflow with juniper *(Juniperus virginiana)* encroachment in a mesic grassland catchment. Hydrological Processes 28, 6173–6182.
Zwieniecki, M.A., Newton, M, 1996. Water-holding characteristics of metasedimentary rock in selected forest ecosystems in southwestern Oregon. Soil Science Society of America Journal 60, 578.