HYDROLOGICAL PROCESSES
*Hydrol. Process.* (2011)
Published online in Wiley Online Library
(wileyonlinelibrary.com) DOI: 10.1002/hyp.8306

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

Michael L. Wine,[1*,†] Tyson E. Ochsner,[2] Apurba Sutradhar[2] and Rachael Pepin[3]

[1] *Department of Natural Resource Ecology and Management, Oklahoma State University, Stillwater, OK 74078, United States*
[2] *Department of Plant and Soil Sciences, Oklahoma State University, Stillwater, OK 74078, United States*
[3] *Department of Horticulture and Landscape Architecture, Oklahoma State University, Stillwater OK 74078, United States*

## Abstract:

In north-central Oklahoma eastern redcedar (*Juniperus virginiana*), encroachment into grassland is widespread and is suspected of reducing streamflow, but the effects of this encroachment on soil hydraulic properties are unknown. This knowledge gap 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. Leaf litter depth, soil organic matter, soil water repellency, soil water content, sorptivity, and unsaturated hydraulic conductivity were measured near Stillwater, OK, along 12 radial transects from eastern redcedar trunks to the center of the grassy intercanopy space. Eastern redcedar encroachment in the second half of the 20th century caused the accumulation of 3 cm of hydrophobic leaf litter near the trunks of eastern redcedar trees. This leaf litter was associated with increased soil organic matter in the upper 6 cm of soil under eastern redcedar trees (5.96% by mass) relative to the grass-dominated intercanopy area (3.99% by mass). Water repellency was more prevalent under eastern redcedar than under grass, and sorptivity under eastern redcedar was $0.10\,mm\,s^{-1/2}$, one seventh the sorptivity under adjacent prairie grasses ($0.68\,mm\,s^{-1/2}$). Median unsaturated hydraulic conductivity under grass was $2.52\,cm\,h^{-1}$, four times greater than under eastern redcedar canopies ($0.57\,cm\,h^{-1}$). Lower sorptivity and unsaturated hydraulic conductivity would tend to decrease infiltration and increase runoff, but other factors such as rainfall interception by the eastern redcedar canopy and litter layer, and preferential flow induced by hydrophobicity must be examined before the effects of encroachment on streamflow can be predicted. 

KEY WORDS hydrophobicity; soil organic matter; moisture content; prairie; rangeland hydrology; water repellency

*Received 4 January 2011; Accepted 10 August 2011*

## INTRODUCTION

Eastern redcedar has encroached at an unprecedented rate into the Great Plains of the U.S. (Coppedge *et al.*, 2001; Briggs *et al.*, 2002; McKinley *et al.*, 2008; Bihmidine *et al.*, 2010). In Oklahoma alone, eastern redcedar is projected to cover 3.5 million hectares by 2013 (Starks *et al.*, 2011). Widespread encroachment concerns many landowners who have undertaken to control eastern redcedar (Clenton *et al.*, 1973; Engle and Kulbeth, 1992; Engle *et al.*, 1996; 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. The effects of Utah juniper (*Juniperus osteosperma*) on soil hydraulic properties have been extensively investigated (Scholl, 1971; Blackburn and Skau, 1974; Lebron *et al.*, 2007; Madsen *et al.*, 2008; Pierson *et al.*, 2010; Robinson *et al.*, 2010) as have the effects of Ashe juniper (*Juniperus ashei*) on the Edwards Plateau, Texas (Hester *et al.*, 1997; Taucer *et al.*, 2008). However, little is known about eastern redcedar effects on soil hydraulic properties.

Although the effects of eastern redcedar encroachment on soil hydraulic properties are key determinants of the fate of throughfall, changes to soil hydraulic properties are often disregarded when modeling the effects of land-cover change (Huisman *et al.*, 2004). Yet, soil hydraulic properties play a central role in determining how water is partitioned between overland flow—the primary streamflow generation process—and soil water recharge, most of which is ultimately lost to evapotranspiration in this water-limited system. The potential impacts on streamflow are important because in the Great Plains, streamflow is a major source of water for public water supply and livestock (Tortorelli, 2009).

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. Juniper

*Correspondence to: Michael L. Wine, Department of Natural Resource Ecology and Management, Oklahoma State University, Stillwater, OK 74078, United States.
E-mail: mwine@okstate.edu
†Present Address: Department of Earth and Environmental Science, New Mexico Institute of Mining and Technology, Socorro, NM 87801, United States.
E-mail: mwine@nmt.edu

leaf litter may also lead to increased soil organic matter in topsoil. When soils with high organic matter content dry down, they can become water repellent or hydrophobic (Jaramillo *et al.*, 2000). 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. At a small scale, dry, hydrophobic soils induce higher rates of runoff (Doerr *et al.*, 2000; Doerr *et al.*, 2003). Soil hydrophobicity also affects infiltration patterns. In areas of hydrophobic soils, infiltration of rainfall is often 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).

In this paper, we assess how eastern redcedar encroachment into grassland modifies soil hydraulic properties. This study's specific objectives are to determine how soil surface conditions—leaf litter depth, organic matter, wettability, and water content—and soil hydraulic properties—sorptivity and hydraulic conductivity—vary along radial transects from the base of eastern redcedar trees to the center of the big bluestem (*Andropogon geradii*) dominated intercanopy spaces.

## MATERIALS AND METHODS

### *Experimental site*

The experimental site is located 11 km southwest of Stillwater, Oklahoma (36°03′N, 97°12 W, 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. The climate is continental, and annual precipitation is highly variable (median annual precipitation, 1895–2010 = 831 mm; range = 424–1571). Annual potential evapotranspiration averages 1170 mm. The vegetation structure at the site consists of eastern redcedar trees interspersed among tallgrass prairie species, primarily big bluestem. These species colonized the site after cotton (*Gossypium hirsutum*) cultivation was abandoned at least five decades ago.

### *Experimental design*

The experimental design was based on that of Madsen *et al.* (2008). The intensive field component of the study was conducted from 20 to 24 September, 2010. Within a two-hectare area, 12 representative eastern redcedar trees

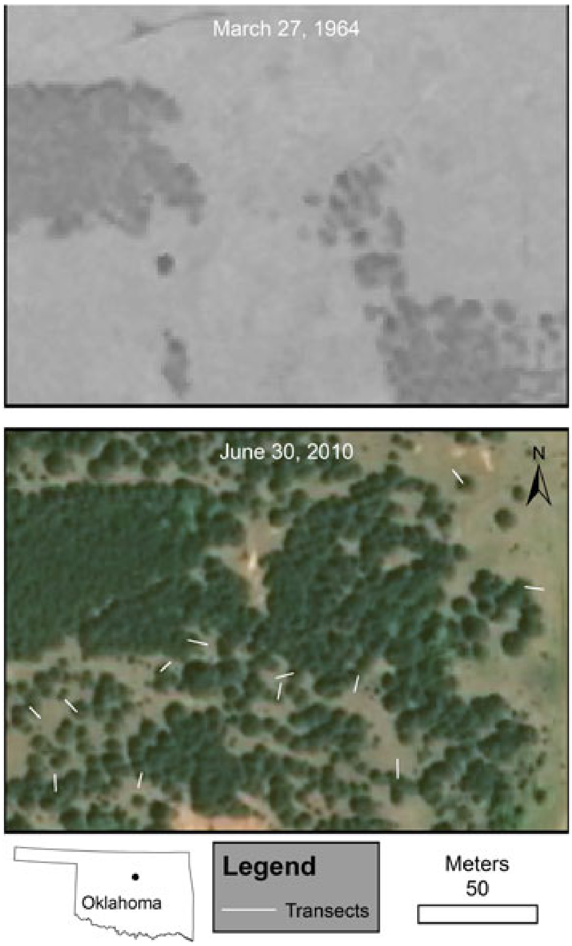


Figure 1. Eastern redcedar increased substantially in abundance from 1964 to 2010. The 1964 aerial photograph was from the USGS, and the 2010 orthoimagery was photographed by the USDA-FSA-APFO. The black dot on the map of Oklahoma indicates the location of the Cross Timbers Experimental Range

were chosen (Figure 1). Their average canopy radius (CR) was 3.4 m (±.6 m). Prior to the study, surface soils had dried down following 1.6 cm of rainfall on September 12. For each tree, we measured soil surface conditions and soil hydraulic parameters every 61 cm starting 30 cm from the base of each tree and extending into the center of the intercanopy 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, leaf litter depth, soil water repellency, soil water content, sorptivity, and unsaturated hydraulic conductivity 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 collected from the 0–6 cm depth under each tree and composited. Similar composite samples were collected from each intercanopy area. These samples were dried at 45 °C, ground, and analyzed for total carbon by the Oklahoma State University Soil, Water, and



DOI: 10.1002/hyp

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 matter (San Jose *et al.*, 1998). Surface soil hydrophobicity was measured by assessing whether a water droplet remained on the surface or infiltrated after 5 s (Krammes and Debano, 1965). Volumetric water content of the upper 6 cm of soil was measured using an ML2x Theta Probe (Delta-T Devices, Cambridge, England) with the manufacturer's calibration.

Soil hydraulic properties were measured in the field using 15.9 $cm^2$ Mini Disk tension infiltrometers (Decagon Devices, Pullman, WA) at 1.0 cm of suction. This suction was chosen so that sufficient water (at least 15 mL) would infiltrate within the time constraints of the study. Infiltration was measured for no more than 30 min in part because the measurement process itself—as water molecules from the infiltrometer attract the polar functional groups of amphiphilic molecules—can render the soil hydrophilic. As a result, in other studies, transient variations in infiltration rate have been observed during long (100 min) measurement periods (Logsdon, 1997). Soil texture of the upper 6 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 (Zhang, 1997). 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.

Daily maximum 5-min rainfall intensities from 1994 to 2010 were obtained from the Marena station of the Oklahoma Mesonet, located 3 km northwest of the study site. From 1998 to 2010, daily mean soil moisture at 5 cm depth under ungrazed grasses was also measured at this station using heat dissipation sensors. Heat dissipation measurements were converted to a fractional water index (FWI), which ranges from 0 for very dry soil to 1 for soil at field capacity (Illston *et al.*, 2008).

### *Data analysis*

In 36 cases, cumulative infiltration into the soil over a period of 30 min was less than 15 mL, the minimum necessary to accurately calculate hydraulic conductivity (Decagon Devices, 2011). 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. The lowest measured sorptivity and hydraulic conductivity were $0.0024\,mm\,s^{-1/2}$ and $0.1259\,cm\,h^{-1}$, respectively. This approach seems reasonable because hydraulic conductivity and sorptivity in the hydrophobic soils of the study site approached zero in certain cases.

Since the 12 trees examined in this study varied in CR, we analyzed the data by dividing the distance of the observation from the tree trunk by the CR 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 $\alpha = .10$ was used throughout the study. Mann–Whitney tests were used to test for significant differences in 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 and unsaturated hydraulic conductivity data were positively skewed, and ANOVAs were performed on these data after square and third root transformations, respectively (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

The topsoil was covered primarily by eastern redcedar leaf litter under and near the eastern redcedar canopy and by grass beyond the tree canopy (Figure 2A). Grass leaf litter was minimal and is not reported. Median leaf litter depth decreased monotonically from 3 cm at the eastern redcedar trunk to less than 0.5 cm at one quadrant beyond the canopy edge. Median soil organic matter was 49%

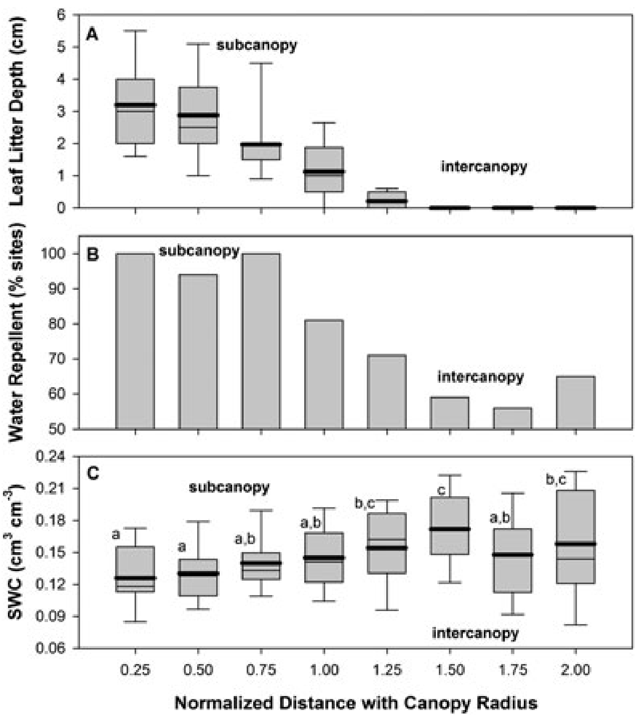


Figure 2. Whiskers indicate the 10th and 90th percentiles. From bottom to top, the three lines in each box represent the first quartile, median, and third quartile. The heavy black lines represent the mean, and similar letters indicate no statistically significant differences. The four subcanopy quadrants are 0.25–1.0, and the four intercanopy quadrants are 1.25–2.0. (A) Leaf litter depth. (B) Percent of sites that failed to absorb applied water drops within 5 s. (C) Volumetric soil water content



DOI: 10.1002/hyp

higher under eastern redcedar trees (5.96 % by mass) than in the intercanopy area (3.99 % by mass), a significant difference ($p = 0.0043$, Figure 3). Soil water repellency was prevalent both under the canopy and in the intercanopy area (Figure 2B). Of sites under eastern redcedar, 94% exhibited water repellency; in contrast, 65% of intercanopy sites exhibited some degree of water repellency. 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 (0.12 $cm^3 cm^{-3}$) and highest just beyond the canopy edge (0.17 $cm^3 cm^{-3}$, Figure 2C, Table I). Median soil water content was 0.054 $cm^3 cm^{-3}$ greater at CR 1.5 than at CR 0.25. Differences in mean soil water content along the transect were significant ($p = 0.005$), though the effects of distance from the tree trunk only explained 14% of the total variability in soil water content.

Median sorptivity and unsaturated hydraulic conductivity were lowest from the tree trunk to CR 0.75 and thereafter increased monotonically until CR 1.5 (Figure 4A,B). Median sorptivity ranged from 0.05 $mm\,s^{-1/2}$ at CR 0.25 to 0.71 $mm\,s^{-1/2}$ at CR 2.0. Median unsaturated hydraulic conductivity ranged from 0.236 $cm\,h^{-1}$ at CR 0.25 to 3.182 $cm\,h^{-1}$ at CR 2.0. Significant differences in mean unsaturated hydraulic conductivity along the transects ($p < 0.001$) explained 57% of the variability in unsaturated hydraulic conductivity. Significant differences in mean sorptivity along the transects ($p < 0.001$) explained 60% of the variability in sorptivity.

On September 20, 2010—the first day of the intensive field campaign—the FWI at the Marena Mesonet station was 0.73. From 1998 to 2010, the FWI was lower than or equal to this value (indicating drier soil) on 1648 days or 35% of the time. The greatest probability that the soil would be as dry as or drier than this value occurred between May and October, but most notably in August when over 75% of days exhibited dry, potentially hydrophobic soil (Figure 5A).

Among the months when soil water repellency is most probable, all had maximum 5-min rainfall intensities well in excess of the measured unsaturated hydraulic conductivity (Figure 5B). The data suggest that at a small scale, considerably greater infiltration excess overland flow occurs under eastern redcedars relative to in tallgrass prairie. From 1994 to 2010, 1583 precipitation events were recorded. Of these, the maximum 5-min rainfall intensity exceeded median unsaturated hydraulic conductivity under tallgrass prairie 380 times (in 24% of storms), but under eastern redcedar 920 times (in 58% of storms).

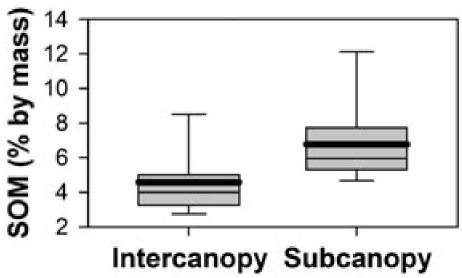


Figure 3. Soil organic matter under tallgrass prairie species (intercanopy) *versus* under eastern redcedar canopies

## DISCUSSION

### *Leaf litter and soil organic matter*

Eastern redcedar encroached into the study area in the second half of the 20th century (Figure 1) bringing with it

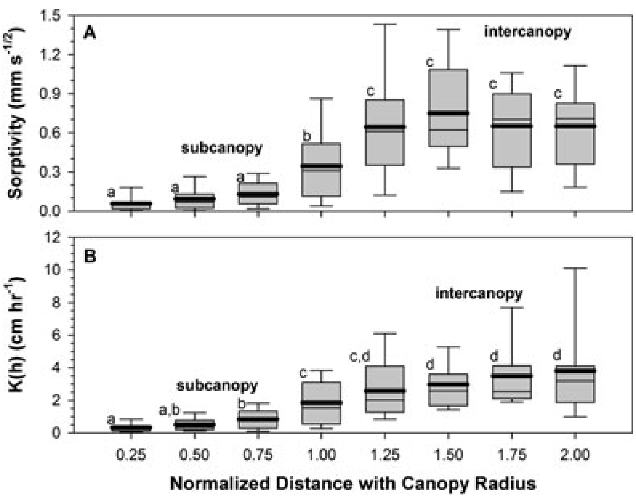


Figure 4. Variation in (A) sorptivity and (B) unsaturated hydraulic conductivity *versus* distance from eastern redcedar trunk normalized by canopy radius

Table I. 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 Median | Q1 | Q3 | Unsaturated Hydraulic Conductivity Median | Q1 | Q3 | Sorptivity Median | Q1 | Q3 |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | % | | | ($cm\,h^{-1}$) | | | ($mm\,s^{-1/2}$) | | |
| Subcanopy | 0.25–1 | 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 |



DOI: 10.1002/hyp

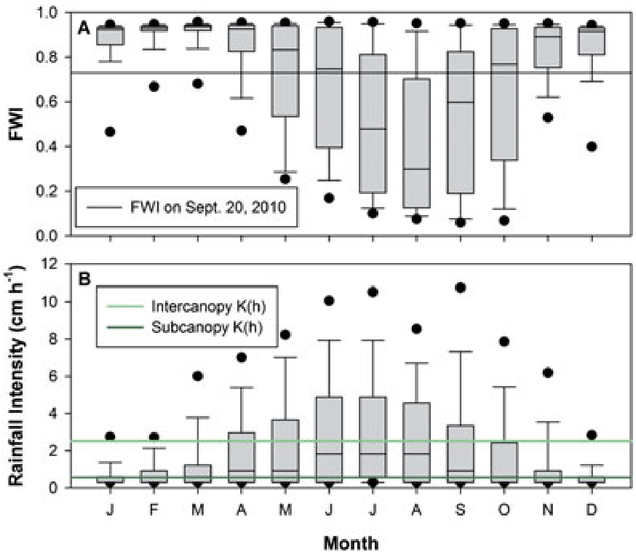


Figure 5. (A) Boxplots of mean daily Fractional Water Index (FWI) from 1998 to 2010, by month. When soils dry down below the horizontal line (representing the FWI on the first day of the intensive field campaign), they may become hydrophobic. (B) Maximum 5-min daily rainfall intensities for days when storms occurred from 1994 to 2010. Overlaid on the boxplots are median values of unsaturated hydraulic conductivity under tallgrass prairie and under eastern redcedar canopies. Black dots indicate 5th and 95th percentiles

life history traits distinct from perennial grasses. Leaf litter of evergreens has more lignin, making it more difficult for microbes to decompose, relative to leaf litter of grasses (Murphy *et al*., 1998). Consequently, litter accumulates under eastern redcedar as we observed.

Juniper leaf litter intercepts throughfall (Owens *et al*., 2006), prevents soil splash (Van Hooff, 1983; Pierson *et al*., 2010), and ensures that macropores are not plugged by debris (Beven and Germann, 1982). Juniper leaf litter has also been reported to channel throughfall to preferential flow pathways in the soil (Madsen *et al*., 2008). Once rainfall has reached the soil surface, leaf litter cover exerts a frictional force on water, slowing its flow and maximizing infiltration (Abrahams *et al*., 1994; Pan and Shangguan, 2006), even into highly water-repellent soils (Pierson *et al*., 2010).

In addition to its direct hydrologic effects, juniper leaf litter serves as a source of soil organic matter (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 significant increase in soil organic matter concentration in the top 6 cm of soil that may be hydrologically important in improving macropore stability and longevity (Beven and Germann, 1982) and in affecting topsoil wettability. More research is needed to determine the effects of eastern redcedar encroachment on soil organic carbon storage and distribution within the soil profile.

### *Soil water repellency*

As eastern redcedar encroaches into tallgrass prairie, in addition to increasing soil organic matter in the topsoil, eastern redcedar may also change the composition of soil organic matter. Water repellency tends to occur under deep leaf litter and has been associated with fungal mycelia formation (Scott and Van Wyk, 1990; Crockford *et al*., 1991). As microbes degrade lignin from the leaf litter layer, they produce waxes that coat soil particles, inducing water repellency (Franco *et al*., 2000). This is consistent with our data in which water repellency was most common at positions with at least 1 cm of eastern redcedar leaf litter. As little as 2% soil organic matter by weight can induce severe soil water repellency (McGhie and Posner, 1981). Since the amount of soil organic matter under grass exceeded this threshold, the absence of strong soil water repellency under grasses might be explained in part by a low proportion of hydrophobic molecules within their soil organic matter.

Though in the present study, greater soil water repellency corresponded to higher levels of soil organic matter, this relationship may not be entirely causal. The correspondence between organic matter and hydrophobicity observed in the present study has been widely observed (Wallis *et al*., 1990; Rodríguez-Alleres *et al*., 2007; Verheijen and Cammeraat, 2007). However, Jungerius and de Jong (1989) observed no correlation between soil organic matter and hydrophobicity, and Wallis *et al*. (1993) observed the greatest water repellency at low levels of soil carbon. Similarly, Teramura (1980) observed soil water repellency at low levels of soil organic matter and no soil water repellency in a treatment with greater soil organic matter. The composition of soil organic matter may explain the complex relationship between soil organic matter and water repellency because soil organic matter is composed of a mixture of components with hydrophilic and hydrophobic functional groups (Ellerbrock *et al*., 2005), and the proportion of hydrophobic molecules—methyl, methylene, and methane groups in aliphatic and aromatic compounds—differs among soils (Capriel *et al*., 1995).

In the present study, soil water repellency tended to decrease as soil water content increased. Similarly, Czachor *et al*. (2010) found that slight reductions in soil water content can cause substantial reductions in soil wettability. However, soil water content in our study 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 matter, and perhaps by leaching of hydrophobic compounds in eastern redcedar's foliage (Hemmerly, 1970; Gawde *et al*., 2009) into the soil. In the present study, 100% of sites were nonwettable at CR 0.25 and CR 0.75 notwithstanding volumetric water contents of up to 0.18 $cm^3 cm^{-3}$. 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 0.07 $cm^3 cm^{-3}$ higher.



DOI: 10.1002/hyp

Although the present study from 20 to 24 September 2010 describes days when water repellency is apparent, water repellency is not always present under eastern redcedar. On September 16 four days prior to beginning the study, no trace of water repellency was measurable when preliminary measurements were conducted. Soils' affinity for water can vary because water repellent substances in soils are amphiphilic—they interact with water when soils wet and repel water when soils dry down (Hurra and Schaumann, 2006). Furthermore, soil organic matter and its constituents may vary seasonally, causing seasonal variation in soil water repellency (Buczko *et al*., 2005).

Soil water repellency is most important in systems in which the production of hydrophobic compounds is large relative to the surface area of soil grains that must be coated with hydrophobic substances to induce water repellency. Thus, the potential for development of hydrophobicity is related to climate and edaphic factors. In many arid regions, production of hydrophobic substances is limited by water availability (Jaramillo *et al*., 2000). In contrast, in many humid regions, soil water repellency may be expressed less frequently because topsoils are usually moister. Thus, Oklahoma's grassland-forest ecotone has potential to develop soil water repellency (Figure 5A) because precipitation is usually over 80 cm, providing plants with the water necessary to generate abundant hydrophobic compounds, yet high evaporative demand from June through September dries the topsoil during these months. Historically, soil water repellency was first documented in sandy soils (DeBano, 2000), and when different soil textures are compared, sandy soils often exhibit the strongest water repellency (Huffman *et al*., 2001). Despite the relatively fine-textured soils in the present study, including silty loam and clay loam, the climate of moderately high precipitation accompanied by high evaporative demand along Oklahoma's grassland-forest ecotone fosters the accumulation of water-repellent substances and expression of water repellency under eastern redcedar.

### *Soil water content*

The data in Figure 2C reveal interesting spatial patterns in soil water content in the vicinity of eastern redcedars. Lower water content under eastern redcedar trees may be attributed to high rainfall interception by junipers and their leaf litter (Skau, 1964; Owens *et al*., 2006; Lebron *et al*., 2007). Higher water content just beyond the canopy edge may result from a combination of lower interception by the grass species relative to eastern redcedar and reduced solar radiation due to shading from the tree canopy. Intermediate levels of soil water content beyond CR 1.5 may result from low 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 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.

In Nebraska, Smith and Stubbendieck (1990) found lower soil water content under eastern redcedar canopies than in the adjacent intercanopy zone, consistent with the results in Figure 2C. Similarly, in Kansas, lower soil water content was observed during the non-growing season under eastern redcedars relative to grassland (Smith and Johnson, 2004). Engle *et al*. (1987) found slightly lower soil moisture at the dripline of eastern redcedars than 3 m away from the canopy edge. 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.

### *Sorptivity and unsaturated hydraulic conductivity*

The trend of low sorptivity and hydraulic conductivity near eastern redcedar tree trunks and increasing values 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. The highest sorptivity and conductivity values were associated with the absence of leaf litter, relatively low water repellency and soil organic matter, and relatively high initial soil water contents. Sorptivity is a key parameter affecting the early stages of the rainfall infiltration process. The lower sorptivity values under eastern redcedar would result in earlier runoff production if rainfall were reaching the soil surface under redcedar and grass at the same rate. However, canopy and litter interception may be higher under eastern redcedar than in the grass interspaces. Therefore, the initial rate of water delivery to the soil surface under redcedar may be lower than under grass for the same rainfall event.

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 these evergreen trees than in the intercanopy. Similarly, Pierson *et al*. (2010) found lower runoff under Pinyon-Juniper trees with hydrophobic soils, implying greater infiltration under these trees relative to hydrophilic intercanopy areas. They attributed this effect to leaf litter promoting infiltration into the hydrophobic soils.

There are concerns that eastern redcedar encroachment reduces streamflow (Oklahoma Conservation Commission, 2006; Starks *et al*., 2011). We found lower sorptivity and hydraulic conductivity under eastern redcedar than in adjacent intercanopy spaces, which would result in greater runoff and streamflow if there were no other effects of redcedar, but clearly there are other effects.

In addition to the aforementioned rainfall interception effects, leaf litter exerts a frictional force slowing the flow



DOI: 10.1002/hyp

of water that may laterally distribute throughfall to locations where vertical transport can occur, such as macropores (Ritsema *et al*., 1993; Ritsema and Dekker, 1995). Greater porosity has been commonly observed under trees relative to grasses (Bachmair *et al*., 2009; Neary *et al*., 2009).

Thus, a plausible hypothesis may be that, when soils are dry, infiltration under eastern redcedar occurs largely via preferential flow paths that bypass much of the soil matrix. Increased preferential flow is common in hydrophobic soils and can infiltrate much or all overland flow induced by hydrophobic soils (Doerr and Moody, 2004; Lichner *et al*., 2007; Madsen *et al*., 2008; Lichner *et al*., 2010; Nyman *et al*., 2010; Robinson *et al*., 2010).

Though the present study focuses on hydraulic properties when soils are unsaturated, the soils in our study site do become hydrophilic and probably remain in that condition for a considerable proportion of the year depending on the amount and seasonal distribution of precipitation (Figure 5A). When soils are hydrophilic, hydraulic conductivities are likely higher in the presumably more porous soil—under eastern redcedar. The net effects of eastern redcedar encroachment on streamflow will arise from complex interactions between climate, precipitation, vegetation, the litter layer, and the soil. The soil hydraulic property effects reported in this study are an important and previously undocumented part of the overall picture, but clearly more research is needed.

### *Ecological implications amidst a changing climate*

In hydrophobic soils where preferential flow occurs, deeper wetting has been observed than would have occurred via piston flow (Robinson *et al*., 2010). In Pinyon-Juniper woodland in southeast Utah, this preferential flow process appeared to sequester soil water for plant use by reducing soil water evaporation (Robinson *et al*., 2010). Lab experiments also suggest that soil water repellency may conserve water for plant use by the aforementioned mechanism (Hillel and Berliner, 1974). It seems likely that a similar process would occur under eastern redcedar canopies. In addition, water-repellent soils under eastern redcedar may prevent shallow-rooted grasses from establishing (Osborn *et al*., 1967; Wallis *et al*., 1990; Tilman and Wedin, 1991). In this way, water repellency may also serve as a form of allelopathy (Doerr *et al*., 2000).

As the climate changes, increasing levels of $CO_2$ may increase soil water repellency (Gordon and Hallett, 2009). Longer droughts and heat waves are predicted under climate change; combined, these could lead to a greater duration of and perhaps more severe water repellency (Goebel *et al*., 2011). Thus, if climate change promotes the increase of soil water repellency, we can expect the observed effects on soil hydraulic properties to be accentuated.

## CONCLUSION

Rapid eastern redcedar encroachment into north-central Oklahoma during the second half of the 20th century transformed the landscape of this region and its hydrological processes. As eastern redcedars encroached into tallgrass prairie, hydrophobic leaf litter accumulated. As a result, organic matter in the topsoil increased under eastern redcedars. A corresponding increase in soil water repellency and decreases in sorptivity and unsaturated hydraulic conductivity were observed under eastern redcedar. Water repellency of the topsoil under redcedars is most likely to be expressed from May to October when soils are often dry. When soils are dry and hydrophobic, there may exist a greater potential for rapid preferential flow under eastern redcedar. We project that persistent eastern redcedar encroachment and global climate change will interact to promote greater severity, duration, and spatial prevalence of soil water repellency. Further research is necessary to determine how the significant impacts of eastern redcedar encroachment on soil surface conditions and soil hydraulic properties ultimately affect streamflow and the catchment water balance.

## ACKNOWLEDGEMENTS

We wish to thank the students in Oklahoma State University's 2010 Soil Physics Practicum for their indispensable field assistance in this project. We thank Drs. Chris Zou and Don Turton in the Oklahoma State University Dept. of Natural Resources Ecology and Management for developing the experiment site and providing us access. We thank the three anonymous reviewers whose comments greatly improved this paper. Oklahoma Mesonet data were provided courtesy of the Oklahoma Mesonet, a cooperative venture between Oklahoma State University and the University of Oklahoma and supported by the taxpayers of Oklahoma. The Oklahoma Agricultural Experiment Station and an Afanasiev Distinguished Graduate Student Fellowship provided financial support for this project.

## REFERENCES

Abrahams AD, Parsons AJ, Wainwright J. 1994. Resistance to overland flow on semiarid grassland and shrubland hillslopes, Walnut Gulch, southern Arizona. *Journal of Hydrology* **156**: 431–446.

Bachmair S, Weiler M, Nützmann, G. 2009. Controls of land use and soil structure on water movement: Lessons for pollutant transfer through the unsaturated zone. *Journal of Hydrology* **369**: 241–252.

Beven K, Germann P. 1982. Macropores and water flow in soils. *Water Resources Research* **18**: 1311–1325.

Bihmidine S, Bryan NM, Payne KR, Parde MR, Okalebo JA, Cooperstein SE, Awada T. 2010. Photosynthetic performance of invasive *Pinus ponderosa* and *Juniperus virginiana* seedlings under gradual soil water depletion. *Plant Biology* **12**: 668–675.

Blackburn WH, Skau CM. 1974. Infiltration rates and sediment production of selected plant communities in Nevada. *Journal of Range Management* **27**: 476–480.

Briggs JM, Hoch GA, Johnson LC. 2002. Assessing the rate, mechanisms, and consequences of the conversion of tallgrass prairie to *Juniperus virginiana* forest. *Ecosystems* **5**: 578–586.

Buczko U, Bens O, Huttl R. 2005. Variability of soil water repellency in sandy forest soils with different stand structure under Scots pine (*Pinus sylvestris*) and beech (*Fagus sylvatica*). *Geoderma* **126**: 317–336.

Capriel P, Beck T, Borchert H, Gronholz J, Zachmann G. 1995. Hydrophobicity of the organic matter in arable soils. *Soil Biology and Biochemistry* **27**: 1453–1458.

Carsel RF, Parrish RS. 1988. Developing joint probability distributions of soil water retention characteristics. *Water Resources Research* **24**: 755–769.

Clenton EO, Blan KR, Eaton BJ, Russ OG. 1973. Evaluation of eastern redcedar infestations in the northern Kansas Flint Hills. *Journal of Range Management* **26**: 256–260.

Coppedge BR, Engle DM, Masters RE, Gregory MS. 2001. Avian response to landscape change in fragmented southern Great Plains grasslands. *Ecological Applications* **11**: 47–59.

Crockford H, Topalidis S, Richardson DP. 1991. Water repellency in a dry sclerophyll eucalypt forest — measurements and processes. *Hydrological Processes* **5**: 405–420.

Czachor H, Doerr SH, Lichner L. 2010. Water retention of repellent and subcritical repellent soils: New insights from model and experimental investigations. *Journal of Hydrology* **380**: 104–111.

DeBano LF. 2000. Water repellency in soils: A historical overview. *Journal of Hydrology* **231–232**: 4–32.

Decagon Devices. 2011. *Mini disk infiltrometer user's manual*. Pullman: WA.

Dekker LW, Ritsema CJ. 1996. Preferential flow paths in a water repellent clay soil with grass cover. *Water Resources Research* **32**: 1239–1249.

Doerr SH, *et al*. 2003. Soil water repellency as a potential parameter in rainfall-runoff modelling: Experimental evidence at point to catchment scales from Portugal. *Hydrological Processes* **17**: 363–377.

Doerr SH, Moody, JA. 2004. Hydrological effects of soil water repellency: On spatial and temporal uncertainties. *Hydrological Processes* **18**: 829–832.

Doerr SH, Shakesby RA, Walsh RPD. 2000. Soil water repellency: Its causes, characteristics and hydro-geomorphological significance. *Earth-Science Reviews* **51**: 33–65.

Ellerbrock RH, Gerke HH, Bachmann J, Goebel MO. 2005. Composition of organic matter fractions for explaining wettability of three forest soils. *Soil Science Society of America Journal* **69**: 57–66.

Engle DM, Bernardo DJ, Hunter TD, Stritzke JF, Bidwell TG. 1996. A decision support system for designing juniper control treatments. *Ai Applications* **10**: 1–11.

Engle DM, Kulbeth JD. 1992. Growth dynamics of crowns of eastern redcedar at 3 locations in Oklahoma. *Journal of Range Management* **45**: 301–305.

Engle DM, Stritzke JF, Claypool PL. 1987. Herbage standing crop around eastern redcedar trees. *Journal of Range Management* **40**: 237–239.

Franco CMM, Clarke PJ, Tate ME, Oades JM. 2000. Hydrophobic properties and chemical characterisation of natural water repellent materials in Australian sands. *Journal of Hydrology* **231–232**: 47–58.

Gawde AJ, Cantrell CL, Zheljazkov VD. 2009. Dual extraction of essential oil and podophyllotoxin from *Juniperus virginiana*. *Industrial Crops and Products* **30**: 276–280.

Goebel M-O, Bachmann J, Reichstein M, Janssens IA, Guggenberger G. 2011. Soil water repellency and its implications for organic matter decomposition - is there a link to extreme climatic events? *Global Change Biology* **17**: 2640–2656.

Gordon D, Hallett P. 2009. Rise in CO2 affects soil water transport through repellency. *Biologia* **64**: 532–535.

Helsel DR, Hirsch RM. 2002. *Statistical methods in water resources. Techniques of water-resources investigations of the United States Geological Survey*. USGS: Reston, VA; 510.

Hemmerly TE. 1970. Economic uses of eastern red cedar. *Economic Botany* **24**: 39–41.

Hendrickx JMH, Dekker LW, Boersma OH. 1993. Unstable wetting fronts in water-repellent field soils. *Journal of Environmental Quality* **22**: 109–118.

Hester JW, Thurow TL, Taylor, Jr. CA 1997. Hydrologic characteristics of vegetation types as affected by prescribed burning. *Journal of Range Management* **50**: 199–204.

Hillel D, Berliner P. 1974. Waterproofing surface-zone soil aggregates for water conservation. *Soil Science* **118**: 131–135.

Huffman EL, MacDonald LH, Stednick JD. 2001. Strength and persistence of fire-induced soil hydrophobicity under ponderosa and lodgepole pine, Colorado front range. *Hydrological Processes* **15**: 2877–2892.

Huisman J, Breuer L, Frede H. 2004. Sensitivity of simulated hydrological fluxes towards changes in soil properties in response to land use change. *Physics and Chemistry of the Earth, Parts A/B/C* **29**: 749–758.

Hurra J, Schaumann G. 2006. Properties of soil organic matter and aqueous extracts of actually water repellent and wettable soil samples. *Geoderma* **132**: 222–239.

Illston BG, *et al*. 2008. Mesoscale monitoring of soil moisture across a statewide network. *Journal of Atmospheric & Oceanic Technology* **25**: 167–182.

Jaramillo DF, Dekker LW, Ritsema CJ, Hendrickx JMH. 2000. Occurrence of soil water repellency in arid and humid climates. *Journal of Hydrology* **231**: 105–111.

Jungerius PD, de Jong JH. 1989. Variability of water repellence in the dunes along the Dutch coast. *Catena* **16**: 491–497.

Krammes JS, Debano LF. 1965. Soil wettability - a neglected factor in watershed management. *Water Resources Research* **1**: 283–286.

Lebron I, *et al*. 2007. Ecohydrological controls on soil moisture and hydraulic conductivity within a pinyon-juniper woodland. *Water Resources Research* **43**: W08422.

Lichner L, *et al*. 2007. Field measurement of soil water repellency and its impact on water flow under different vegetation. *Biologia* **62**: 537–541.

Lichner L, *et al*. 2010. Vegetation impact on the hydrology of an aeolian sandy soil in a continental climate. *Ecohydrology* **3**: 413–420.

Logsdon SD. 1997. Transient variation in the infiltration rate during measurement with tension infiltrometers. *Soil Science* **162**: 233–241.

Madsen MD, Chandler DG, Belnap J. 2008. Spatial gradients in ecohydrologic properties within a pinyon-juniper ecosystem. *Ecohydrology* **1**: 349–360.

McGhie DA, Posner AM. 1981. The effect of plant top material on the water repellence of fired sands and water repellent soils. *Australian Journal of Agricultural Research* **32**: 609–620.

McKinley D, Blair J. 2008. Woody plant encroachment by *Juniperus virginiana* in a mesic native grassland promotes rapid carbon and nitrogen accrual. *Ecosystems* **11**: 454–468.

McKinley DC, Rice CW, Blair JM. 2008. Conversion of grassland to coniferous woodland has limited effects on soil nitrogen cycle processes. *Soil Biology and Biochemistry* **40**: 2627–2633.

Morton LW, Regen E, Engle DM, Miller JR, Harr RN. 2010. Perceptions of landowners concerning conservation, grazing, fire, and eastern redcedar management in tallgrass prairie. *Rangeland Ecology & Management* **63**: 645–654.

Murphy KL, Klopatek JM, Klopatek CC. 1998. The effects of litter quality and climate on decomposition along an elevational gradient. *Ecological Applications* **8**: 1061–1071.

Neary DG, Ice GG, Jackson CR. 2009. Linkages between forest soils and water quality and quantity. *Forest Ecology and Management* **258**: 2269–2281.

Nyman P, Sheridan G, Lane PNJ. 2010. Synergistic effects of water repellency and macropore flow on the hydraulic conductivity of a burned forest soil, south-east Australia. *Hydrological Processes* **24**: 2871–2887.

Oklahoma Conservation Commission. 2006. Eastern redcedar invading the landscape, Oklahoma City, 4.

Osborn J, Letey J, DeBano F, Terry E. 1967. Seed germination and establishment as affected by non-wettable soils and wetting agents. *Ecology* **48**: 494–497.

Owens MK, Lyons RK, Alejandro CL. 2006. Rainfall partitioning within semiarid juniper communities: Effects of event size and canopy cover. *Hydrological Processes* **20**: 3179–3189.

Pan C, Shangguan Z. 2006. Runoff hydraulic characteristics and sediment generation in sloped grassplots under simulated rainfall conditions. *Journal of Hydrology* **331**: 178–185.

Pierce AM, Reich PB. 2010. The effects of eastern red cedar (*Juniperus virginiana*) invasion and removal on a dry bluff prairie ecosystem. *Biological Invasions* **12**: 241–252.

Pierson FB, *et al*. 2010. Hydrologic vulnerability of sagebrush steppe following pinyon and juniper encroachment. *Rangeland Ecology & Management* **63**: 614–629.

Ritsema CJ, Dekker LW. 1994. How water moves in a water repellent sandy soil .2. Dynamics of fingered flow. *Water Resources Research* **30**: 2519–2531.

Ritsema CJ, Dekker LW. 1995. Distribution flow: A general process in the top layer of water repellent soils. *Water Resources Research* **31**: 1187–1200.

Ritsema CJ, Dekker LW, Heijs AWJ. 1997. Three-dimensional, fingered flow patterns in a water repellent sandy field soil. *Soil Science* **162**: 79–90.

Ritsema CJ, Dekker LW, Hendrickx JMH, Hamminga W. 1993. Preferential flow mechanism in a water repellent sandy soil. *Water Resources Research* **29**: 2183–2193.

Robinson DA, Lebron I, Ryel RJ, Jones SB. 2010. Soil water repellency: A method of soil moisture sequestration in pinyon-juniper woodland. *Soil Science Society of America Journal* **74**: 624–634.

Rodríguez-Alleres M, Benito E, de Blas E. 2007. Extent and persistence of water repellency in north-western Spanish soils. *Hydrological Processes* **21**: 2291–2299.

San Jose JJ, Montes RA, FariÒas MR. 1998. Carbon stocks and fluxes in a temporal scaling from a savanna to a semi-deciduous forest. *Forest Ecology and Management* **105**: 251–262.

Scholl DG. 1971. Soil wettability in Utah juniper stands. *Soil Science Society of America Proceedings* **35**: 344–345.

Scott DF, Van Wyk DB. 1990. The effects of wildfire on soil wettability and hydrological behaviour of an afforested catchment. *Journal of Hydrology* **121**: 239–256.

Skau CM. 1964. Interception, throughfall, and stemflow in Utah and alligator juniper cover types of northern Arizona. *Forest Science* **10**: 283–287.

Smith DL, Johnson L. 2004. Vegetation-mediated changes in microclimate reduce soil respiration as woodlands expand into grasslands. *Ecology* **85**: 3348–3361.

Smith DL, Johnson LC. 2003. Expansion of *Juniperus virginiana* L. In the Great Plains: Changes in soil organic carbon dynamics. *Global Biogeochemical Cycles* **17**: 1–12.

Smith SD, Stubbendieck J. 1990. Production of tall-grass prairie herbs below eastern redcedar. *Prairie Naturalist* **22**: 13–18.

Soil Conservation Service. 1987. *Soil survey of Payne county, Oklahoma*. The Service: Washington, D.C.

Starks PJ, Venuto BC, Eckroat JA, Lucas T. 2011. Measuring eastern redcedar (*Juniperus virginiana* L.) mass with the use of satellite imagery. *Rangeland Ecology & Management* **64**: 178–186.

Stoeser DB. 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.

Taucer PI, Munster CL, Wilcox BP, Owens MK, Mohanty BP. 2008. Large-scale rainfall simulation experiments on juniper rangelands. *Transactions of the ASABE* **51**: 1951–1961.

Teramura AH. 1980. Relationships between stand age and water repellency of chaparral soils. *Bulletin of the Torrey Botanical Club* **107**: 42–46.

Tilman D, Wedin D. 1991. Oscillations and chaos in the dynamics of a perennial grass. *Nature* **353**: 653–655.

Tortorelli RL. 2009. *Water use in Oklahoma 1950–2005*. U.S. Geological Survey: Reston, Va.

Van Els P, Will RE, Palmer MW, Hickman KR. 2010. Changes in forest understory associated with juniperus encroachment in Oklahoma, USA. *Applied Vegetation Science* **13**: 356–368.

Van Hooff P. 1983. Earthworm activity as a cause of splash erosion in a Luxembourg forest. *Geoderma* **31**: 195–204.

Verheijen FGA, Cammeraat LH. 2007. The association between three dominant shrub species and water repellent soils along a range of soil moisture contents in semi-arid Spain. *Hydrological Processes* **21**: 2310–2316.

Volder A, Tjoelker MG, Briske DD. 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**: 3349–3362.

Wallis MG, Horne DJ, McAuliffe KW. 1990. A study of water repellency and its amelioration in a yellow-brown sand .2. Use of wetting agents and their interaction with some aspects of irrigation. *New Zealand Journal of Agricultural Research* **33**: 145–150.

Wallis MG, Horne DJ, Palmer AS. 1993. Water repellency in a New Zealand development sequence of yellow-brown sands. *Australian Journal of Soil Research* **31**: 641–654.

Wilcox BP, Breshears DD, Turin HJ. 2003. Hydraulic conductivity in a pinon-juniper woodland: Influence of vegetation. *Soil Science Society of America Journal* **67**: 1243–1249.

Zhang RD. 1997. Determination of soil sorptivity and hydraulic conductivity from the disk infiltrometer. *Soil Science Society of America Journal* **61**: 1024–1030.




DOI: 10.1002/hyp