

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

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30 SUMMARY:

31 The effects of eastern redcedar (*Juniperus virginiana*) encroachment into grassland on soil
32 hydraulic properties have not been determined. This creates uncertainty in understanding the
33 hydrologic effects of eastern redcedar encroachment and obstructs fact-based management of
34 encroached systems. The objective of this study was to quantify the effects of eastern redcedar
35 encroachment into tallgrass prairie on soil hydraulic properties. Soil water content, soil organic
36 carbon, soil water repellency, sorptivity, and unsaturated hydraulic conductivity were measured
37 along 12 radial transects from eastern redcedar trunks to the center of the grassy intercanopy
38 space. Bulk density and soil water retention were also measured under eastern redcedar and in
39 the tall grass prairie intercanopy area. Soil organic matter in the upper six cm of soil was 49%
40 higher under eastern redcedar trees (5.96 mg kg^{-1}) than in the grass-dominated intercanopy area
41 (3.99 mg kg^{-1}). Median sorptivity under grass was $.68 \text{ mm s}^{-1/2}$, seven times greater than under
42 eastern redcedar canopies ($.10 \text{ mm s}^{-1/2}$). Median unsaturated hydraulic conductivity under grass
43 was 2.52 cm h^{-1} , four times greater than under eastern redcedar canopies ($.57 \text{ cm h}^{-1}$). Porosity
44 was higher under eastern redcedar trees as was soil water retention, both at the dry and wet ends
45 of the retention curve. These results indicate that when managing eastern redcedar encroachment
46 it is critical to consider the soil hydraulic properties of eastern redcedar and tallgrass prairie, both
47 in understanding the mechanisms and hydrologic consequences of encroachment.

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

50 hydrology

51 **Introduction**

52 Eastern redcedar encroachment has been extensively documented in the Southern Plains
53 of the U.S. (Coppedge et al., 2001) though the exact extent of eastern redcedar encroachment
54 remains elusive. Many landowners consider widespread encroachment to be a problem and have
55 undertaken to control eastern redcedar (Clenton et al., 1973; Engle et al., 1996; Engle and
56 Kulbeth, 1992; Morton et al., 2010). Furthermore, climate change may favor encroachment of
57 eastern redcedar into C₄ grassland (Volder et al., 2010). Understanding the effects of eastern
58 redcedar encroachment on soil hydraulic properties is critical to managing present and future
59 encroachment. Whereas the effects of Utah juniper (*Juniperus osteosperma*) on soil hydraulic
60 properties have been extensively investigated in Utah (Lebron et al., 2007; Madsen et al., 2008;
61 Pierson et al., 2010; Robinson et al., 2010), little is known about eastern redcedar effects on soil
62 hydraulic properties. Although these effects of eastern redcedar encroachment are key
63 determinants of the spatiotemporal fate of throughfall, they are not generally considered by land
64 management agencies or ranchers with regard to eastern redcedar removal.

65 Eastern redcedars' thick leaf litter layer distinguishes the soil under an eastern redcedar
66 tree from that under grass (Van Els et al., 2010); in other species in the *Juniperus* genus leaf litter
67 depth has been correlated with the hydrologic effects of the tree. For example, Madsen et al.
68 (2008) found that under Utah juniper litter, soil water content was inversely related to litter
69 depth. When soils with high organic matter content dry down they can become water repellent or
70 hydrophobic (Jaramillo et al., 2000). At a small scale, dry, hydrophobic soils induce higher rates
71 of runoff (Doerr et al., 2000). At a larger scale, runoff from well-vegetated hydrophobic soils
72 often concentrates over more hydrophilic soils or macropores resulting in deep infiltration via
73 preferential flow. This effectively sequesters moisture for plant growth that might have been lost

74 to evaporation had rainfall infiltrated uniformly and shallowly (Jaramillo et al., 2000; Robinson
75 et al., 2010). As a result, in areas of hydrophobic soils, infiltration of rainfall is non-uniform and
76 is associated with unstable wetting fronts (Hendrickx et al., 1993), fingered flow (Ritsema and
77 Dekker, 1994; Ritsema et al., 1997), or preferential flow (Dekker and Ritsema, 1996). Research
78 at Konza Prairie in Kansas uncovered rapid accretion of soil carbon when eastern redcedar
79 encroached into grassland (McKinley and Blair, 2008), indicating that this species could
80 potentially cause soils to become hydrophobic when they are dry. Since hydrophobicity is
81 enhanced when soil water content is low it is not readily observed by conventional, ponded
82 infiltrometers, such as double-ring infiltrometers, which are commonly used to characterize the
83 infiltration rate or soil hydraulic conductivity of soils in water-limited regions (e.g., Blackburn
84 and Skau, 1974; Wilcox et al., 2003). Understanding the capacity of soil to absorb and conduct
85 water in unsaturated conditions may be more relevant for soils exhibiting hydrophobicity.

86 The high soil organic matter observed under eastern redcedar (McKinley and Blair,
87 2008), could increase soil water retention at high suctions because at such suctions soil water
88 retention is sensitive to clay content and soil organic matter (Gupta and Larson, 1979).

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

94 **Materials and Methods**

95 *Experimental Site*

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

108 *Experimental Design*

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

118 *Measurements*

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

130 Infiltration was measured in the field using 15.9 cm² Mini Disk tension infiltrometers
131 (Decagon Devices, Pullman, WA) at 1.0 cm of suction. Soil texture of the upper six cm of soil
132 was determined by the hydrometer method and class average van Genuchten parameters (Carsel
133 and Parrish, 1988) were used in calculating A_1 and A_2 , dimensionless coefficients related to
134 sorptivity and hydraulic conductivity, respectively. Parameters related to sorptivity (C_1) and
135 hydraulic conductivity (C_2) were calculated by fitting a second order polynomial equation to the
136 cumulative infiltration plotted against the square root of time (Zhang, 1997). Sorptivity and
137 hydraulic conductivity were then calculated as the quotient of the regression-fit parameters
138 divided by the dimensionless coefficients. Surface soil hydrophobicity was measured by
139 assessing whether a water droplet beaded on the surface or infiltrated after five seconds
140 (Krammes and Debano, 1965).

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

152 *Data Analysis*

153 In 36 cases, cumulative infiltration into the soil over a period of 30 minutes was less than
154 15 mL. In these cases the hydraulic conductivity and sorptivity were considered below the
155 detection limit and these values were approximated by dividing the lowest measured hydraulic
156 conductivity at that tree by two. This approach seems reasonable because hydraulic conductivity
157 and sorptivity in the hydrophobic soils of the study site approached zero in certain cases.

158 Since the twelve trees examined in this study varied in canopy radius (CR), all data
159 analysis was conducted by dividing the distance of the observation from the tree trunk by the
160 canopy radius and grouping these normalized distances into quartiles (Madsen et al., 2008). The
161 number of measurements included in each quartile ranged from 15 to 17. A significance level of
162 $\alpha = .10$ was used throughout the study. Mann-Whitney tests were used to test for significant
163 differences in bulk density and soil organic matter because of small samples sizes. Analysis of

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

171 **Results**

172 *Soil surface cover, organic matter, and water content*

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

186 *Hydrophobicity, sorptivity, and unsaturated hydraulic conductivity*

187 Soil water repellency was prevalent both under the canopy and in the intercanopy area
188 (Fig. 3). Of sites under eastern redcedar 94% exhibited water repellency; in contrast 65% of
189 intercanopy sites repelled water. Median sorptivity and unsaturated hydraulic conductivity were
190 lowest from the tree trunk to CR .75 and thereafter increased monotonically until CR 1.5 (Fig.
191 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
192 unsaturated hydraulic conductivity ranged from .236 cm h⁻¹ at CR .25 to 3.182 cm h⁻¹ at CR 2.0.
193 From CR 1.5 through 2.0, the central tendency of unsaturated hydraulic conductivity and
194 sorptivity increased slightly. Significant differences in mean unsaturated hydraulic conductivity
195 among the quadrants ($p < .001$) explained 57% of the variability in unsaturated hydraulic
196 conductivity. Significant differences in mean sorptivity among the quadrants ($p < .001$)
197 explained 60% of the variability in sorptivity.

198 *Soil water retention, bulk density, and porosity*

199 Soils collected under the eastern redcedar canopy exhibited higher volumetric water
200 content at both dry and wet ends of the soil water retention curve (Fig. 5). Median bulk density
201 under the cedar canopy was significantly lower and porosity higher, relative to the intercanopy (p
202 = .0472, Table 2).

203 **Discussion**

204 *Leaf litter and soil organic carbon*

205 Juniper leaf litter may influence the hydrology of encroached systems by intercepting
206 precipitation (Owens et al., 2006) and by serving as a source of soil carbon (Smith and Johnson,
207 2003) and hydrophobic molecules (Doerr et al., 2000; Gawde et al., 2009). Whereas Smith and
208 Johnson (2003) found that eastern redcedar encroachment into grassland caused no net increase

209 in soil carbon storage, in the upper 25 cm of soil, the present study notes a dramatic increase in
210 soil organic carbon in the top 6 cm of soil that may be hydrologically important.

211 *Soil water content*

212 In Nebraska, Smith and Stubbendieck (1990) found lower soil water content under
213 eastern redcedar canopies than in the adjacent interstitial zone, consistent with the results in Fig.
214 2c. In contrast, Pierce and Reich (2010) found increased soil water content under eastern
215 redcedar relative to grassland. They attributed this to infiltration of runoff from higher on the
216 sloped study site. Engle et al. (1987) found slightly lower soil moisture at the dripline of eastern
217 redcedars than 3 m away from the canopy edge. However, the data in Fig. 2c reveal a complex
218 spatial pattern in soil water content in the vicinity of eastern redcedars. Lower water content
219 under the eastern redcedar trees may be attributed to high rainfall interception by junipers
220 (Lebron et al., 2007; Owens et al., 2006; Skau, 1964). Higher water content just beyond the
221 canopy edge may result from a combination of lower interception by the grass species and
222 reduced solar radiation due to shading from the cedar tree canopy. Intermediate levels of soil
223 water content beyond CR 1.5 may result from low levels of rainfall interception by the grass and
224 higher levels of solar radiation well beyond the juniper canopy. Our results differ from those of
225 Madsen et al. (2008), in that the latter study in a Pinyon-Juniper woodland found that soil water
226 content remained constant beyond the tree canopy. Uniformly high soil water content in the
227 intercanopy area in that study may have resulted from low evaporative demand since the
228 investigation was conducted in the winter. In contrast, the present study was conducted at a time
229 of year with higher evaporative demand.

230 *Soil water repellency*

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

248 *Sorptivity and unsaturated hydraulic conductivity*

249 Though the effects of vegetation on the sorptivity of a soil are a critical determinant of
250 the spatiotemporal fate of throughfall, sorptivity has only rarely been quantified on rangelands
251 (e.g., Madsen et al., 2008). The trend of low sorptivity near eastern redcedar tree trunks and
252 increasing sorptivity from CR 0.5 to CR 1.5 in the present study was similar to that reported by
253 Madsen et al. (2008) for Pinyon-Juniper woodland. However, in the present study, sorptivity and

254 unsaturated hydraulic conductivity in the subcanopy were lower relative to the Pinyon-Juniper
255 woodland. Lower subcanopy sorptivity in the present study may have resulted from finer
256 textured soils or from greater inputs of hydrophobic compounds from plants, since the average
257 annual precipitation in the present study is 60 cm greater than in the Pinyon-Juniper woodland.

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

272 *Soil water retention and bulk density*

273 Soil water retention and bulk density data should be considered preliminary because these
274 samples were taken only from one site each. The authors are aware of no prior attempt to
275 quantify encroachment effects on soil water retention. At low suctions, soil water retention is
276 most strongly related to porosity and at the high suctions, it is related to several factors, including

277 soil organic matter (Gupta and Larson, 1979). Our results are similar to work from Sri Lanka that
278 uncovered higher soil organic matter and soil water retention at an afforested site, relative to an
279 adjacent grassland, with similar land use history (Mapa, 1995). That study concluded that the
280 high porosities indicate that “reforested areas can accept and store more water” than grassland.
281 However, further research is needed to assess if this assertion is valid in the case of eastern
282 redcedar encroachment into tallgrass prairie. Plant roots provide an important force in creating
283 macropores (Angers and Caron, 1998). Another potential influence on soil porosity in redcedar
284 encroached systems is livestock grazing, which would increase the bulk density of surface soil
285 under grass (Daniel et al., 2002), but not under redcedar canopies.

286 **Conclusion**

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

299 understanding the mechanism of encroachment and the effects of encroachment on the
 300 partitioning of throughfall.

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305 **References**

- 306 Angers, D.A. and Caron, J., 1998. Plant-induced Changes in Soil Structure: Processes and
 307 Feedbacks. *Biogeochemistry*, 42(1): 55-72.
- 308 Blackburn, W.H. and Skau, C.M., 1974. INFILTRATION RATES AND SEDIMENT
 309 PRODUCTION OF SELECTED PLANT COMMUNITIES IN NEVADA. *Journal of Range*
 310 *Management*, 27(6): 476-480.
- 311 Blonquist, J.M., Jones, S.B. and Robinson, D.A., 2005. Standardizing Characterization of
 312 Electromagnetic Water Content Sensors. *Vadose Zone J.*, 4(4): 1059-1069.
- 313 Carsel, R.F. and Parrish, R.S., 1988. Developing Joint Probability Distributions of Soil Water
 314 Retention Characteristics. *Water Resources Research*, 24.
- 315 Cisar, J.L., Williams, K.E., Vivas, H.E. and Haydu, J.J., 2000. The occurrence and alleviation by
 316 surfactants of soil-water repellency on sand-based turfgrass systems. *Journal of*
 317 *Hydrology*, 231: 352-358.
- 318 Clenton, E.O., Blan, K.R., Eaton, B.J. and Russ, O.G., 1973. Evaluation of Eastern Redcedar
 319 Infestations in the Northern Kansas Flint Hills. *Journal of Range Management*, 26(4):
 320 256-260.
- 321 Coppedge, B.R., Engle, D.M., Masters, R.E. and Gregory, M.S., 2001. Avian response to
 322 landscape change in fragmented Southern Great Plains grasslands. *Ecological*
 323 *Applications*, 11(1): 47-59.
- 324 Czachor, H., Doerr, S.H. and Lichner, L., 2010. Water retention of repellent and subcritical
 325 repellent soils: New insights from model and experimental investigations. *Journal of*
 326 *Hydrology*, 380(1-2): 104-111.
- 327 Daniel, J.A., Potter, K., Altom, W., Aljoe, H. and Stevens, R., 2002. Long-term grazing density
 328 impacts on soil compaction. *Transactions of the ASAE*, 45(6): 1911-1915.
- 329 Dekker, L.W. and Ritsema, C.J., 1996. Preferential flow paths in a water repellent clay soil
 330 with grass cover. *Water Resources Research*, 32(5): 1239-1249.
- 331 Doerr, S.H., Shakesby, R.A. and Walsh, R.P.D., 2000. Soil water repellency: its causes,
 332 characteristics and hydro-geomorphological significance. *Earth-Science Reviews*,
 333 51(1-4): 33-65.
- 334 Engle, D.M., Bernardo, D.J., Hunter, T.D., Stritzke, J.F. and Bidwell, T.G., 1996. A decision
 335 support system for designing juniper control treatments. *Ai Applications*, 10(1): 1-
 336 11.

- 337 Engle, D.M., Bodine, T.N. and Stritzke, J.F., 2006. Woody Plant Community in the Cross
338 Timbers Over Two Decades of Brush Treatments. *Rangeland Ecology &*
339 *Management*, 59(2): 153-162.
- 340 Engle, D.M. and Kulbeth, J.D., 1992. Growth Dynamics of Crowns of Eastern Redcedar at 3
341 Locations in Oklahoma. *Journal of Range Management*, 45(3): 301-305.
- 342 Engle, D.M., Stritzke, J.F. and Claypool, P.L., 1987. Herbage Standing Crop around Eastern
343 Redcedar Trees. *Journal of Range Management*, 40(3): 237-239.
- 344 Gawde, A.J., Cantrell, C.L. and Zheljzkov, V.D., 2009. Dual extraction of essential oil and
345 podophyllotoxin from *Juniperus virginiana*. *Industrial Crops and Products*, 30(2):
346 276-280.
- 347 Gupta, S.C. and Larson, W.E., 1979. ESTIMATING SOIL-WATER RETENTION
348 CHARACTERISTICS FROM PARTICLE-SIZE DISTRIBUTION, ORGANIC-MATTER
349 PERCENT, AND BULK-DENSITY. *Water Resources Research*, 15(6): 1633-1635.
- 350 Helsel, D.R. and Hirsch, R.M., 2002. *Statistical Methods in Water Resources*. Techniques of
351 Water-Resources Investigations of the United States Geological Survey. USGS, 510
352 pp.
- 353 Hemmerly, T.E., 1970. Economic Uses of Eastern Red Cedar. *Economic Botany*, 24(1): 39-
354 41.
- 355 Hendrickx, J.M.H., Dekker, L.W. and Boersma, O.H., 1993. Unstable Wetting Fronts in Water-
356 Repellent Field Soils. *Journal of Environmental Quality*, 22(1): 109-118.
- 357 Jaramillo, D.F., Dekker, L.W., Ritsema, C.J. and Hendrickx, J.M.H., 2000. Occurrence of soil
358 water repellency in arid and humid climates. *Journal of Hydrology*, 231: 105-111.
- 359 Krammes, J.S. and DeBano, L.F., 1965. SOIL WETTABILITY - A NEGLECTED FACTOR IN
360 WATERSHED MANAGEMENT. *Water Resources Research*, 1(2): 283-&.
- 361 Lebron, I. et al., 2007. Ecohydrological controls on soil moisture and hydraulic conductivity
362 within a pinyon-juniper woodland. *Water Resour. Res.*, 43(8): W08422.
- 363 Madsen, M.D., Chandler, D.G. and Belnap, J., 2008. Spatial gradients in ecohydrologic
364 properties within a pinyon-juniper ecosystem. *Ecohydrology*, 1(4): 349-360.
- 365 Mapa, R.B., 1995. EFFECT OF REFORESTATION USING *TECTONA-GRANDIS* ON
366 INFILTRATION AND SOIL-WATER RETENTION. *Forest Ecology and Management*,
367 77(1-3): 119-125.
- 368 McKinley, D. and Blair, J., 2008. Woody Plant Encroachment by *Juniperus virginiana* in a
369 Mesic Native Grassland Promotes Rapid Carbon and Nitrogen Accrual. *Ecosystems*,
370 11(3): 454-468.
- 371 Morton, L.W., Regen, E., Engle, D.M., Miller, J.R. and Harr, R.N., 2010. Perceptions of
372 Landowners Concerning Conservation, Grazing, Fire, and Eastern Redcedar
373 Management in Tallgrass Prairie. *Rangeland Ecology & Management*, 63(6): 645-
374 654.
- 375 Owens, M.K., Lyons, R.K. and Alejandro, C.L., 2006. Rainfall partitioning within semiarid
376 juniper communities: effects of event size and canopy cover. *Hydrological Processes*,
377 20(15): 3179-3189.
- 378 Pierce, A.M. and Reich, P.B., 2010. The effects of eastern red cedar (*Juniperus virginiana*)
379 invasion and removal on a dry bluff prairie ecosystem. *Biological Invasions*, 12(1):
380 241-252.
- 381 Pierson, F.B. et al., 2010. Hydrologic Vulnerability of Sagebrush Steppe Following Pinyon
382 and Juniper Encroachment. *Rangeland Ecology & Management*, 63(6): 614-629.

- 383 Ritsema, C.J. and Dekker, L.W., 1994. HOW WATER MOVES IN A WATER REPELLENT
384 SANDY SOIL .2. DYNAMICS OF FINGERED FLOW. *Water Resources Research*, 30(9):
385 2519-2531.
- 386 Ritsema, C.J., Dekker, L.W. and Heijs, A.W.J., 1997. Three-dimensional, fingered flow
387 patterns in a water repellent sandy field soil. *Soil Science*, 162(2): 79-90.
- 388 Robinson, D.A., Lebron, I., Ryel, R.J. and Jones, S.B., 2010. Soil Water Repellency: A Method
389 of Soil Moisture Sequestration in Pinyon-Juniper Woodland. *Soil Science Society of
390 America Journal*, 74(2): 624-634.
- 391 Skau, C.M., 1964. Interception, Throughfall, and Stemflow in Utah and Alligator Juniper
392 Cover Types of Northern Arizona. *Forest Science*, 10: 283-287.
- 393 Smith, D.L. and Johnson, L.C., 2003. Expansion of *Juniperus virginiana* L. in the Great Plains:
394 Changes in soil organic carbon dynamics. *Global Biogeochemical Cycles*, 17(2).
- 395 Smith, S.D. and Stubbendieck, J., 1990. Production of tall-grass prairie herbs below eastern
396 redcedar. *Prairie Naturalist*, 22(1): 13-18.
- 397 Soil Conservation Service, 1987. Soil survey of Payne County, Oklahoma. The Service,
398 Washington, D.C.
- 399 Stoesser, D.B., 2005. Preliminary integrated geologic map databases for the United States:
400 Central states, Montana, Wyoming, Colorado, New Mexico, Kansas, Oklahoma, Texas,
401 Missouri, Arkansas, and Louisiana. USGS, Reston.
- 402 Van Els, P., Will, R.E., Palmer, M.W. and Hickman, K.R., 2010. Changes in forest understory
403 associated with *Juniperus* encroachment in Oklahoma, USA. *Applied Vegetation
404 Science*, 13(3): 356-368.
- 405 Volder, A., Tjoelker, M.G. and Briske, D.D., 2010. Contrasting physiological responsiveness
406 of establishing trees and a C4 grass to rainfall events, intensified summer drought,
407 and warming in oak savanna. *Global Change Biology*, 16(12): 3349-3362.
- 408 Wessolek, G., Stoffregen, H. and Taumer, K., 2009. Persistency of flow patterns in a water
409 repellent sandy soil - Conclusions of TDR readings and a time-delayed double tracer
410 experiment. *Journal of Hydrology*, 375(3-4): 524-535.
- 411 Wilcox, B.P., Breshears, D.D. and Turin, H.J., 2003. Hydraulic conductivity in a pinon-juniper
412 woodland: Influence of vegetation. *Soil Science Society of America Journal*, 67(4):
413 1243-1249.
- 414 Zhang, R.D., 1997. Determination of soil sorptivity and hydraulic conductivity from the disk
415 infiltrometer. *Soil Science Society of America Journal*, 61(4): 1024-1030.
- 416
417
418

419 Table 1. Median, first quartile, and third quartile of water content, hydraulic conductivity, and
 420 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

421

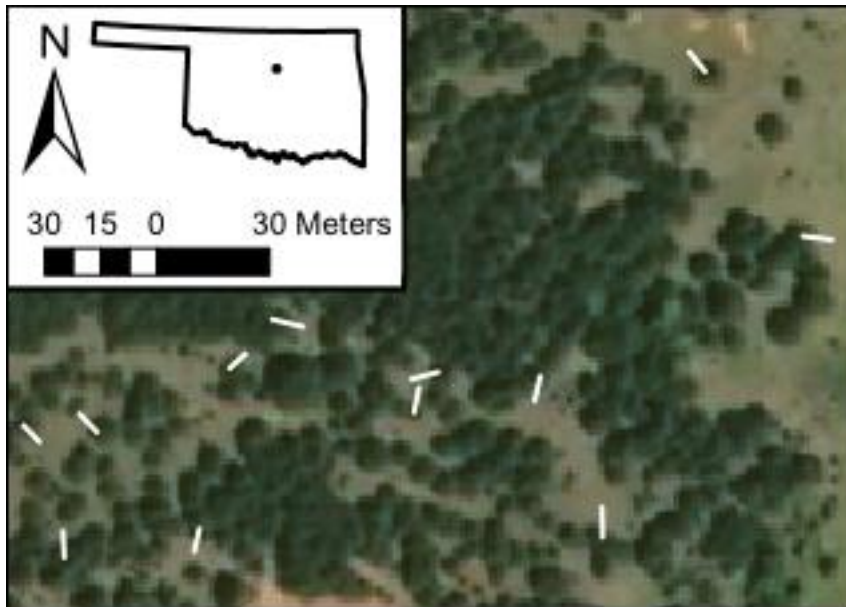
422

423 Table 2. Soil bulk density and porosity beneath the canopy of an eastern redcedar and in the
 424 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

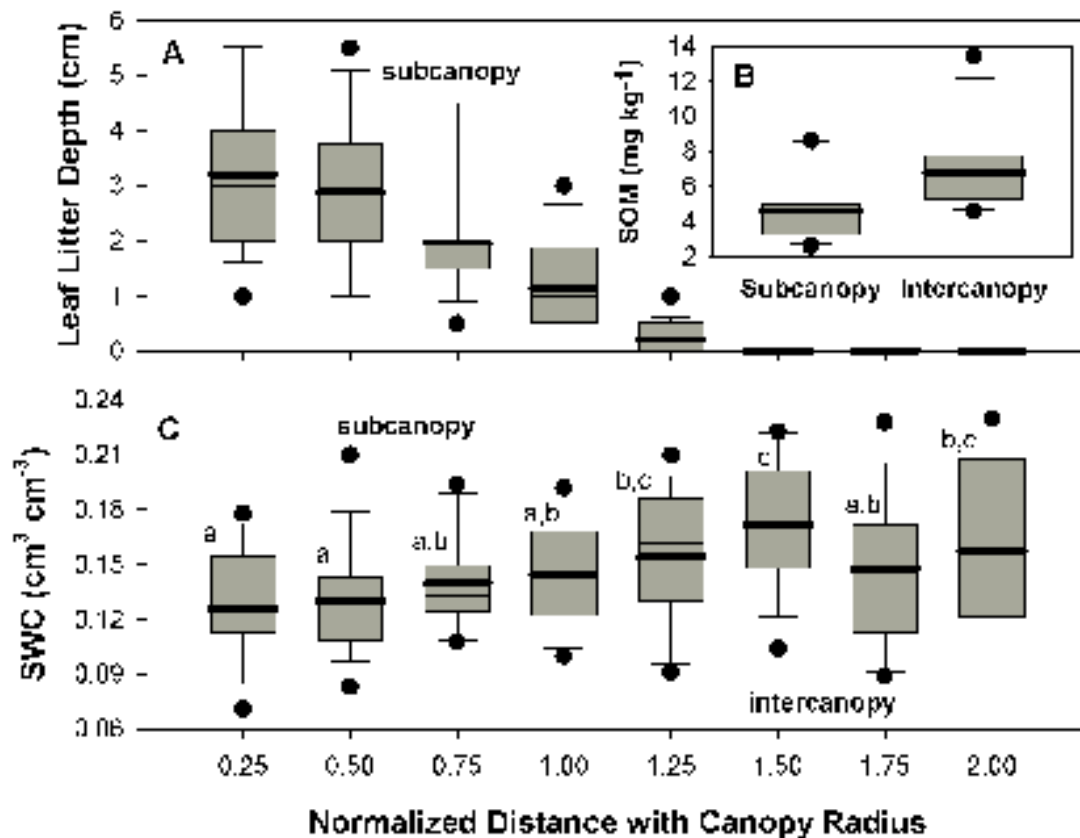
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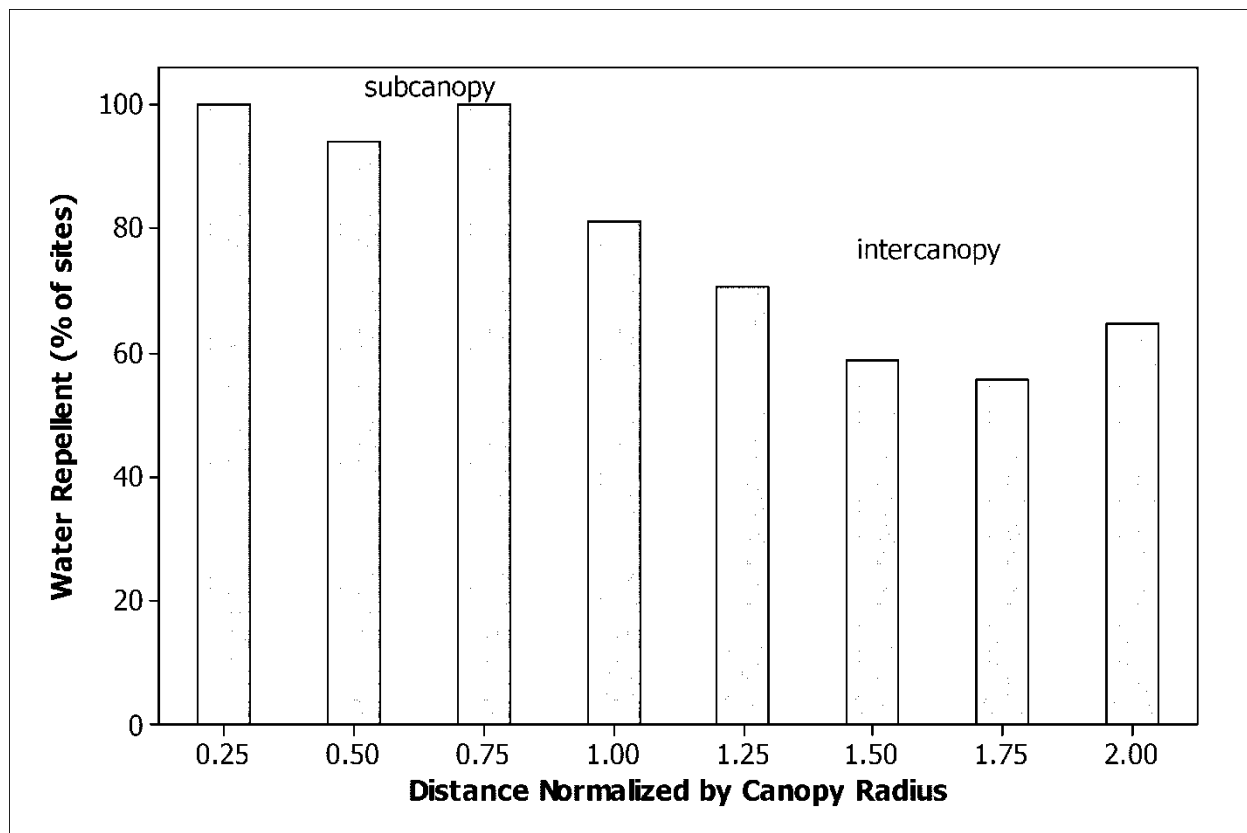


427

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

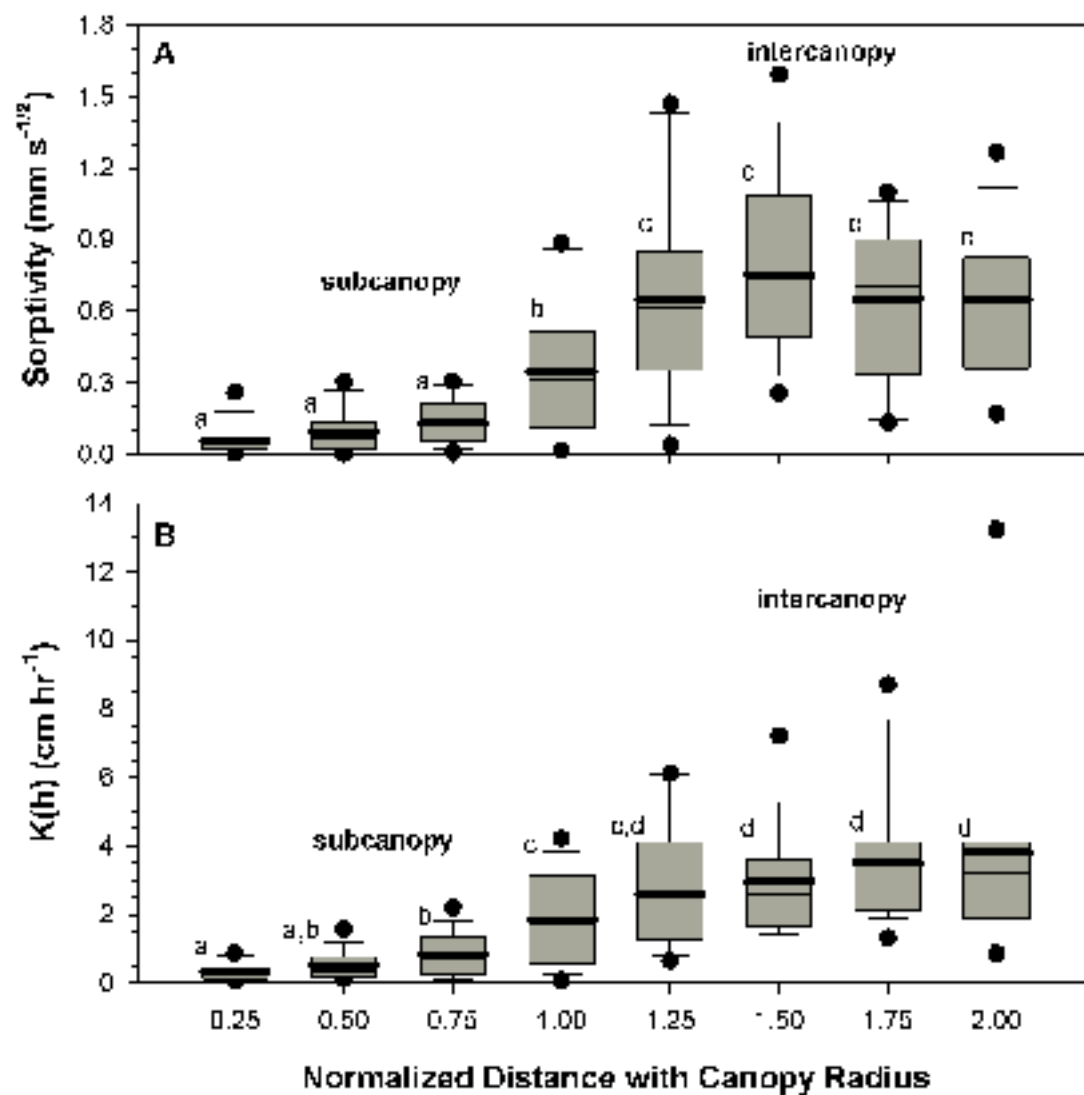


431
 432 Figure 2. Black dots represent outliers and whiskers indicate the 5th and 95th percentiles. From
 433 bottom to top, the three lines in each box represent the first quartile, median, and third quartile.
 434 The heavy black lines represent the mean and similar letters indicate no statistically significant
 435 differences. The four subcanopy quadrants are 0.25 -1.0 and the four intercanopy quadrants are
 436 1.25 to 2.0. (a) Leaf litter depth, (b) soil organic matter, and (c) volumetric soil water content.



437

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

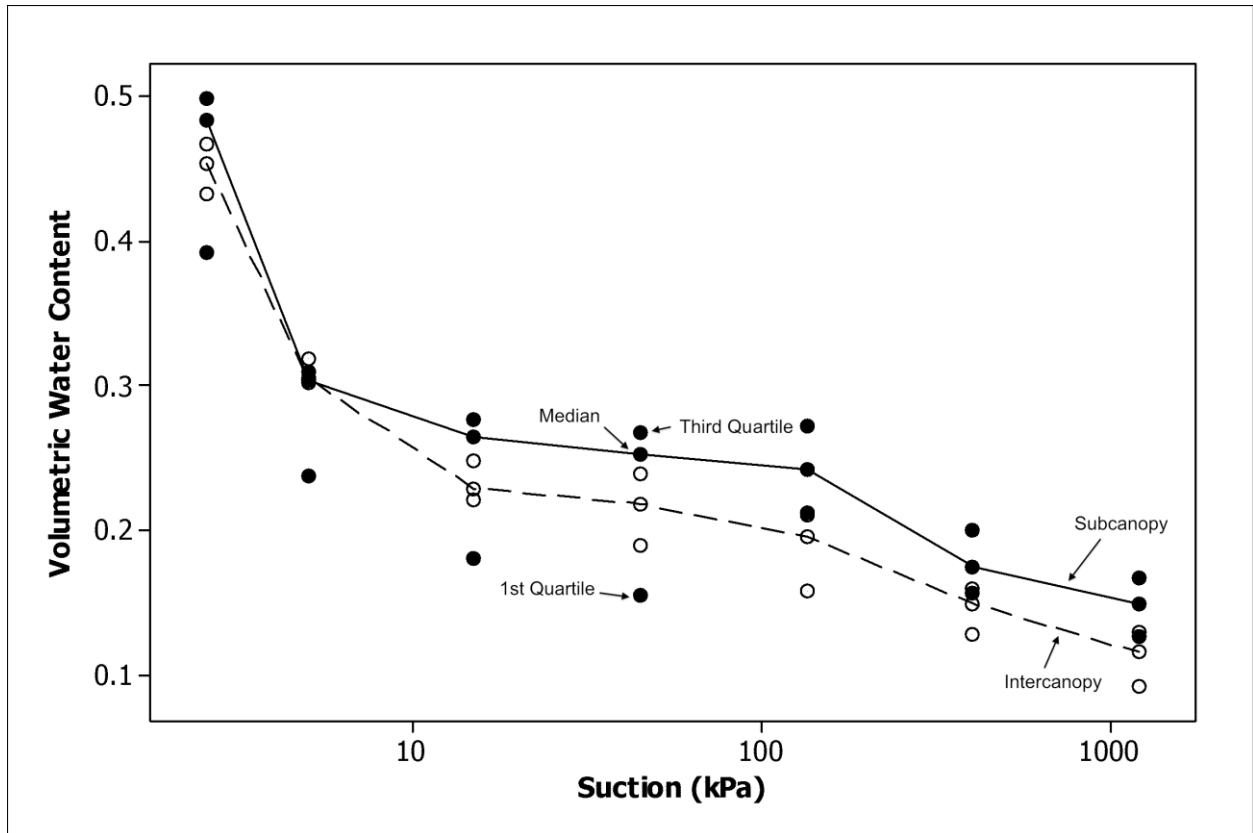


439

440 Figure 4. Variation in (a) sorptivity and (b) unsaturated hydraulic conductivity versus distance

441 from eastern redcedar trunk normalized by canopy radius.

442



443

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