Effects of eastern redcedar encroachment on soil hydraulic properties in Oklahoma's grassland-forest ecotone

Michael L. Wine[a,*], Apurba Sutradhar[b], Rachael Pepin[c]

[a]Department of Natural Resource Ecology and Management, Oklahoma State University, Stillwater, OK 74078, United States

[b]Department of Plant and Soil Sciences, Oklahoma State University, Stillwater, OK 74078, United States

[c]Department of Horticulture and Landscape Architecture, Oklahoma State University, Stillwater, OK 74078, United States

* Corresponding Author. Tel: +1 405 762 3923; *E-mail address:* mwine@okstate.edu (M.L. Wine).

SUMMARY:

The effects of eastern redcedar (*Juniperus virginiana*) encroachment into grassland on soil hydraulic properties have not been determined. This creates uncertainty in understanding the hydrologic effects of eastern redcedar encroachment and obstructs fact-based management of encroached systems. The objective of this study was to quantify the effects of eastern redcedar encroachment into tallgrass prairie on soil hydraulic properties. Soil water content, soil organic carbon, soil water repellency, sorptivity, and unsaturated hydraulic conductivity were measured along 12 radial transects from eastern redcedar trunks to the center of the grassy intercanopy space. Bulk density and soil water retention were also measured under eastern redcedar and in the tall grass prairie intercanopy area. Soil organic matter in the upper six cm of soil was 49% higher under eastern redcedar trees (5.96 mg kg^{-1}) than in the grass-dominated intercanopy area (3.99 mg kg^{-1}). Median sorptivity under grass was .68 mm $s^{-1/2}$, seven times greater than under eastern redcedar canopies (.10 mm $s^{-1/2}$). Median unsaturated hydraulic conductivity under grass was 2.52 cm h^{-1}, four times greater than under eastern redcedar canopies (.57 cm h^{-1}). Porosity was higher under eastern redcedar trees as was soil water retention, both at the dry and wet ends of the retention curve. These results indicate that when managing eastern redcedar encroachment it is critical to consider the soil hydraulic properties of eastern redcedar and tallgrass prairie, both in understanding the mechanisms and hydrologic consequences of encroachment.

Keywords: Hydrophobicity, Water retention, Carbon, Moisture content, Prairie, Rangeland hydrology

Introduction

Eastern redcedar encroachment has been extensively documented in the Southern Plains of the U.S. (Coppedge et al., 2001) though the exact extent of eastern redcedar encroachment remains elusive. Many landowners consider widespread encroachment to be a problem and have undertaken to control eastern redcedar (Clenton et al., 1973; Engle et al., 1996; Engle and Kulbeth, 1992; Morton et al., 2010). Furthermore, climate change may favor encroachment of eastern redcedar into C_4 grassland (Volder et al., 2010). Understanding the effects of eastern redcedar encroachment on soil hydraulic properties is critical to managing present and future encroachment. Whereas the effects of Utah juniper (*Juniperus osteosperma*) on soil hydraulic properties have been extensively investigated in Utah (Lebron et al., 2007; Madsen et al., 2008; Pierson et al., 2010; Robinson et al., 2010), little is known about eastern redcedar effects on soil hydraulic properties. Although these effects of eastern redcedar encroachment are key determinants of the spatiotemporal fate of throughfall, they are not generally considered by land management agencies or ranchers with regard to eastern redcedar removal.

Eastern redcedars' thick leaf litter layer distinguishes the soil under an eastern redcedar tree from that under grass (Van Els et al., 2010); in other species in the Juniperus genus leaf litter depth has been correlated with the hydrologic effects of the tree. For example, Madsen et al. (2008) found that under Utah juniper litter, soil water content was inversely related to litter depth. When soils with high organic matter content dry down they can become water repellent or hydrophobic (Jaramillo et al., 2000). At a small scale, dry, hydrophobic soils induce higher rates of runoff (Doerr et al., 2000). At a larger scale, runoff from well-vegetated hydrophobic soils often concentrates over more hydrophilic soils or macropores resulting in deep infiltration via preferential flow. This effectively sequesters moisture for plant growth that might have been lost to evaporation had rainfall infiltrated uniformly and shallowly (Jaramillo et al., 2000; Robinson et al., 2010). As a result, in areas of hydrophobic soils, infiltration of rainfall is non-uniform and is associated with unstable wetting fronts (Hendrickx et al., 1993), fingered flow (Ritsema and Dekker, 1994; Ritsema et al., 1997), or preferential flow (Dekker and Ritsema, 1996). Research at Konza Prairie in Kansas uncovered rapid accretion of soil carbon when eastern redcedar encroached into grassland (McKinley and Blair, 2008), indicating that this species could potentially cause soils to become hydrophobic when they are dry. Since hydrophobicity is enhanced when soil water content is low it is not readily observed by conventional, ponded infiltrometers, such as double-ring infiltrometers, which are commonly used to characterize the infiltration rate or soil hydraulic conductivity of soils in water-limited regions (e.g., Blackburn and Skau, 1974; Wilcox et al., 2003). Understanding the capacity of soil to absorb and conduct water in unsaturated conditions may be more relevant for soils exhibiting hydrophobicity.

The high soil organic matter observed under eastern redcedar (McKinley and Blair, 2008), could increase soil water retention at high suctions because at such suctions soil water retention is sensitive to clay content and soil organic matter (Gupta and Larson, 1979).

In this paper we assess how eastern redcedar encroachment into grassland modifies soil hydraulic properties. This study's specific objectives are to: (1) quantify soil hydraulic properties under eastern redcedar versus in big bluestem (*Andropogon gerardii*) dominated inter-canopy area and (2) examine how the soil hydraulic properties vary along transects from the tree trunk to the center of the inter-canopy space.

Materials and Methods

Experimental Site

The experimental site is located 11 kilometers southwest of Stillwater, Oklahoma (36°03’N, 97°12W, elev. 331 m). The geology underlying the study site is early Permian shale and sandstone (Stoeser, 2005). Moderately deep soils of the Grainola-Lucien and Stephenville-Darnell complexes dominate the study site (Soil Conservation Service, 1987). Grainola soils are fine, mixed, active, thermic Udertic Haplustalfs; Lucien are loamy, mixed, superactive, thermic, shallow Udic Haplustolls; Stephenville are fine-loamy, siliceous, active, thermic Ultic Haplustalfs; and Darnell are loamy siliceous, active, thermic, shallow Udic Haplustepts. The site is grazed continuously at a rate of one cow-calf pair per 13 ha. (This underestimates the grazing rate because much of the site is encroached.) The climate is continental and annual precipitation averages 831 mm (Engle et al., 2006). The vegetation structure at the site consists of eastern redcedar trees interspersed among tallgrass prairie species. These species colonized the site after cotton cultivation was abandoned at least five decades ago.

Experimental Design

The experimental design followed Madsen et al. (2008). The intensive field component of the study was conducted from 20-24 September, 2010. Within a two-hectare area twelve eastern redcedar trees were chosen in undisturbed locations. The average canopy radius was 3.4 m (±.6 m, Fig. 1). Prior to the study, surface soils had dried down following 1.6 cm of rainfall on September 12th. For each tree we measured soil hydraulic parameters every 61 cm starting 30 cm from the base of each tree and extending into the center of the inter-canopy area. Trees and transect orientations were chosen to equally represent all cardinal directions. The transect length beyond the canopy averaged 3.4 m (±.4). This study design provided 140 individual sampling locations.

Measurements

At each sampling location along each transect soil sorptivity, unsaturated hydraulic conductivity, volumetric water content, leaf litter depth, and water drop penetration time were measured. Aside from leaf litter depth, all other measurements were made after removal of leaf litter and vegetation from the soil surface. To determine soil organic matter, two samples were composited from under each tree and two from the adjacent intercanopy from the upper 6 cm of soil. These were dried, ground, and processed by the Oklahoma State University Soil, Water, and Forage Analytical Lab using a TruSpec® (LECO Corp., St. Joseph, Michigan). Total carbon was then multiplied by a scaling factor (1.724) to convert it to organic carbon. Volumetric water content of the upper 6 cm of soil was measured using an ML2x Theta Probe (Delta-T Devices, Cambridge, England). Voltage from the Theta Probe was converted to permittivity and then to volumetric water content following the relationship described by Blonquist et al. (2005).

Infiltration was measured in the field using 15.9 cm^2 Mini Disk tension infiltrometers (Decagon Devices, Pullman, WA) at 1.0 cm of suction. Soil texture of the upper six cm of soil was determined by the hydrometer method and class average van Genuchten parameters (Carsel and Parrish, 1988) were used in calculating A_1 and A_2, dimensionless coefficients related to sorptivity and hydraulic conductivity, respectively. Parameters related to sorptivity (C_1) and hydraulic conductivity (C_2) were calculated by fitting a second order polynomial equation to the cumulative infiltration plotted against the square root of time (Zhang, 1997). Sorptivity and hydraulic conductivity were then calculated as the quotient of the regression-fit parameters divided by the dimensionless coefficients. Surface soil hydrophobicity was measured by assessing whether a water droplet beaded on the surface or infiltrated after five seconds (Krammes and Debano, 1965).

Under one eastern redcedar tree and within a nearby grassy interspace we also obtained both intact and disturbed soil samples to measure soil water retention and bulk density. Intact soil samples were obtained by driving a 5 cm diameter, 5.1 cm deep cylinder into the ground; disturbed samples were obtained adjacent to the intact soil samples and from the same depth. For low levels of suction (≤45 kPa), soil water retention was measured using four intact samples from under one tree and seven intact samples from a nearby grassy intercanopy area using Tempe cells (Soil Moisture Equipment Corp., Santa Barbara, CA). These intact samples were used to measure bulk density. Porosity was estimated assuming a particle density of 2.65 g cm^{-3}. At higher suctions soil water retention was measured using ground and sieved samples in a pressure plate extractor (Soil Moisture Equipment Corp.); eight samples were measured from under the tree canopy and sixteen from the intercanopy.

Data Analysis

In 36 cases, cumulative infiltration into the soil over a period of 30 minutes was less than 15 mL. In these cases the hydraulic conductivity and sorptivity were considered below the detection limit and these values were approximated by dividing the lowest measured hydraulic conductivity at that tree by two. This approach seems reasonable because hydraulic conductivity and sorptivity in the hydrophobic soils of the study site approached zero in certain cases.

Since the twelve trees examined in this study varied in canopy radius (CR), all data analysis was conducted by dividing the distance of the observation from the tree trunk by the canopy radius and grouping these normalized distances into quartiles (Madsen et al., 2008). The number of measurements included in each quartile ranged from 15 to 17. A significance level of α=.10 was used throughout the study. Mann-Whitney tests were used to test for significant differences in bulk density and soil organic matter because of small samples sizes. Analysis of

Variance (ANOVA) was used to determine if statistically significant differences in soil water content were present as a function of normalized distance from the tree trunk. Sorptivity data were positively skewed, and ANOVA was performed on these data after a square root transformation (Helsel and Hirsch, 2002). Unsaturated hydraulic conductivity data were positively skewed, and ANOVA was performed on these data after a third root transformation (Helsel and Hirsch, 2002). Fisher's multiple comparisons test was used with an individual error rate of 5%. All statistical tests were performed in Minitab 16.

Results

Soil surface cover, organic matter, and water content

The topsoil was covered primarily by eastern redcedar leaf litter under and near the eastern redcedar canopy and by grass beyond the tree canopy (Fig. 2a). Grass leaf litter was minimal and is not reported here. Median leaf litter depth decreased monotonically from 3 cm at the eastern redcedar trunk to less than .5 cm at one quadrant beyond the canopy edge. Median soil organic carbon was 49% higher under eastern redcedar trees (5.96 mg kg^{-1}) than in the intercanopy area (3.99 mg kg^{-1}), a significant difference (p = .0043, Fig. 2b). Whereas soil water content was consistently low near the tree trunk, variability in soil water content was considerably greater in the intercanopy area. Median soil volumetric water content was lowest near the tree trunk (.12 cm^3 cm^{-3}) and highest just beyond the canopy edge (.17 cm^3 cm^{-3},Fig. 2c, Table 1). Median soil water content was .054 m^3 m^{-3} greater at CR 1.5 than at CR .25. Differences in mean soil water content among the quadrants were significant (p = .005), though the effects of distance from the tree trunk only explained 14% of the total variability in soil water content.

Hydrophobicity, sorptivity, and unsaturated hydraulic conductivity

Soil water repellency was prevalent both under the canopy and in the intercanopy area (Fig. 3). Of sites under eastern redcedar 94% exhibited water repellency; in contrast 65% of intercanopy sites repelled water. Median sorptivity and unsaturated hydraulic conductivity were lowest from the tree trunk to CR .75 and thereafter increased monotonically until CR 1.5 (Fig. 4a,b). Median sorptivity ranged from .05 mm $s^{-1/2}$ at CR .25 to .71 mm $s^{-1/2}$ at CR 2.0. Median unsaturated hydraulic conductivity ranged from .236 cm h^{-1} at CR .25 to 3.182 cm h^{-1} at CR 2.0. From CR 1.5 through 2.0, the central tendency of unsaturated hydraulic conductivity and sorptivity increased slightly. Significant differences in mean unsaturated hydraulic conductivity among the quadrants ($p < .001$) explained 57% of the variability in unsaturated hydraulic conductivity. Significant differences in mean sorptivity among the quadrants ($p < .001$) explained 60% of the variability in sorptivity.

Soil water retention, bulk density, and porosity

Soils collected under the eastern redcedar canopy exhibited higher volumetric water content at both dry and wet ends of the soil water retention curve (Fig. 5). Median bulk density under the cedar canopy was significantly lower and porosity higher, relative to the intercanopy ($p = .0472$, Table 2).

Discussion

Leaf litter and soil organic carbon

Juniper leaf litter may influence the hydrology of encroached systems by intercepting precipitation (Owens et al., 2006) and by serving as a source of soil carbon (Smith and Johnson, 2003) and hydrophobic molecules (Doerr et al., 2000; Gawde et al., 2009). Whereas Smith and Johnson (2003) found that eastern redcedar encroachment into grassland caused no net increase in soil carbon storage, in the upper 25 cm of soil, the present study notes a dramatic increase in soil organic carbon in the top 6 cm of soil that may be hydrologically important.

Soil water content

In Nebraska, Smith and Stubbendieck (1990) found lower soil water content under eastern redcedar canopies than in the adjacent interstitial zone, consistent with the results in Fig. 2c. In contrast, Pierce and Reich (2010) found increased soil water content under eastern redcedar relative to grassland. They attributed this to infiltration of runoff from higher on the sloped study site. Engle et al. (1987) found slightly lower soil moisture at the dripline of eastern redcedars than 3 m away from the canopy edge. However, the data in Fig. 2c reveal a complex spatial pattern in soil water content in the vicinity of eastern redcedars. Lower water content under the eastern redcedar trees may be attributed to high rainfall interception by junipers (Lebron et al., 2007; Owens et al., 2006; Skau, 1964). Higher water content just beyond the canopy edge may result from a combination of lower interception by the grass species and reduced solar radiation due to shading from the cedar tree canopy. Intermediate levels of soil water content beyond CR 1.5 may result from low levels of rainfall interception by the grass and higher levels of solar radiation well beyond the juniper canopy. Our results differ from those of Madsen et al. (2008), in that the latter study in a Pinyon-Juniper woodland found that soil water content remained constant beyond the tree canopy. Uniformly high soil water content in the intercanopy area in that study may have resulted from low evaporative demand since the investigation was conducted in the winter. In contrast, the present study was conducted at a time of year with higher evaporative demand.

Soil water repellency

Whereas past studies have uncovered soil hydrophobicity under other species of juniper (Madsen et al., 2008; Robinson et al., 2010) and under grasses (Cisar et al., 2000; Wessolek et al., 2009), few studies have directly examined the effects of both. In the present study soil water repellency followed a similar trend to soil water content, indicating that in soils that are high in organic matter, small vegetation-induced variations in water content are an important determinant of the presence or absence of hydrophobicity. Similarly, Czachor et al. (2010) found that slight reductions in soil water content can cause substantial reductions in soil wettability. However, soil water content was not statistically different between CR 0.25-CR 1.0 and CR 1.75, yet hydrophobicity was 38 percentage points lower at CR 1.75, indicating that the presence or absence of soil water repellency is controlled by interactions between soil water content, soil organic carbon, and perhaps by leaching of hydrophobic compounds in eastern redcedar's foliage (Gawde et al., 2009; Hemmerly, 1970) into the soil. In the present study 100% of sites were nonwettable at CR .25 and CR .75 notwithstanding volumetric water contents of up to .18 cm^3 cm^{-3}. Thus, the present study likely describes an upper bound for the occurrence of water repellency. Though subcanopy water repellency in the present study was similar to that reported by Madsen et al. (2008) median subcanopy water content in the present study was .07 cm^3 cm^{-3} higher.

Sorptivity and unsaturated hydraulic conductivity

Though the effects of vegetation on the sorptivity of a soil are a critical determinant of the spatiotemporal fate of throughfall, sorptivity has only rarely been quantified on rangelands (e.g., Madsen et al., 2008). The trend of low sorptivity near eastern redcedar tree trunks and increasing sorptivity from CR 0.5 to CR 1.5 in the present study was similar to that reported by Madsen et al. (2008) for Pinyon-Juniper woodland. However, in the present study, sorptivity and unsaturated hydraulic conductivity in the subcanopy were lower relative to the Pinyon-Juniper woodland. Lower subcanopy sorptivity in the present study may have resulted from finer textured soils or from greater inputs of hydrophobic compounds from plants, since the average annual precipitation in the present study is 60 cm greater than in the Pinyon-Juniper woodland.

The results of the present study apparently contrast with past work using methods that mask the effects of soil water repellency on infiltration or hydraulic conductivity. For example, Wilcox et al. (2003) measured unsaturated and saturated hydraulic conductivity in a Pinyon-Juniper woodland and found higher hydraulic conductivity under trees than in the intercanopy. Similarly, Pierson et al. (2010) found lower runoff under Pinyon-Juniper trees. They attributed this effect to leaf litter promoting infiltration into the hydrophobic soils. Ponded infiltrometer measurements made near the study site under eastern redcedar have indicated higher infiltration rates relative to grassland (Chris Zou, unpublished data). The present study shows that after soils under eastern redcedars dry down and become hydrophobic they resist wetting via piston flow. However, adjacent grassland and encroached watersheds at this site do not indicate increased stormflows after eastern redcedar encroachment (Donald Turton, unpublished data). Thus, a plausible hypothesis may be that eastern redcedar encroachment increases preferential flow when storms occur after soils have dried down, a process that has been shown under Pinyon-Juniper woodland (Robinson et al., 2010).

Soil water retention and bulk density

Soil water retention and bulk density data should be considered preliminary because these samples were taken only from one site each. The authors are aware of no prior attempt to quantify encroachment effects on soil water retention. At low suctions, soil water retention is most strongly related to porosity and at the high suctions, it is related to several factors, including soil organic matter (Gupta and Larson, 1979). Our results are similar to work from Sri Lanka that uncovered higher soil organic matter and soil water retention at an afforested site, relative to an adjacent grassland, with similar land use history (Mapa, 1995). That study concluded that the high porosities indicate that “reforested areas can accept and store more water” than grassland. However, further research is needed to assess if this assertion is valid in the case of eastern redcedar encroachment into tallgrass prairie. Plant roots provide an important force in creating macropores (Angers and Caron, 1998). Another potential influence on soil porosity in redcedar encroached systems is livestock grazing, which would increase the bulk density of surface soil under grass (Daniel et al., 2002), but not under redcedar canopies.

Conclusion

This experiment investigated the effects of eastern redcedar encroachment into tallgrass prairie on soil hydraulic properties. Under eastern redcedar’s thick leaf litter layer, soil organic carbon was 49% higher in the upper 6 cm of soil than in the intercanopy. We uncovered a spatial gradient in soil water content in which soil water content was lowest under the eastern redcedar tree, peaked just beyond the canopy edge, and declined slightly in the center of the grassy intercanopy area. The water drop penetration test indicated that soil water repellency was ubiquitous under the eastern redcedar canopy, though the grassy intercanopy area also exhibited hydrophobicity. The water repellent nature of the soil under the eastern redcedar trees’ thick litter layer was associated with a significantly lower soil sorptivity and unsaturated hydraulic conductivity. Soils under eastern redcedar exhibited high porosity, lower bulk density, and greater water retention at the dry and wet ends of the soil water retention curve. Quantifying the effects of eastern redcedar encroachment on soil hydraulic properties will facilitate an understanding the mechanism of encroachment and the effects of encroachment on the partitioning of throughfall.

Acknowledgements

We wish to thank Oklahoma State University's Soil Physics Practicum class and Tyson Ochsner for their indispensable field assistance in this project and guidance throughout the project. We appreciated field assistance from Don Turton, Chris Zou, and Vinny Guidotti De faria.

References

Angers, D.A. and Caron, J., 1998. Plant-induced Changes in Soil Structure: Processes and Feedbacks. Biogeochemistry, 42(1): 55-72.

Blackburn, W.H. and Skau, C.M., 1974. INFILTRATION RATES AND SEDIMENT PRODUCTION OF SELECTED PLANT COMMUNITIES IN NEVADA. Journal of Range Management, 27(6): 476-480.

Blonquist, J.M., Jones, S.B. and Robinson, D.A., 2005. Standardizing Characterization of Electromagnetic Water Content Sensors. Vadose Zone J., 4(4): 1059-1069.

Carsel, R.F. and Parrish, R.S., 1988. Developing Joint Probability Distributions of Soil Water Retention Characteristics. Water Resources Research, 24.

Cisar, J.L., Williams, K.E., Vivas, H.E. and Haydu, J.J., 2000. The occurrence and alleviation by surfactants of soil-water repellency on sand-based turfgrass systems. Journal of Hydrology, 231: 352-358.

Clenton, E.O., Blan, K.R., Eaton, B.J. and Russ, O.G., 1973. Evaluation of Eastern Redcedar Infestations in the Northern Kansas Flint Hills. Journal of Range Management, 26(4): 256-260.

Coppedge, B.R., Engle, D.M., Masters, R.E. and Gregory, M.S., 2001. Avian response to landscape change in fragmented Southern Great Plains grasslands. Ecological Applications, 11(1): 47-59.

Czachor, H., Doerr, S.H. and Lichner, L., 2010. Water retention of repellent and subcritical repellent soils: New insights from model and experimental investigations. Journal of Hydrology, 380(1-2): 104-111.

Daniel, J.A., Potter, K., Altom, W., Aljoe, H. and Stevens, R., 2002. Long-term grazing density impacts on soil compaction. Transactions of the ASAE, 45(6): 1911-1915.

Dekker, L.W. and Ritsema, C.J., 1996. Preferential flow paths in a water repellent clay soil with grass cover. Water Resources Research, 32(5): 1239-1249.

Doerr, S.H., Shakesby, R.A. and Walsh, R.P.D., 2000. Soil water repellency: its causes, characteristics and hydro-geomorphological significance. Earth-Science Reviews, 51(1-4): 33-65.

Engle, D.M., Bernardo, D.J., Hunter, T.D., Stritzke, J.F. and Bidwell, T.G., 1996. A decision support system for designing juniper control treatments. Ai Applications, 10(1): 1-11.

Engle, D.M., Bodine, T.N. and Stritzke, J.F., 2006. Woody Plant Community in the Cross Timbers Over Two Decades of Brush Treatments. Rangeland Ecology & Management, 59(2): 153-162.

Engle, D.M. and Kulbeth, J.D., 1992. Growth Dynamics of Crowns of Eastern Redcedar at 3 Locations in Oklahoma. Journal of Range Management, 45(3): 301-305.

Engle, D.M., Stritzke, J.F. and Claypool, P.L., 1987. Herbage Standing Crop around Eastern Redcedar Trees. Journal of Range Management, 40(3): 237-239.

Gawde, A.J., Cantrell, C.L. and Zheljazkov, V.D., 2009. Dual extraction of essential oil and podophyllotoxin from Juniperus virginiana. Industrial Crops and Products, 30(2): 276-280.

Gupta, S.C. and Larson, W.E., 1979. ESTIMATING SOIL-WATER RETENTION CHARACTERISTICS FROM PARTICLE-SIZE DISTRIBUTION, ORGANIC-MATTER PERCENT, AND BULK-DENSITY. Water Resources Research, 15(6): 1633-1635.

Helsel, D.R. and Hirsch, R.M., 2002. Statistical Methods in Water Resources. Techniques of Water-Resources Investigations of the United States Geological Survey. USGS, 510 pp.

Hemmerly, T.E., 1970. Economic Uses of Eastern Red Cedar. Economic Botany, 24(1): 39-41.

Hendrickx, J.M.H., Dekker, L.W. and Boersma, O.H., 1993. Unstable Wetting Fronts in Water-Repellent Field Soils. Journal of Environmental Quality, 22(1): 109-118.

Jaramillo, D.F., Dekker, L.W., Ritsema, C.J. and Hendrickx, J.M.H., 2000. Occurrence of soil water repellency in arid and humid climates. Journal of Hydrology, 231: 105-111.

Krammes, J.S. and Debano, L.F., 1965. SOIL WETTABILITY - A NEGLECTED FACTOR IN WATERSHED MANAGEMENT. Water Resources Research, 1(2): 283-&.

Lebron, I. et al., 2007. Ecohydrological controls on soil moisture and hydraulic conductivity within a pinyon-juniper woodland. Water Resour. Res., 43(8): W08422.

Madsen, M.D., Chandler, D.G. and Belnap, J., 2008. Spatial gradients in ecohydrologic properties within a pinyon-juniper ecosystem. Ecohydrology, 1(4): 349-360.

Mapa, R.B., 1995. EFFECT OF REFORESTATION USING TECTONA-GRANDIS ON INFILTRATION AND SOIL-WATER RETENTION. Forest Ecology and Management, 77(1-3): 119-125.

McKinley, D. and Blair, J., 2008. Woody Plant Encroachment by Juniperus virginiana in a Mesic Native Grassland Promotes Rapid Carbon and Nitrogen Accrual. Ecosystems, 11(3): 454-468.

Morton, L.W., Regen, E., Engle, D.M., Miller, J.R. and Harr, R.N., 2010. Perceptions of Landowners Concerning Conservation, Grazing, Fire, and Eastern Redcedar Management in Tallgrass Prairie. Rangeland Ecology & Management, 63(6): 645-654.

Owens, M.K., Lyons, R.K. and Alejandro, C.L., 2006. Rainfall partitioning within semiarid juniper communities: effects of event size and canopy cover. Hydrological Processes, 20(15): 3179-3189.

Pierce, A.M. and Reich, P.B., 2010. The effects of eastern red cedar (Juniperus virginiana) invasion and removal on a dry bluff prairie ecosystem. Biological Invasions, 12(1): 241-252.

Pierson, F.B. et al., 2010. Hydrologic Vulnerability of Sagebrush Steppe Following Pinyon and Juniper Encroachment. Rangeland Ecology & Management, 63(6): 614-629.

Ritsema, C.J. and Dekker, L.W., 1994. HOW WATER MOVES IN A WATER REPELLENT SANDY SOIL .2. DYNAMICS OF FINGERED FLOW. Water Resources Research, 30(9): 2519-2531.

Ritsema, C.J., Dekker, L.W. and Heijs, A.W.J., 1997. Three-dimensional, fingered flow patterns in a water repellent sandy field soil. Soil Science, 162(2): 79-90.

Robinson, D.A., Lebron, I., Ryel, R.J. and Jones, S.B., 2010. Soil Water Repellency: A Method of Soil Moisture Sequestration in Pinyon-Juniper Woodland. Soil Science Society of America Journal, 74(2): 624-634.

Skau, C.M., 1964. Interception, Throughfall, and Stemflow in Utah and Alligator Juniper Cover Types of Northern Arizona. Forest Science, 10: 283-287.

Smith, D.L. and Johnson, L.C., 2003. Expansion of Juniperus virginiana L. in the Great Plains: Changes in soil organic carbon dynamics. Global Biogeochemical Cycles, 17(2).

Smith, S.D. and Stubbendieck, J., 1990. Production of tall-grass prairie herbs below eastern redcedar. Prairie Naturalist, 22(1): 13-18.

Soil Conservation Service, 1987. Soil survey of Payne County, Oklahoma. The Service, Washington, D.C.

Stoeser, D.B., 2005. Preliminary integrated geologic map databases for the United States: Central states, Montana, Wyoming, Colorado, New Mexico, Kansas, Oklahoma, Texas, Missouri, Arkansas, and Louisiana. USGS, Reston.

Van Els, P., Will, R.E., Palmer, M.W. and Hickman, K.R., 2010. Changes in forest understory associated with Juniperus encroachment in Oklahoma, USA. Applied Vegetation Science, 13(3): 356-368.

Volder, A., Tjoelker, M.G. and Briske, D.D., 2010. Contrasting physiological responsiveness of establishing trees and a C4 grass to rainfall events, intensified summer drought, and warming in oak savanna. Global Change Biology, 16(12): 3349-3362.

Wessolek, G., Stoffregen, H. and Taumer, K., 2009. Persistency of flow patterns in a water repellent sandy soil - Conclusions of TDR readings and a time-delayed double tracer experiment. Journal of Hydrology, 375(3-4): 524-535.

Wilcox, B.P., Breshears, D.D. and Turin, H.J., 2003. Hydraulic conductivity in a pinon-juniper woodland: Influence of vegetation. Soil Science Society of America Journal, 67(4): 1243-1249.

Zhang, R.D., 1997. Determination of soil sorptivity and hydraulic conductivity from the disk infiltrometer. Soil Science Society of America Journal, 61(4): 1024-1030.

Table 1. Median, first quartile, and third quartile of water content, hydraulic conductivity, and sorptivity below the eastern redcedar canopy and in the grass-dominated intercanopy space.

Unit	Normalized Distance	n	Volumetric Water Content			Unsaturated Hydraulic Conductivity			Sorptivity		
			Median	Q1	Q3	Median	Q1	Q3	Median	Q1	Q3
				%			(cm h-1)			(mm s-1/2)	
Subcanopy	.25-1	69	13.3	11.7	15.6	0.566	0.212	1.097	0.098	0.045	0.254
Intercanopy	1.25-2.5	65	15.4	12.7	19.1	2.517	1.951	3.902	0.682	0.471	0.893

Table 2. Soil bulk density and porosity beneath the canopy of an eastern redcedar and in the intercanopy space.

	n	Bulk Density		Porosity	
		Mean	SE	Mean	SE
		g cm^{-3}		cm^3 cm^{-3}	
Subcanopy	4	1.12	0.11	0.58	0.04
Intercanopy	7	1.34	0.04	0.49	0.02

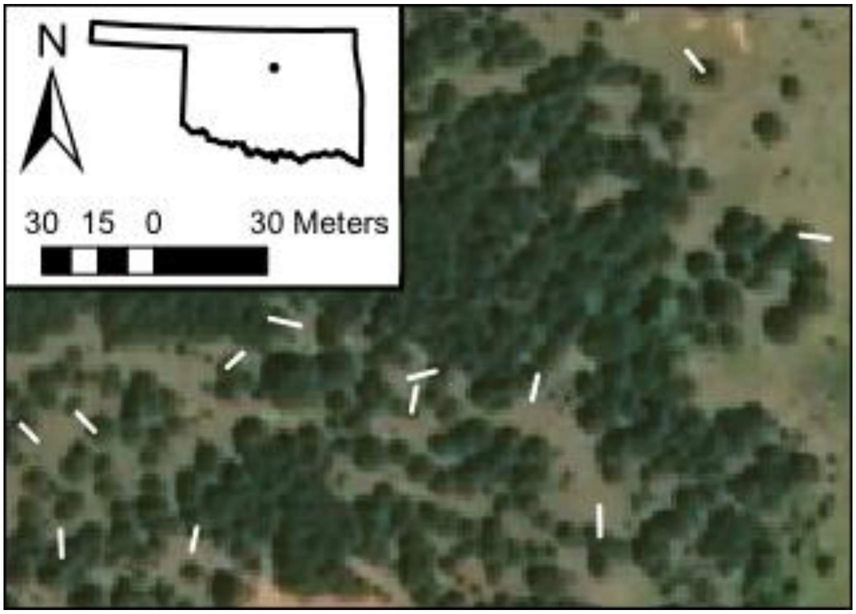

Figure 1. White lines indicate transects positions at the study site. The black dot indicates the location of the Cross Timbers Experimental Range. Orthoimagery was photographed by the USDA-FSA-APFO in 2010.

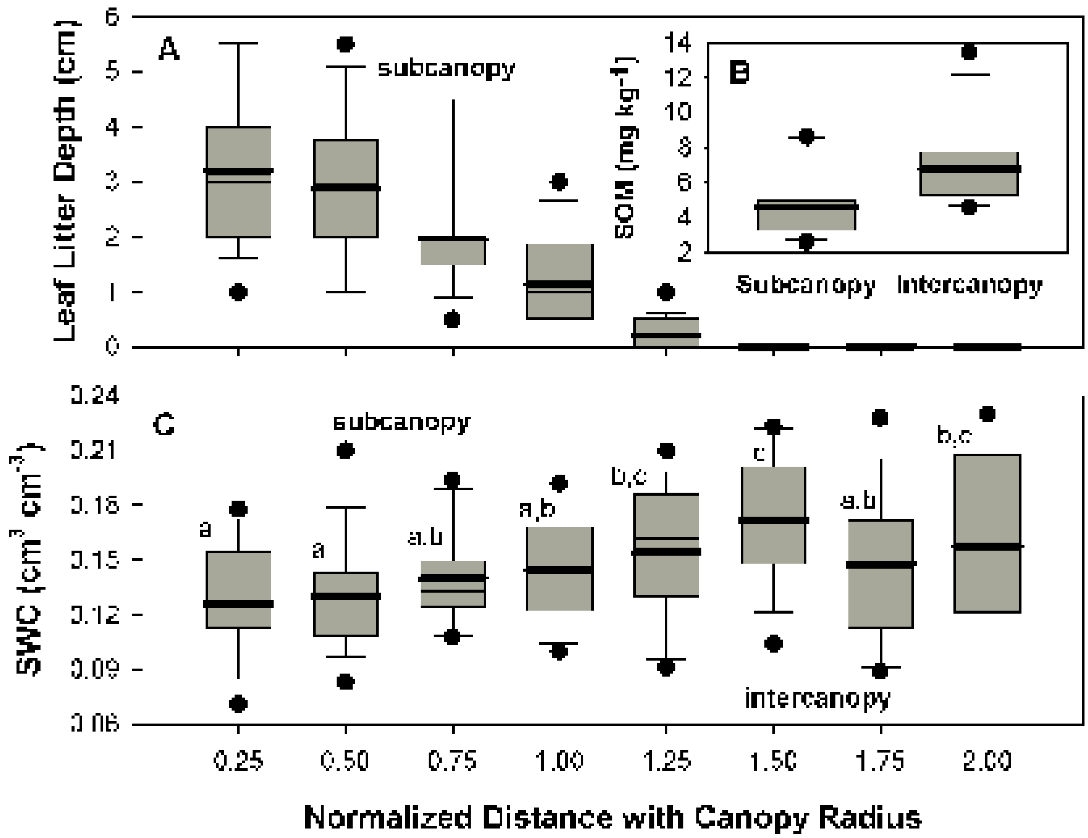

Figure 2. Black dots represent outliers and whiskers indicate the 5th and 95th percentiles. From bottom to top, the three lines in each box represent the first quartile, median, and third quartile. The heavy black lines represent the mean and similar letters indicate no statistically significant differences. The four subcanopy quadrants are 0.25 -1.0 and the four intercanopy quadrants are 1.25 to 2.0. (a) Leaf litter depth, (b) soil organic matter, and (c) volumetric soil water content.

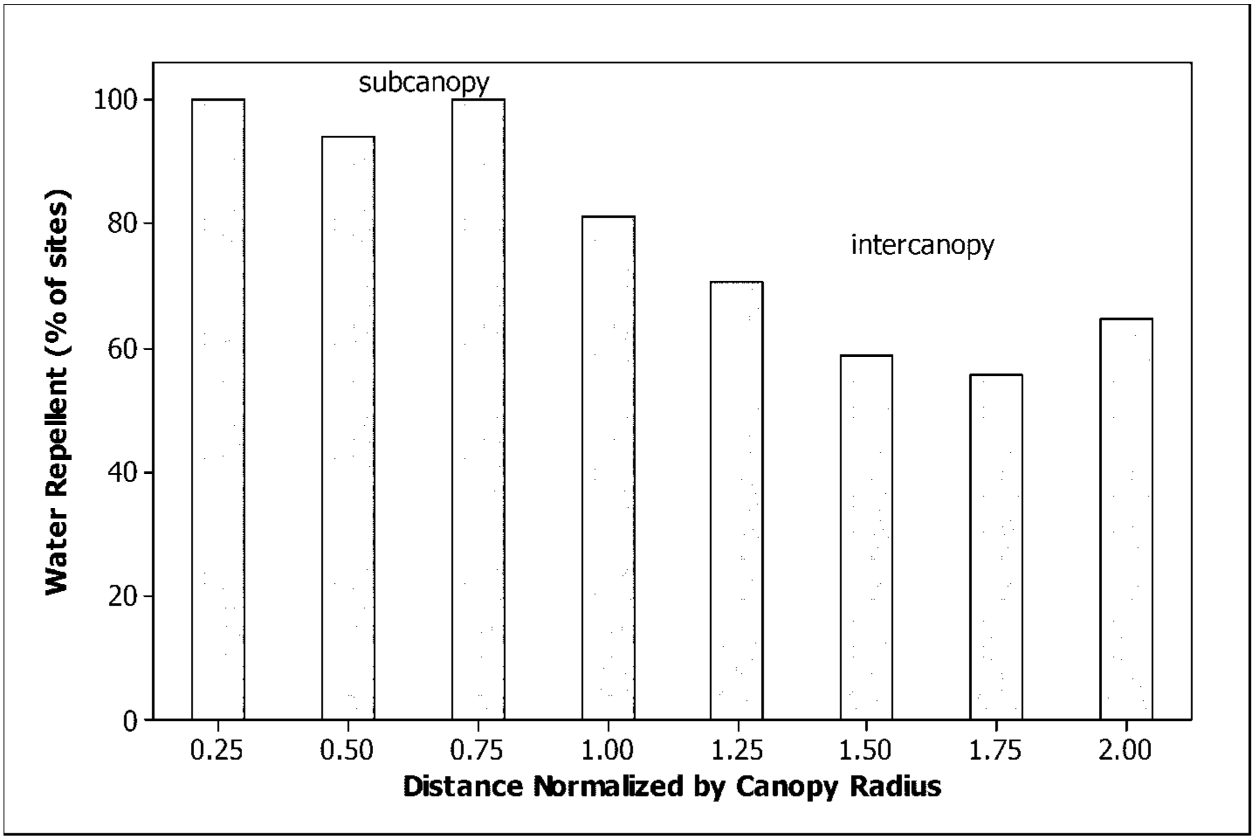

Figure 3. Percent of sites that failed to absorb applied water drops within five seconds.

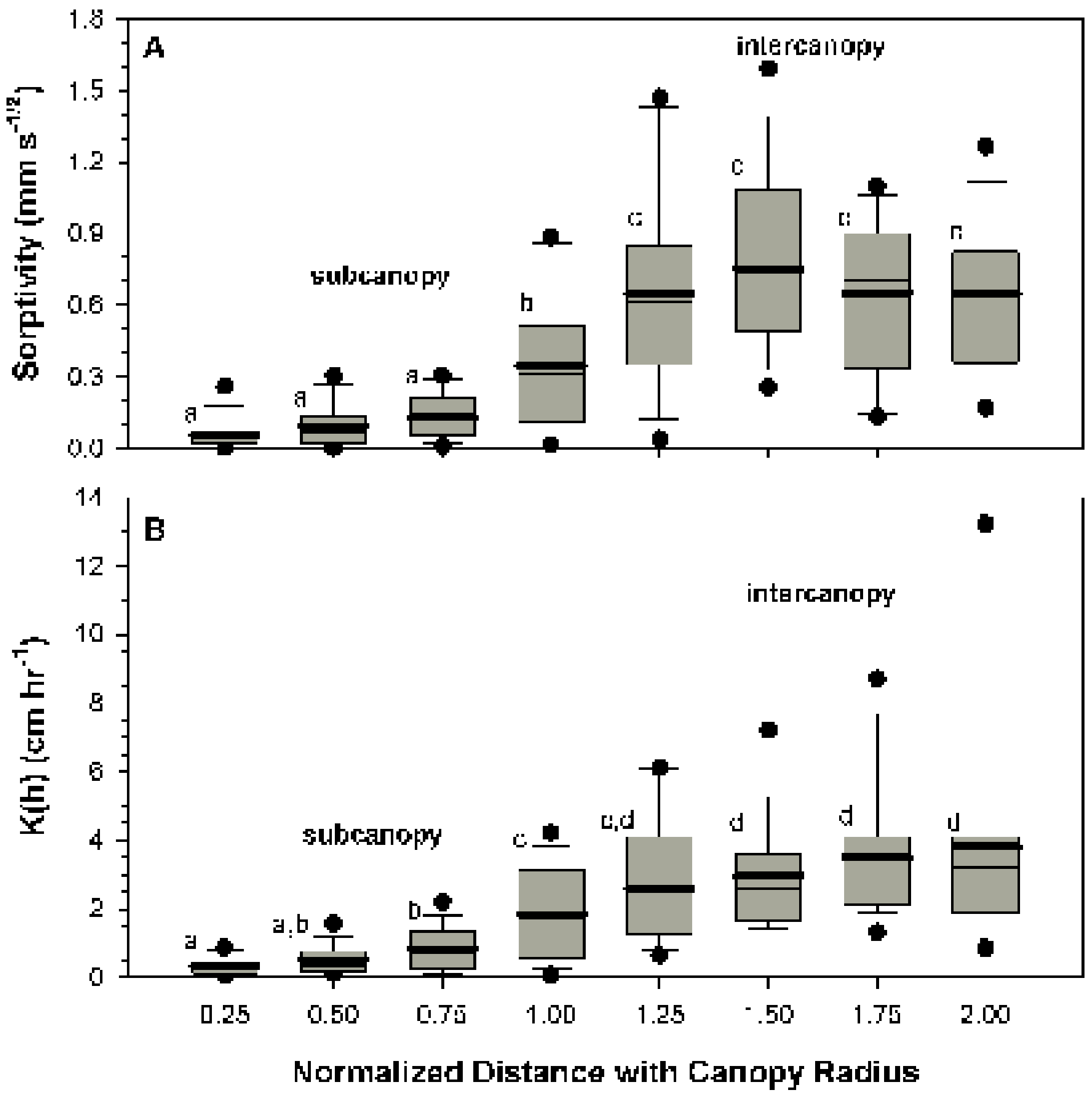

Figure 4. Variation in (a) sorptivity and (b) unsaturated hydraulic conductivity versus distance from eastern redcedar trunk normalized by canopy radius.

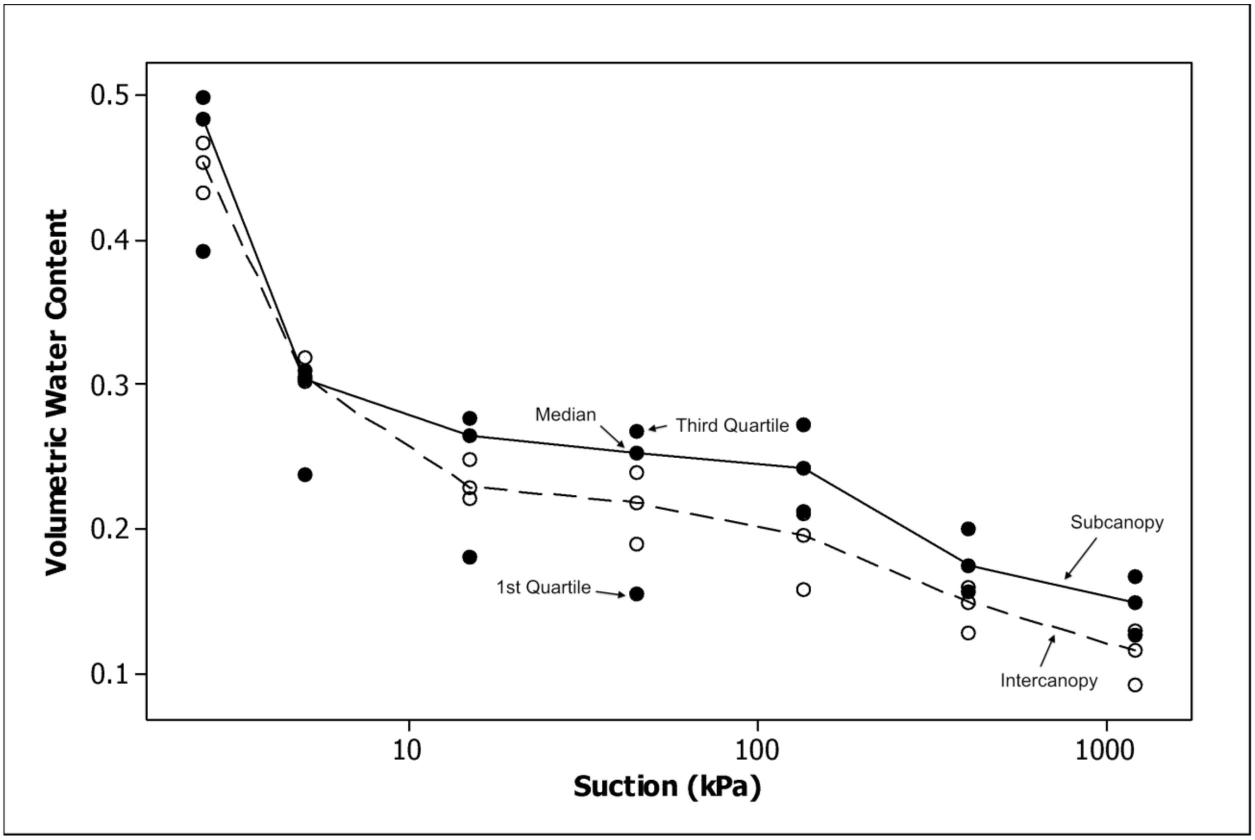

Figure 5. Soil water retention under an eastern redcedar and in a nearby intercanopy area. The solid line and solid dots correspond to samples from under an eastern redcedar tree and the dashed line and hollow dots correspond to the intercanopy. Dots represent the first, second and third quartile of each. Lines connect medians.