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Measurements of Canopy Interception and Transpiration of Eastern Redcedar Grown in Open Environments

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Abstract

Eastern redcedar (*Juniperus virginiana* L.) is rapidly encroaching and degrading native prairie and rangeland landscapes in the Great Plains of the U.S. Little is known concerning the impacts of increasing redcedar density and areal coverage on local and regional water budgets through transpiration (T_r) and canopy interception (C_I) of precipitation. Limited T_r and C_I studies have been conducted in dense stands of redcedar but results from these studies may not be applicable to redcedar growing in open environments. Four redcedar trees (two large, two small) were located in central Oklahoma to measure T_r. Two limbs (one on the north face and one on the south face) on each of the large trees were instrumented with sapflux sensors to measure T_r from August 2010 through mid-July 2012. Limb level T_r was scaled to tree level T_r using ratios of both leaf and bole areas. Whole tree T_r was measured on two small redcedar trees from mid-May 2011 through mid-July 2012. Transpiration of the small redcedars was found to respond quickly to precipitation events, while the large redcedars did not. Redcedar T_r was compared to that of native grasses. The large redcedars exhibited higher T_r rates than native grasses while the small redcedars transpired at rates closely matching native grasses. Four different redcedars were instrumented to measure C_I from October 2009 through mid-July of 2012. Redcedar canopies were found to intercept 100% of precipitation for events ≤ 2.4 mm. Redcedar canopies reduce annual precipitation received at the surface by about 33%, and as much as 39% in the western portion of the state. Significant canopy interception of precipitation, coupled with T_r rates as large as or larger than native grasses and with year-round T_r, suggests increases in redcedar density and areal coverage could affect local water resources (e.g. reducing infiltration, runoff, and ground water recharge rates).

Keywords: juniper, transpiration, canopy interception, leaf area, sap flux, water use

1. Introduction

Eastern redcedar (*Juniperus virginiana* L.), herein referred to as redcedar, is a coniferous evergreen species common to the eastern half of the U.S. (Lawson, 1990). In recent decades, it has been rapidly encroaching and degrading native prairie and rangeland landscapes in the Great Plains of the U.S. McKinley, Norris, Blair and Johnson (2008) state that redcedar has encroached upon about 7 million hectares of grasslands in the eastern portion of the Great Plains. Historically, native prairies experienced periodic burns that destroyed redcedar seedlings and limited their encroachment (Abrams & Gibson, 1991; Van Auken, 2000). Woody plant invasion of prairies and the effects of fire exclusion on structure and function of prairie systems have been clearly documented (Bragg & Hulbert, 1976; Abrams & Gibson, 1991). Snook (1985) estimated 600,000 hectares of Oklahoma's native grassland had been encroached upon by redcedar as early as 1950. Recent estimates indicate as much as 3.2 million hectares of grassland have been encroached by redcedar in the state (Drake & Todd, 2002), and suggest an average rate of land encroachment of approximately 121,400 hectares per year.

Invasive alien and aggressively encroaching native plant species are of worldwide concern (Clout & Poorter, 2005), as they reduce biodiversity (Horncastle, et al., 2005; Le Maitre et al., 2011), may negatively impact soil processes and nutrient cycling (Blank, 2008; Corbin & D'Antonio, 2014), and reduce land available for production of food and fiber (Engle, 1985; Le Maitre et al., 2011). Considerable research has been conducted assessing the impacts of invasive plant species on local and regional hydrology (Le Matire et al., 2011). Le Maitre et al. (2002) studied the impact of invasive alien trees in the Sonderend, Keurbooms, Upper Wilge, and Sabie-Sand catchments in South Africa. At the time of the study (2002), 44, 54, 2, and 23%, respectively, of each catchment had been invaded by non-native trees resulting in 7.2, 22.1, 6.0, and 9.4% reductions in river flow. These authors stated that given an annual expansion rate of 10–15% that 51, 77, and 70% of the Sonderend, Keurbooms, and Upper Wilge catchments would be invaded by alien trees in 13 to 63 years. The invadable areas of the Sabie-Sand catchment were deemed already invaded, but tree density would further increase leading to 100% canopy cover in 26-30 years. Resulting projected reductions in river flows would increase to 41.5, 95.5, 25.1, and 22.3%. Doody and Benyon (2011) showed that invasive willows (*Willow* spp.) growing within (i.e., with permanent access to water) Australian streams had peak T_r rates of 15.2 mm d^{-1}, and that these willows had evapotranspiration (E_T) rates greater than open water even when the trees were subjected to drought, heat stresss, and insect infestations. These authors calculated that over a three-year period a water savings of 5.5 ML yr^{-1} ha^{-1} of vertically projected crown area could be achieved by removing in-stream willows.

There is some concern that an increase in redcedar density and areal coverage may affect local water budgets through increased transpiration (T_r) and canopy interception (C_I) of precipitation over that of the grassland communities that redcedar typically replaces. It is the semi-arid and transitional zones between semi-arid and humid regions where impacts of redcedar encroachment are most likely to have a noticeable impact on local and regional hydrology (Huxman et al., 2005). Owens, Lyons, and Alejandro (2006) showed Ashe juniper *(J. ashei)* canopies completely captured precipitation amounts < 2.5 mm per storm, while intercepting about 20% of precipitation in storm amounts > 70 mm over a 15 hour period. Thurow and Hester (1997) found 27% and 37%, on average, of gross precipitation was intercepted by redberry juniper (*J. pinchotii*) and Ashe juniper, respectively. Eddleman (1986) and Larsen (1993) reported up to 74% of precipitation was intercepted by western juniper (*J. occidentalis*) in central Oregon.

Dugas, Hicks, and Wright (1998) used the Bowen ratio energy balance approach to measure actual evapotranspiration (E_{Ta}) of Ashe juniper in Texas and found average water use rates of about 1.9 mm d^{-1} during a March through October measurement period. Lane and Barnes (1987) used a water balance approach to estimate water use of Utah juniper (*J. osteosperma*), with and without mixtures of Pinyon pine (*Pinus edulis*), in Arizona, Utah, and New Mexico. The E_{Ta} ranged from 414 mm yr^{-1} (1.13 mm d^{-1}) in Arizona to 121 mm yr^{-1} (0.33 mm d^{-1}) in New Mexico. These researchers also showed E_{Ta} for an Arizona site dominated by alligator juniper (*J. deppeanna*) was about 432 mm yr^{-1} (1.2 mm d^{-1}). Leffler, Ryel, Hipps, Ivans, and Caldwell (2002) measured an E_{Ta} of 0.85 mm d^{-1} from March to October in Utah juniper using an Eddy covariance approach in Utah.

Water use studies on eastern redcedar are few in number (Huddle, Awada, Martin, Zhou, & Pegg, 2011). Duesterhaus (2008) measured C_I in a dense stand of redcedar of about 45 years in age in the Kansas Flint Hills (sub-humid climate) and found it varied from 17 to 77% of total storm precipitation, depending upon storm size and intensity. Annual average C_I was about 52%. Duesterhaus (2008), using eddy covariance techniques at the same site, measured E_{Ta} over the course of a year and found rates of about 2.4 mm d^{-1}. Landon, Rus, Dietsch, Johnson, and Eggemeyer (2009) used sap flow velocity techniques on a 15.2 cm diameter redcedar located in a riparian zone of the Republican River in Nebraska and found redcedar T_r varied from 0.76 to 0.98 mm d^{-1} over the course of a six month study period. Awada et al. (2012) used sap velocity measurements on selected trees within an even-aged (about 58 years old) stand of redcedar in the semi-arid Sandhills of Nebraska and reported annual average T of about 1.1 mm d^{-1}.

All of the redcedar studies mentioned above were either conducted on a whole tree-stand basis or individual trees within a stand. Moore and Owens (2006) demonstrated that Ashe juniper juveniles released from the effects of an adult overstory transpire more water and assimilate more carbon than either Ashe juniper grown in open conditions or trees grown in stands. Transpiration and carbon assimilation of open grown Ashe junipers was intermediate between that of the released juveniles and adult trees growing in dense stands. Thus, measurement of T_r within dense stands of redcedars may not reflect that measured in redcedars growing in open conditions. This may be due to differences in microclimates experienced by each tree (e.g., reduction of solar radiation on trees within the stand canopy, reduction of wind speed within the stand, higher vapor pressure within dense canopies, etc.). Many fields impacted by redcedar encroachment do not currently represent thick stands of trees, but have a number of openly growing redcedars of various sizes. Thus, it would be instructive to measure T_r and C_I of redcedars growing in open environments.

The objectives of this paper are: 1) to report on long-term measurements of T_r, C_I, stem flow (S_F), and throughfall (T_F) for redcedar in central Oklahoma, which is located in a transitional zone between semi-arid and humid climates, 2) to compare the intra- and inter-annual variability of T_r of two size classes of redcedar, 3) compare T_r for the two size classes where T_r has been normalized by leaf area or above ground dry mass (AGDM), and 4) evaluate T_r in context of simultaneous measurements of actual E_T (E_{Ta}), potential E_T (E_{Tp}; defined as the evaporation of water from an extended surface of a short green crop that fully shades the ground and is well supplied with water [Rosenberg, Blad, & Verma, 1983]), and measurements of volumetric soil water content made at a nearby natural prairie site.

2. Method

2.1 Site Descriptions

Two sites were chosen for study in Canadian County, OK, for measurement of C_I and T_r. Canadian County is located in the center of the state and in the center of a steep west-to-east precipitation gradient (Figure 1). Site 1 was located on the USDA-ARS Grazinglands Research Laboratory, near El Reno, OK, (lat 35°33’38” N, long 98°03’33” W) where two large (≈ 5.5 m tall) redcedar trees were selected for measurement of T_r. Both trees (T1 and T2) were located on a Port silt loam (fine-silty, mixed, thermic, Cumulic Haplustolls) (Fisher and Swafford, 1976), and surrounding vegetation was mainly native prairie grasses. Two additional trees (CI 1 and CI 2) were located for measurement of T_F, S_F, and C_I.

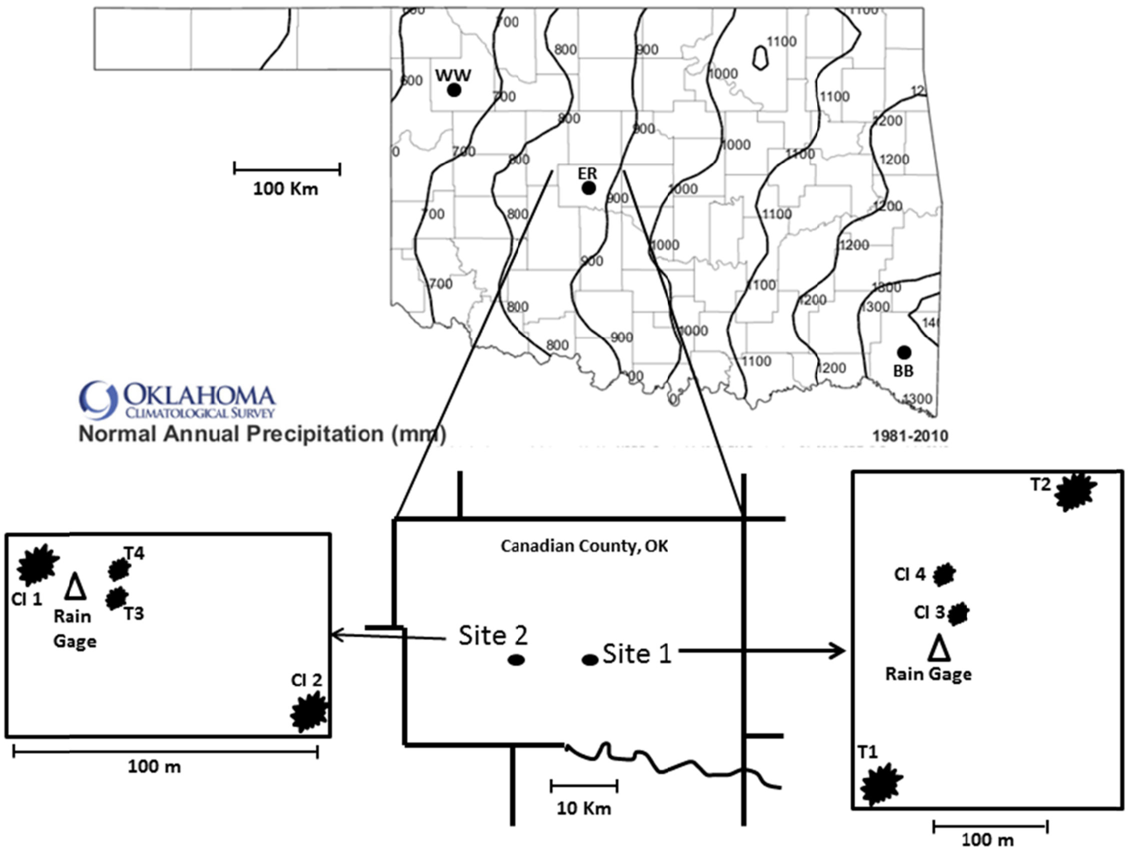

Figure 1. Study site locations in Candian County, Oklahoma. Trees T1, T2, T3, and T4 were used in the transpiration study, and trees CI 1, CI 2, CI 3, and CI 4 were used in the canopy interception study. The state map shows the precipitation isohyets (in mm) across the state. (Source: Oklahoma Climate Survey, University of Oklahoma, Norman, Oklahoma. Used by permission.) The locations of Woodward (WW), El Reno (ER), and Broken Bow (BB), Oklahoma are also shown

At Site 2 (lat 35°33’40” N, long 98°12’14” W), two small trees (T3 and T4; ≈1.0 and 1.5 m tall, respectively) were selected for measurement of T_r, and two larger trees (CI 3 and CI 4) for measurement of T_F, S_F, and C_I. All trees were on a Grant-Quinlan (fine-silty, mixed, thermic, Udic Argiustolls) soil (Fisher & Swafford, 1976), and all trees were isolated and located in a mixed grass species setting. The soils at the two sites are similar in their basic physical properties (Table 1).

Table 1. Basic soil properties of the two study sites. Data taken from Fisher and Swafford (1976)

Site	Drainage	Permeability	Available Water Capacity	Range Site	Soil Depth	Soil Texture
		mm hr^{-1}	cm^3 cm^3		cm	
1	Well drained	15 - 51	4 - 6	Loamy bottom land	0 – 77	SiL†
					77 - 178	SiL, SiCL
2	Well drained	15 – 51	4 – 6	Loamy prairie soil	0 – 25	SiL
					25 – 117	SiCL, SiL
					117 – 152	SiL, vfSaL
					152	Sandstone

†C = clay, L = Loam, Si = silt, Sa = sandy, vf = very fine.

According to the National Climatic Data Center (2002), Canadian County (El Reno, OK weather station) has an annual average temperature of 15^{o}C, with the highest mean daily temperature occurring in July (28^{o}C) and lowest mean daily temperature occurring in January (1.5^{o}C) (Figure 2). Canadian County exhibits a bi-modal distribution of precipitation with an average annual (30-year normal) precipitation of 870 mm yr^{-1} (Figure 2). Thirty one percent of the precipitation occurs in May-June and 19% occurs in September-October (National Climatic Data Center, 2002).

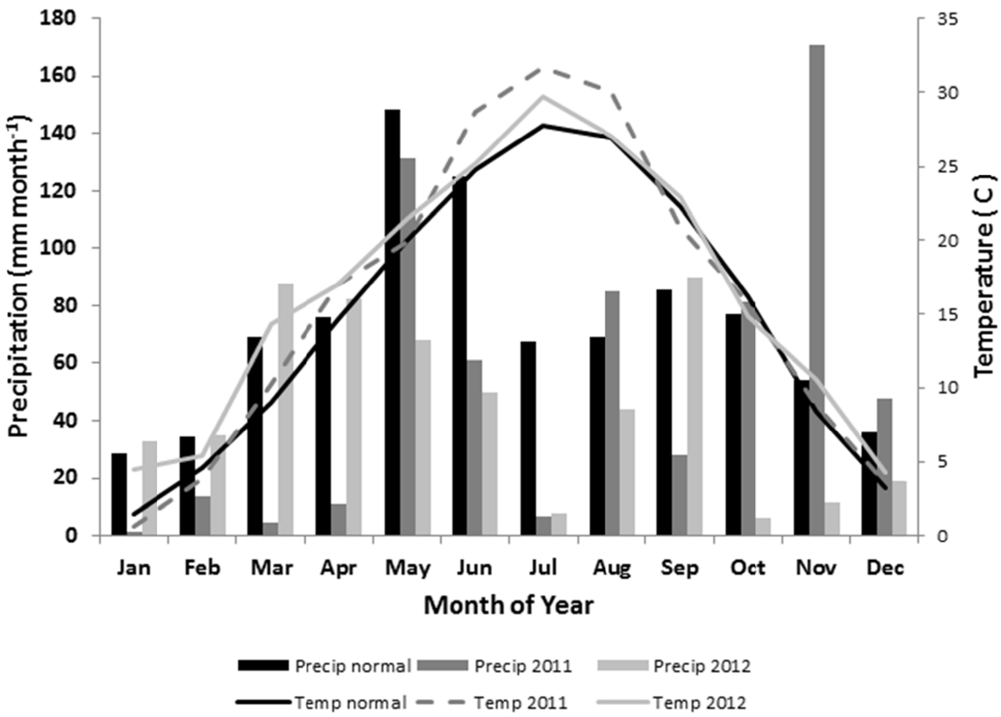

Figure 2. Monthly normals of total precipitation and average daily temperature, and actual monthly precipitation and average daily temperature for the time period of this study

2.2 Canopy Interception

Canopy interception is calculated as:

$$C_I = G_P - T_F - S_F. \tag{1}$$

Gross precipitation (G_P) is the total amount of precipitation that falls within the vertically projected canopy area of a given redcedar, and was calculated from precipitation measurements and vertically projected canopy area. All units in Equation 1 are in mL. Vertically-projected redcedar canopy area was determined by measuring the least and greatest diameters of the drip line and using the mean diameter to calculate the canopy area as a circle (Engle and Kulbeth, 1992). The increase in canopy area and its impact on G_P computations was accounted for by adjusting canopy area on a monthly basis at the rate calculated by linear interpolation using beginning-of-study and end-of-study canopy area measurements and time. For each tree in the study, a power function was fit through the C_I versus precipitation data. The data were linearized and the functions were analyzed for statistical differences between slopes and intercepts of the separate functions.

A tipping bucket rain gauge, located in an open area at each site well away from any obstructions, was used to measure 5-minute precipitation, from which G_P was calculated. To measure T_F, three transects were laid out equidistant from each other under each tree. Three 7.6 L plastic buckets (collection area = 405 cm^2) were placed on each transect and leveled; one near the base of the tree, one just inside the drip line of the tree, and one midway between the other two. Total water volume collected from the nine buckets was averaged and multiplied by the ratio of throughfall bucket surface area to vertically projected canopy area to estimate total T_F. Precipitation collected in these containers was measured using a graduated cylinder. Only data collected within one to two hours after a precipitation event were used in this study to minimize the impact of evaporation from the through fall collectors. Frozen precipitation was not measured in this study. Stem flow was collected by placing a collar around the base of the tree just below the branch line and funneling it into a sealed 56.7 L plastic drum. The collar was constructed of large diameter, thick-walled garden hose and secured tightly to the tree using heavy gauge wire passed through the center of the hose. To prevent leaking around the collar, silicone was placed in the valley formed by the trunk of the tree and the hose.

2.3 Effective Precipitation

The interaction of redcedar canopies and local precipitation characteristics will vary across precipitation gradients and this variation will affect the amount of overall precipitation reaching the soil surface below the canopy. We use the functions derived in Section *2.2* and daily precipitation data (1 January 2011 through 30 June 2012 time period) obtained from meteorological stations (i.e., Mesonets) (McPherson et al., 2007) located at three climatically distinct locations in Oklahoma to calculate average (based on the four functions) annual percent reductions in precipitation received beneath the redcedar canopies (i.e., "effective precipitation"). These locations are Woodward, OK (lat 36^{o}26'01''N, long 99^{o}23'25"W) in northwest Oklahoma, El Reno (central Oklahoma), and Broken Bow (lat 34^{o}01'46"N, long 94^{o}44'21"W) located in southeast Oklahoma (Figure 1). Woodward receives about 600 mm of annual precipitation compared to 870 mm and 1400 mm for El Reno and Broken Bow, respectively (National Climatic Data Center, 2002).

2.3 Transpiration

Sapflux *(F)* was measured using Dynagauge sap flow sensors (Dynamax, Inc., Houston, TX) that use an energy balance approach to estimate transpiration (Sakuratani, 1981; Baker and Van Bavel, 1987; Steinberg, Van Bavel & McFarland, 1989). These sensors require no calibration or insertion of a heater or thermocouples into the stem. The sapflux sensor consists of a heater strip and thermopiles above and below the heater. A constant current is supplied to the sensor and the voltage monitored to precisely ascertain the amount of energy supplied to the heater. Temperature differences above and below the heater are used to measure heat conducted in the stem, and the amount of heat lost to the ambient conditions (i.e., radial heat flux) is measured by a thermopile placed adjacent to the heater (Dynamax, 2005). The *F* is then calculated from the following:

$$F = Q_f / (C_p * \Delta T), \tag{2}$$

where Q_f is the amount of power input (J s^{-1}), C_p is the specific heat of water (J g K^{-1}), and ΔT is the temperature differential (K) between the upper and lower thermopiles of the sensor. In Equation 2, *F* is the flux rate of sap in grams per second (g s^{-1}). Because sap is ≈ 99% water, *F* is a reasonable and direct estimate of T_r, especially when integrated over daily and longer time periods (Dynamax, 2005). Thus, in this study $F = T_r$.

Uneven irradiance of a tree canopy may cause T_r to vary within the canopy (Steinberg, McFarland, &Worthington, 1990; Cermak, Jenik, Kucera, & Zidek, 1984). Thus, for the two larger trees used in the transpiration study (T1, T2), two limbs on each tree (one on the north/ northeast tree face the other on the south tree face) were identified for installation of sapflux sensors (described below). Limb circumference above and below each sensor was measured and for each limb the average cross-sectional area determined. The sensors were installed and maintained periodically according to manufacturer instructions. The small redcedars at Site 2 were fitted with appropriate-sized sap flow sensors at each tree's base to measure whole tree T_r.

Bole cross-sectional area and vertically-projected canopy area were determined for all trees used in the transpiration study. Bole cross-sectional area was calculated from circumference measurements of the trunk at 30 cm above the ground for T1 and T2, and at 10 cm above the ground for T3 and T4. The height of measurement was selected as the mid-pont distance between the soil surface and the bottommost limb on a given tree. Bole or limb cross-sectional areas and thermal conductivity of the wood (k = 0.42 W $m^{-1}K^{-1}$); Dynamax, 2005) were used in the initial calculations of F (Equation 2). During post-processing of the data, the sheath conductance of the sensor was adjusted daily as needed using sensor data obtained during zero sap flow conditions (predawn) (Dynamax, 2005). Additionally, the stem cross-sectional area was adjusted as needed to account for increased girth during the primary growing period. Thirty-minute totals of F (i.e., T_r) were measured.

For T1, measurements were made from October 2010 through early June of 2012. Measurements on T2 commenced on November 2010 and ended on August 2011. One of the two sensors on T2 failed in early 2011, limiting usable data from this tree. Measurements at Site 2 began in May 2011 and were terminated in early June of 2012. Only the data for 2011 and 2012 from T1, T3, and T4 are reported herein. The daily T_r values were normalized using tree leaf area (Steinberg et al., 1990) and AGDM to facilitate comparison of T_r between trees on both a daily and monthly basis.

2.4 Leaf Area

Hicks and Dugas (1998) produced two equations for predicting leaf area of Ashe juniper: one predicting total tree leaf area from tree vertically projected canopy area (r^2 = 0.97), and one predicting shoot (small branches radiating from the basal crown) leaf area from shoot cross-sectional area (r^2 = 0.93). Tree canopy areas in their study ranged from about 0.87 to 23 m^2, and shoot cross-sectional areas ranged from 0.000002 to 0.009 m^2. They suggested these equations could produce accurate estimates of leaf area for redcedar, but these relationships should be validated. Kiniry (1998) developed two equations to predict total tree leaf area of redcedar based on tree mass; one equation for trees with above-ground, oven dry biomass (AGDM) between 0.44 and 2.5 kg (r^2=0.94) and one for trees with AGDM < 400 g (r^2 = 0.97). Kiniry (Personal Communication) made measurements of bole and canopy diameters on selected redcedars during the original study, but these data were not included in the original analysis. We hypothesized that a single equation could be developed from these data to predict leaf area of Ashe juniper and redcedar. We compiled the datasets of Hicks and Dugas (1998) and Kiniry (Personal communication) and conducted an analysis of variance and t-tests to determine if slopes and intercepts were of the two species-specific data sets were statistically different.

2.5 Canopy Area vs. AGDM

In an earlier study, Starks, Venuto, Eckroat, and Lucas (2011) showed redcedar canopy area is strongly related to its AGDM. A portion of that study was conducted at locations near and at Site 2 of this study, and an analysis of that data is reported here. At these locations, four 900 m^2 plots (30 m x 30 m) were randomly identified for destructive tree harvest. Before trees were harvested, canopy diameters of 142 trees were measured. Vertically-projected redcedar canopy area was determined using the same method described above. All trees were cut at ground level, numbered, and basal bole diameter and tree height recorded. All trees were weighed on a portable platform scale, and a 3 to 5 cm thick cross section of bole was cut from the base of each tree to determine moisture content. Representative stems and branches were fed through a shredder, and dried, along with the boles, in a forced-air oven at 60°C to a constant mass to determine moisture content. The leaf area and AGDM data are used to facilitate comparison of transpiration between the two size classes of redcedars.

2.6 Scaling Factors

Scaling factors were developed to estimate whole-tree T_r from the branch level measurements made on T1 and T2. The scaling methodologies were: 1) ratios of bole cross-sectional area to limb cross-sectional area, and 2) ratios of tree leaf area to limb leaf area. For T1, the two limb ratios for a given scaling methodology were averaged. Because of sensor failure on T2, only the north limb data were used to compare scaling factors. The scaling factors were calculated for the beginning of each month in 2011 for T1, and for the months September-December, 2010 and January-March, 2011 for T2.

2.7 Ancillary Data and Measurements

E_{Tp} is a measure of atmospheric demand and is used herein for qualitative comparison with T_r. Daily E_{Tp} was calculated using the FAO Penman-Monteith equation (Allen, Pereira, Raes, & Smith, 1998), as implemented in the reference E_T calculator developed by Raes (2009). Required weather data were obtained from the El Reno Mesonet station (lat 35°32'54" N, long 98°2'11" W, 419 m above mean sea level) and included maximum, minimum, and mean air temperature and relative humidity, average daily dew point temperature, average daily wind speed, and total incoming solar radiation. A crop resistance value of 70 s m^{-1} is used by E_T calculator. Description of the Mesonet, its instrumentation and data collection and quality assurance measures can be found in Brock et al. (1995) and McPherson et al. (2007).

Redcedar typically encroaches in unmanaged grassland areas in Oklahoma. Therefore, comparison of redcedar T_r with E_{Ta} of grasslands provides an assessment of potential hydrological impacts of redcedar encroachment of grassland areas. E_{Ta} measurements were made over native grassland by the U.S. Department of Energy (DoE) 4 km east of Site 1 using an energy balance Bowen ratio (EBBR) system. Although located some distance from Site 1, the EBBR data are reflective of native grass E_{Ta} in the area. The "best estimate of EBBR" data was obtained from the DoE data archives (http://www.archive.ar.gov/). Measurements began at this site in the summer of 1997 and continued through August 2011. Thus, only eight months of E_{Ta} were available for comparison with large redcedar T_r and only 3 months of data for comparison with the small redcedar T_r. Daily totals were calculated from half-hourly data.

Soil water content also impacts plant transpiration. Hourly volumetric soil moisture (θ_v) measurements at five depths (5, 10, 20, 50, and 100 cm) were made adjacent to the DoE site by the Natural Resources Conservation Service (NRCS) from the summer of 1997 to present using hydra probe (Stevens Water Monitoring, Inc., Portland, OR) soil moisture sensors. The θ_v data corresponding to the study period were downloaded from the NRCS web site (http://www.wcc.nrcs.usda.gov/scan/Oklahoma/oklahoma.html). Daily averages were computed from the hourly data and used to help interpret differences and variations in redcedar T_r.

3. Results

3.1 Weather Conditions During the Study

Annual precipitation in 2011 for Canadian County was about 74% of normal (Figure 2), although during the main part of the growing season (April – August) precipitation was only about 57% of normal. Mean daily air temperatures were mostly above normal for most of 2011 and well above normal from April through August (average of about 112% above normal). Below average precipitation coupled with much above normal air temperature created severe drought conditions during much of the year. Greater than normal precipitation during November 2011 through March of 2012 briefly interrupted the drought. However, below normal precipitation and above normal air temperatures returned in May 2012 and lasted through the remainder of the study period.

3.2 Leaf Area and AGDM

The leaf area vs. bole diameter data of Kiniry (n = 22, Personal Communication) and the leaf area vs. shoot diameter data of Hicks and Dugas (n = 36; Dugas, Personal Communication) were analyzed for statistical similarity of slopes and intercepts. Results from the statistical analysis revealed equal variances in both the bole/shoot ($P < 0.05$) and leaf area ($P < 0.05$) data and no statistical difference in either slopes or intercepts ($P < 0.05$) between the two data sets. Thus, the two data sets were combined and a linear regression of full cylinder leaf area on bole (i.e., stem) diameter was performed resulting in the following relationship:

$$y = (4810.8 * x) - 0.1414 \tag{3}$$

where x is the bole (shoot) cross-sectional area (m^2) and y is the resulting full cylinder leaf area (m^2) ($r^2 = 0.97$). Because of the statistical similarity of leaf areas vs. stem cross-sectional areas for both Ashe juniper and redcedar (small diameter trees), it was assumed the canopy area vs. leaf area relationships of Hicks and Dugas (1998) would be adequate to estimate redcedar leaf areas for the trees at both Sites.

Individual redcedar canopy area, measured by Starks et al. (2011) for 142 redcedars at Site 2, averaged 6.2 m^2. Tree canopy area was highly correlated with individual tree weight ($r = 0.97$; $P < 0.0001$) and, of all parameters measured, tree canopy area was the best indirect indicator of individual tree mass. The canopy area (x) vs. AGDM (y) of Kiniry (Personal Communication) was combined with these data to provide relationships between canopy area and dry weight over a large range of tree sizes. The data were fit with a second-order polynomial (Equation 4) and revealed a strong relationship ($r^2 = 0.98$).

$$y = 0.1437*x^2 + 4.0889*x \tag{4}$$

Table 2. Vertically projected canopy area of Eastern redcedar trees used in the precipitation interception study

Tree ID	Date	Canopy Area	Rate of Increase‡	Rate of Increase†
		m^2	$m^2\ d^{-1}$	$m^2\ d^{-1}$
CI 1	1 Oct 2009	11.86		
	12 Jul 2012	31.42	0.0193	--
CI 2	1 Oct 2009	14.82		
	12 Jul 2012	26.92	0.0119	--
CI 3	1 Oct 2009	9.3		
	25 Oct 2011	13.63	0.0057	--
	8 Nov 2011	18.10	0.0115	0.319
	12 Jul 2012	24.08	0.0146	0.0242
CI 4	1 Oct 2009	19.76		
	25 Nov 2010	24.3	0.0117	--
	12 Jul 2012	33.6	0.0136	0.0149

‡ Using first date of measurement as base.

† Using previous year's measurement as base.

Table 3. Selected characteristics of redcedars used in the transpiration study. Trees T3 and T4 were whole-tree measurements; thus, north and south limb data are not relevant (NR)

Tree ID	Date	Height	Cross-sectional or Surface Area‡				Tree AGDM†	Tree Leaf Area§	South Limb Leaf Area¶	North Limb Leaf Area¶
			Bole	South Limb	North Limb	Canopy				
		m	m^2				kg	m^2		
T1	27 Aug 2010	5.5	0.07	0.0031	0.00206	29.90	250.7	352.3	14.7	12.4
	12 Jul 2012	NR	0.11	0.0031	0.0028	43.80	454.8	524.6	17.2	16.7
T2	08 Nov 2010	5.5	0.07	0.0033	0.0033	30.42	257.4	358.7	15.7	5.9
	12 Jul 2012	NR	0.08	0.0050	0.0033	38.04	363.5	453.2	24.5	5.9
T3	10 May 2011	1.55	0.00114	NR	NR	0.83	3.5	5.3	NR	NR
	04 Oct 2011	1.78	--	NR	NR	0.92	3.9	--	NR	NR
	10 May 2012	1.91	--	NR	NR	1.34	5.7	--	NR	NR
	12 July 2012	2.08	0.00185	NR	NR	1.89	8.2	8.8	NR	NR
T4	10 May 2011	0.91	0.00079	NR	NR	0.47	2.0	3.7	NR	NR
	04 Oct 2011	1.17	--	NR	NR	0.74	3.1	--	NR	NR
	12 Jul 2012	1.24	0.00116	NR	NR	0.78	3.3	5.4	NR	NR

‡Cross-sectional surface area shown for bole and limbs, vertically projected surface area is shown for the canopy.

†Above ground dry mass calculated from Equation (4).

§Estimated from: tree leaf area (m2) = 12.4 * x -18.5 (Hicks and Dugas, 1998), where x = canopy area in m^2.

¶Estimated from Equation (3).

3.3 Other Tree Measurements

Canopy areas at the end of the CI study were two to three times larger than that measured at the beginning of the study (Table 2). The rate of increase in canopy area was from 0.01 to 0.02 m^2 d^{-1}. More frequent measurements of canopy area on tree CI 3 indicated the rate of canopy area increase varied from year to year.

Despite being of similar size at the start of the study (Table 3), T1 and T2 differed considerably in most aspects by the end of the study. T1 showed the largest increase in bole diameter, canopy area, AGDM, and tree level leaf area. Canopy area of T1 increased by1.5 times over the study period (0.02 m^2d^{-1}) and its AGDM increased 204 kg (0.3 kg d^{-1}), while T2 increased its canopy area by 1.25 times and it's AGDM by only 106 kg (0.2 kg d^{-1}).

Over the course of the study period, T3 increased in height at a rate of about 1.2 mm d^{-1} and increased its canopy area by about 24.7 cm^2 d^{-1} (Table 3). Bole area of this tree increased about 0.6 cm^2 d^{-1}, above ground dry mass increased from 3.5 to 8.2 kg (0.01 kg d^{-1}), and leaf area increased 82 cm^2 d^{-1} over the study period. T4 height increased at a rate of about 0.7 mm d^{-1}, canopy area increased about 7.2 cm^2 d^{-1}, AGDM increased from 2.0 to 3.3 kg (0.003 kg d^{-1}), while its leaf area increased from 3.7 to 5.4 m^2 (40 cm^2 d^{-1}).

3.3 Canopy Interception

Evaluation of the tipping bucket rain gage data collected at each site revealed that mean precipitation, per event, at Site 1 was higher than at Site 2 (Table 4), but both sites exhibited similar median values. Precipitation was more variable at Site 1, and both maximum and minimum precipitation totals were higher. Precipitation events tended to last longer than at Site 1, but Site 2 tended to experience more intense precipitation events.

Table 4. Descriptive statistics for total precipitation, storm duration, and storm intensity (= total precipitation / storm duration) for rainfall events occurring at each site

Statistic	Total Precipitation	Storm Duration	Storm Intensity
	mm	Min	mm hr^{-1}
Site 1 (n = 62)			
Mean	15.72	584	4.31
Median	10.46	355	1.83
Standard Deviation	17.83	825	6.15
Maximum	74.20	3705	78.60
Minimum	0.76	5	0.001
Site 2 (n = 57)			
Mean	12.98	228	97.04
Median	10.67	85	5.41
Standard Deviation	10.52	283	269.91
Maximum	39.37	1345	1446.41
Minimum	0.25	5	0.21

Canopy interception versus precipitation is shown in Figure 3 for each tree used in this portion of the study. Due to either overflow in the stemflow container, overturned throughfall buckets, or a lengthy time period between cessation of a given rainfall event and measurement of stemflow and throughfall, some of the rainfall events shown in Table 4 could not be used in the calculation of C_I. See insets to Figure 3 for *n*-size used in determination of C_I.

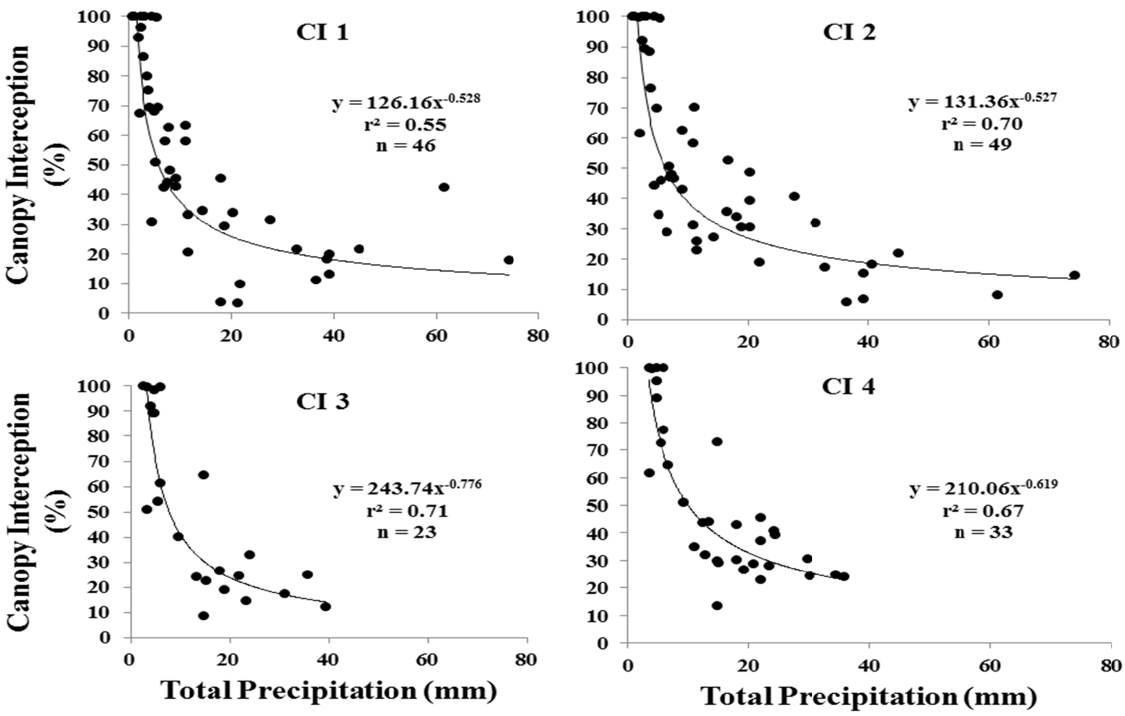

Figure 3. Scatter plots of canopy interception of precipitation for the four redcedars used in this study. The regression equation, coefficient of determination (r^2), and the number of rainfall events (n) is also shown

The scatter observed in Figure 3 is primarily due to the interactions of tree canopy morphology with precipitation intensity, and wind speed and direction associated with each storm event. On average, redcedar canopies captured 100% of precipitation for events ≤ 2.4 mm. Statistical analysis revealed that both the exponent in the function for CI 3 and the slope value for CI 4 were statistically different ($P \leq 0.05$) than those for their counterparts in the remaining three equations. Thus, the data were not pooled to generate a single equation to predict C_I from precipitation.

Measured throughfall (T_F) and stemflow (S_F) varied, as expected, with precipitation amount. Mean and median values of T_F at Site 1 were 45 and 50% of gross precipitation (G_P), respectively. At Site 2, mean and median values of T_F were 50 and 62% of G_P, respectively. Mean S_F varied from 1.3 to 3.3% of G_P, but for larger precipitation events S_F reached a maximum value of 5 to 8% depending upon tree.

3.4 Effective Precipitation

Figure 4 shows the cumulative distribution of daily rainfall from January 2011 through June 2012 for Broken Bow, El Reno, and Woodward, Oklahoma (Figure 1). Woodward had fewer days with rain and less total rainfall than either El Reno or Broken Bow (Table 5) over the given time period. From Figure 4 it is observed that rainfall events tended to be smaller at Woodward when compared to El Reno and Broken Bow. The number of rainfall events and total rainfall per day increased moving eastward from Woodward to Broken Bow.

Smaller and less numerous rainfall events at Woodward resulted in an effective precipitation value of 437 mm beneath redcedars at that location, which represents ≈ 39% reduction (Table 5) in total rainfall over the period January 2011 – June 2012. At El Reno, this reduction was ≈ 33% while at Broken Bow it was ≈ 27% (Table 5).

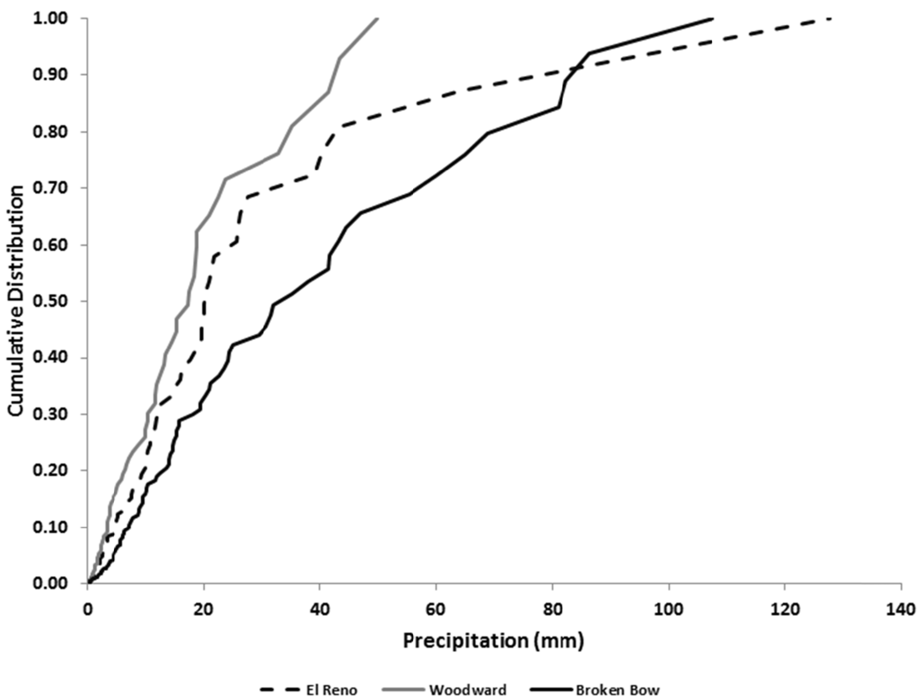

Figure 4. Cumulative distribution of daily rainfall totals from January 2011 through June 2012 for Broken Bow, El Reno, and Woodward, Oklahoma

Table 5. Number of days with rain, total measured rainfall, percentage intercepted by redcedar canopy (% C_I), and estimated amount of precipitation (effective precipitation) reaching the surface beneath the redcedar canopy for Woodward (northwest), El Reno (central), and Broken Bow (southeast), Oklahoma. The time period represented is January 2011 through June 2012

Location	Number of Days with Rain	Measured Rainfall	Canopy Interception	Effective Precipitation
		mm	%	mm
Woodward	107	714	38.8	437
El Reno	124	998	32.8	671
Broken Bow	147	1770	26.6	1299

3.6 Transpiration

3.6.1 Branch Level

Average daily T_r from the south-facing branch of T1 was about 46% higher, on average, than that of the north-facing branch (Figure 5), even though limb leaf areas were approximately equal (Table 3). Both branches showed an increase in T_r as air temperature increased and the growing season progressed. The sensor on the south-facing branch of T2 failed after about three months use, but prior to sensor failure the south-facing branch transpired about 2.2 times that observed from the north-facing branch. For the months where comparisons could be made, T_r from the north sides of T1 and T2 were comparable (Figure 5).

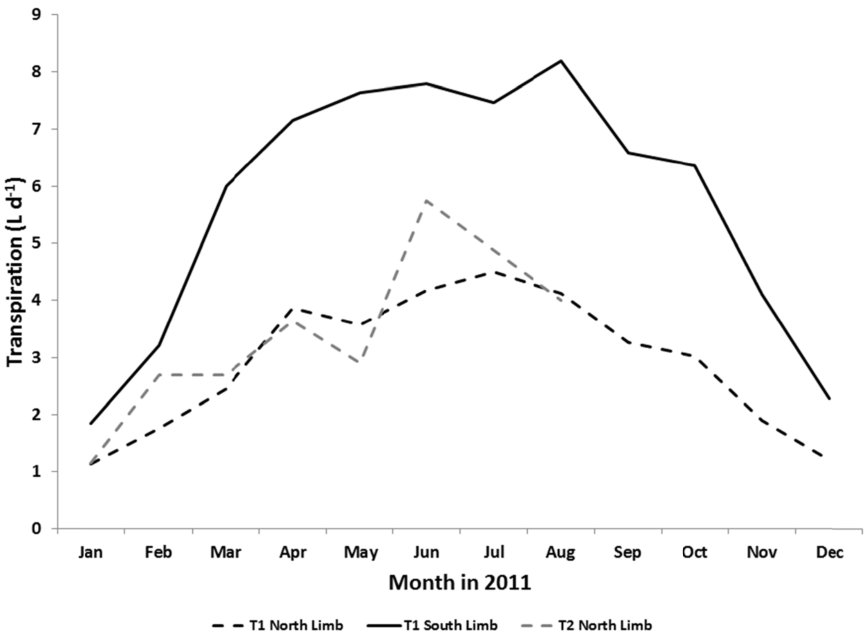

Figure 5. Branch-level average daily transpiration from two limbs (one on the north face of the tree and the other on the south face of the tree) of T1 and from the north face of T2

3.6.2 Whole Tree

As discussed in Section *2.6*, scaling factors based on ratios of bole cross-section:limb cross-section and canopy leaf area:limb leaf area were developed and applied to monthly branch-level totals of T_r to estimate whole-tree T_r of T1 and T2. The two scaling methodologies yielded similar results (Figure 6).

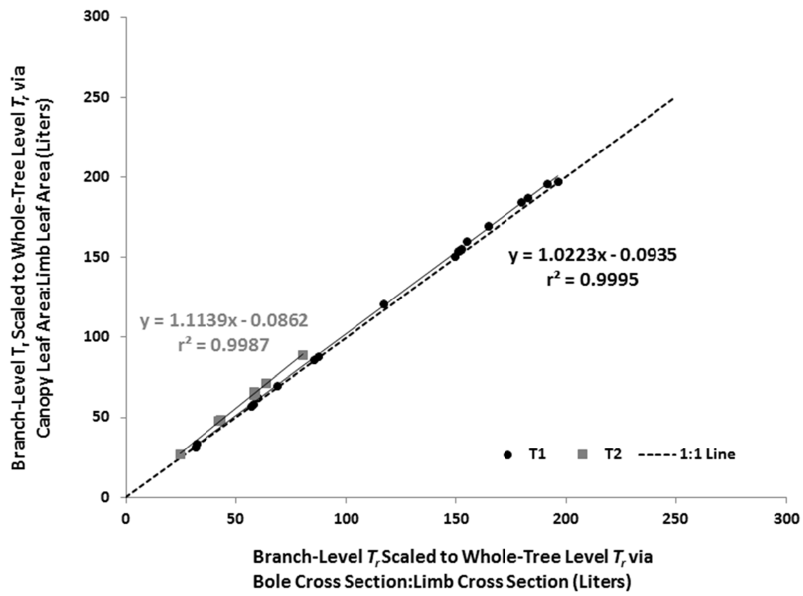

Figure 6. Double mass plot of average daily whole-tree transpiration (T_r) calculated for each month of the study period. Whole-tree T_r was estimated from limb measurements for the large redcedars at Site 1. The x-axis represents limb measurements of transpiration scaled to whole-tree T_r using the ratio of the cross-sectional area of the tree trunk (bole) to the cross-sectional area of the limbs. The y-axis represents limb measurements of T_r scaled to whole-tree T_r using the ratio of tree leaf area to limb leaf area. Both limbs on T1 were used to develop an average value for both the cross-sectional and leaf area scaling factors. Only the north limb on T2 was used because of sensor failure on the south limb. The 1:1 line is shown

Daily whole-tree T_r for T1, T3, and T4 is plotted in Figure 7 for the July 2011 through May 2012 time period. From Figure 7 it is observed that the three trees exhibit similar seasonal patterns; maximum T_r in the summer months, and minimum T_r in the winter months. Similarity of patterns over shorter time intervals is also observed. For example, relatively small T_r values for all three trees occur in late July 2011 followed by increasing T_r through mid-August 2011. From mid-August 2011 T_r decreases for all three trees until late in the month. These patterns can be observed for two-week time periods approximately centered on 26 Sep 011, 26 Nov 2011, 26 Dec 2011, and 26 Feb 2012 (Figure 7).

Maximum T_r for T1 was 331 L d^{-1} (16 May 2012), with several days during the time period having $T_r \geq 250$ L d^{-1} (Figure 7). Maximum T_r for T3 and T4 was 6.9 and 1.9 L d^{-1} (22 May 2012 for both trees). Excluding days where $T_r = 0$ (n =2 for T1 and n = 5 for both T3 and T4), minimum T_r was 0.9 L d^{-1} for T1(3 October 2011), and 0.05 L d^{-1} for both T3 and T4 (5 May 2012). For the time period shown in Figure 7, average daily T_r for T1 was 132.4 ± 76.6 L d^{-1}, while that for T3 and T4 was 2.2 ± 1.6 and 0.8 ± 0.5 L d^{-1}.

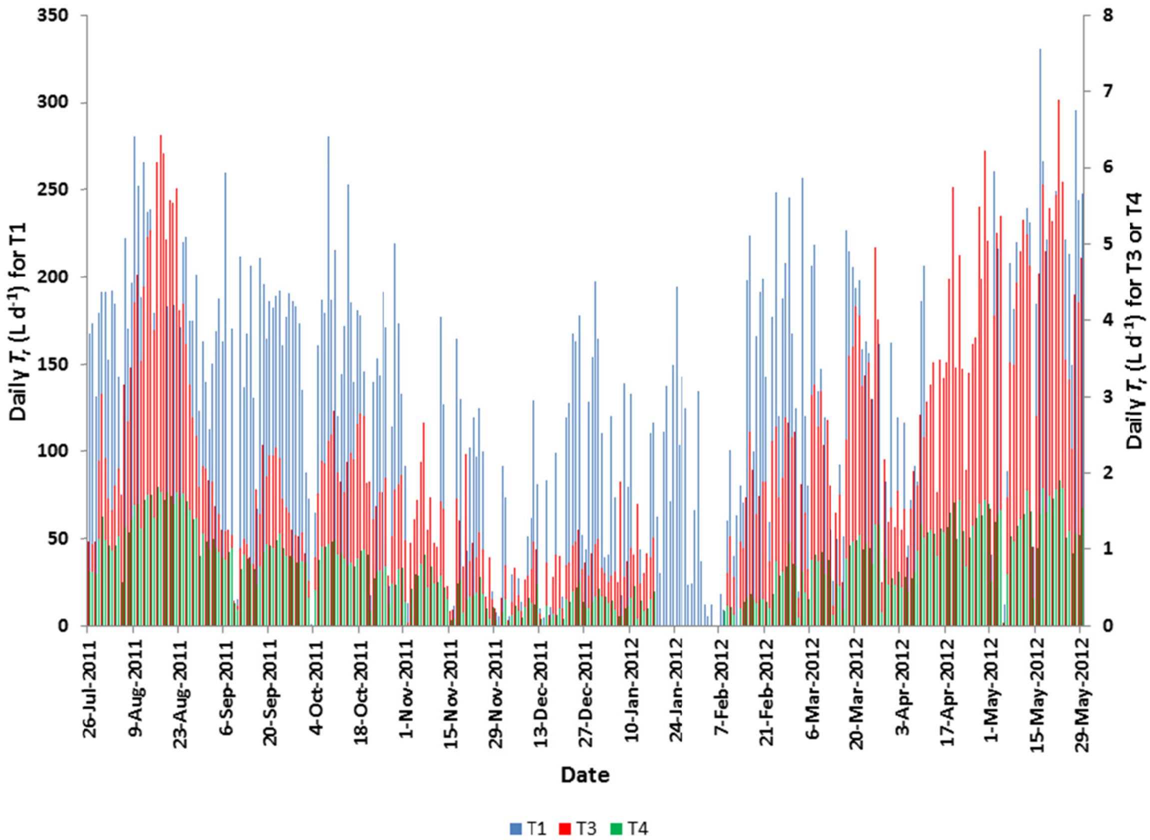

Figure 7. Daily whole-tree transpiration for the large redcedar T1 at Site 1, and daily whole-tree transpiration for the small redcedars T3 and T4 at Site 2

To facilitate comparison with E_{TP} and E_{Ta}, total monthly T_r values for T1, T3, and T4 were divided by the number of measurement days in that month and by the month-specific vertically projected canopy areas (calculated from the data in Table 3) to provide estimates of average daily T_r for each tree and each month in units of mm d^{-1}. The results are plotted in Figure 8. E_{Tp} and E_{Ta} of native grass is also shown. As expected, E_{Tp} was higher than T_r for all redcedars and higher than E_{Ta} throughout the measurement period. It is observed that the pattern of T_r for T1, T3, and T4 and E_{Ta} where greatly influenced by E_{Tp}. Over the period of comparison, E_{Tp} was from 1.4 to 2.5 times larger than T_r of T1, and from 2.3 to 5.5 and 3.8 to 7.1 times larger than T_r of T3 and T4. For the eight months where comparison is possible, T1's T_r was from 2 to 9 times larger than E_{Ta} of the native grass at Site 1. E_{Ta} was about 85 and 90% of T_r from T3 and T4, respectively, over the four months where comparisons could be made. T_r for T1 exceeded 5 mm d^{-1} during June-August of 2011(and in June 2012), but averaged 3.7 mm d^{-1} during the study period. T3 reached 5.3 mm d^{-1} in June 2011, but averaged 2.0 mm d^{-1} over the study period. T4 averaged 1.5 mm d^{-1} and never exceeded 3.1 mm d^{-1} over the study period.

T_r of T3 and T4 showed rapid response to soil wetting/drying events (Figure 9). During each of the precipitation events on 19 – 21 May 2011, 25 May 2011, 10 -12 June 2011, 28– 29 June 2011, 4 July 2011, and 12– 13 July 2011, T_r usually lowered during the event, and then rapidly increased after precipitation ceased. This rapid increase in T_r was generally followed by a steady decrease beginning within two to three days after precipitation ceased. The impact of these precipitation events was not as apparent for the larger trees at Site1.

The overall trend in redcedar T_r was driven by atmospheric demand (as indicated by ET_p), with the highest T_r rates during the summer months and minimum rates in late November through early January. However, the amount of water lost by redcedars through T_r is modified by the amount of available soil water. For example, the upper layers of the soil profile (5, 10, 20 cm) at Site 1 fell below the wilting point in May 2011 through October 2011 (Figure 10), but T1 continued to transpire at rates > 4 mm d^{-1} (Figure 8). These rates are higher than those measured for T3 and T4, suggesting T1was drawing water from much deeper in the soil profile. Volumetric soil water content at 100 cm remained above wilting point throughout the measurement period. According to Sprackling and Read (1979), rooting depth of redcedars is about 0.45 * tree height (h), while its root spread is about 1.56 * h. T1 was estimated to be 5.5 m in height, yielding a root depth of 2.5 m and a soil volume occupied by its roots of 145 m^3. Thus, T1 ostensibly had access to soil water that smaller redcedars, T3 and T4, could not access.

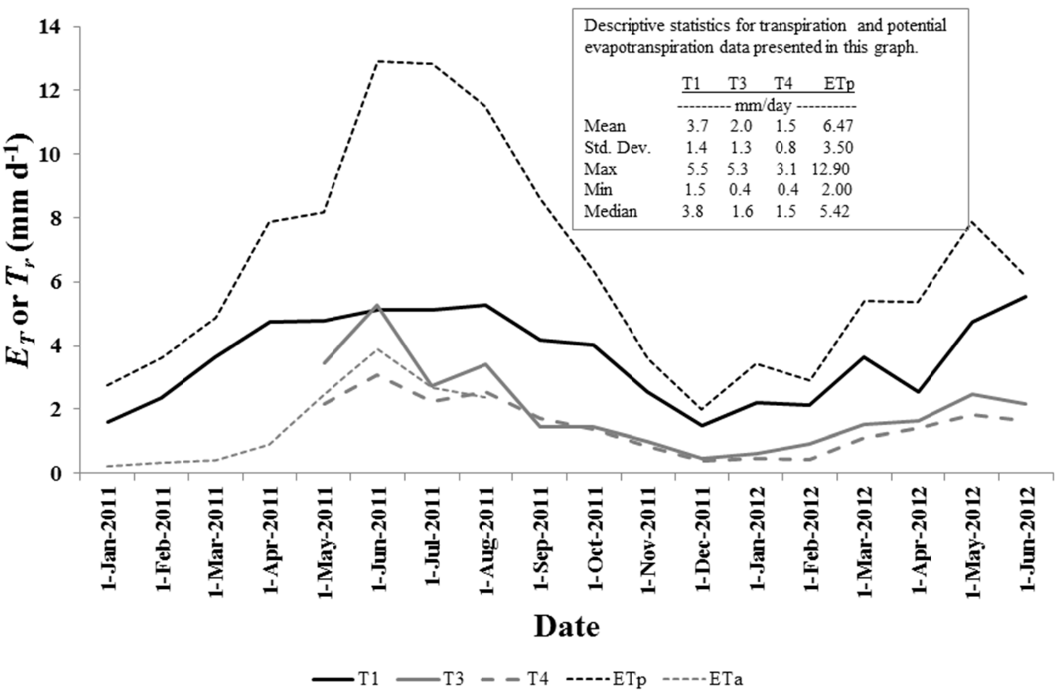

Figure 8. Time series plots of average daily potential evapotranspiraton (E_{Tp}), actual evapotranspiration (E_{Ta}) of native grass site near Site 1, and whole tree transpiration of redcedars at Site 1 (T1) and Site 2 (T3, T4). The inset provides descriptive statistics of each (except E_{Ta}) over the course of the study period. Statistics for E_{Ta} were not included due to the brevity of the available data record

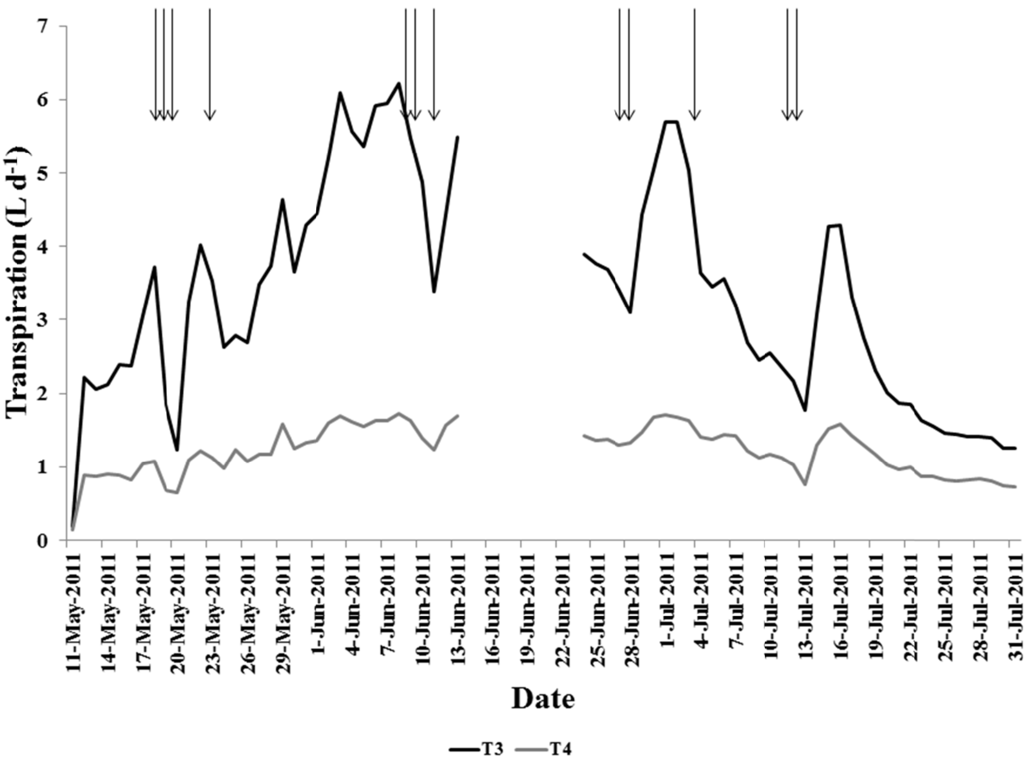

Figure 9. Daily whole tree transpiration for T3 and T4 at Site 2. The arrows indicate dates on which precipitation occurred

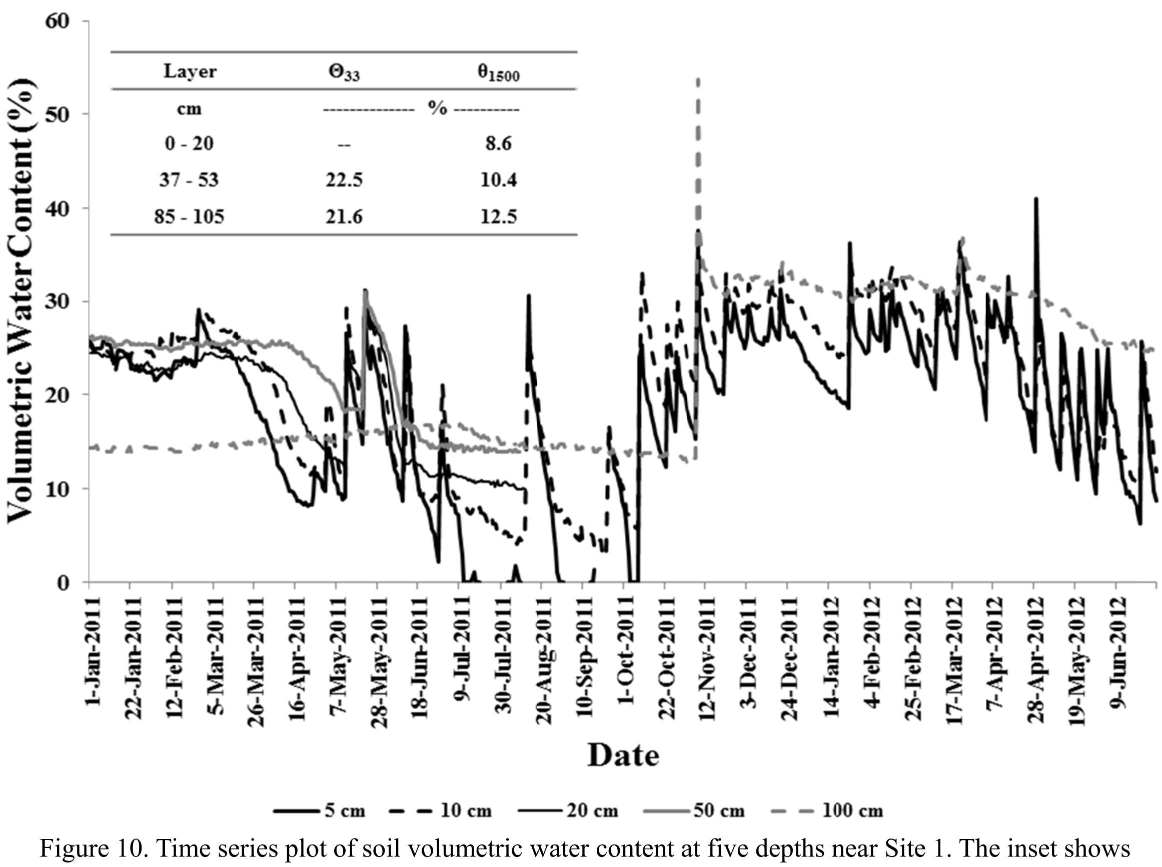

Figure 10. Time series plot of soil volumetric water content at five depths near Site 1. The inset shows volumetric water content at "field capacity" (θ_{33}) and "wilting point" (θ_{1500}) in a given layer of the soil profile

4. Discussion

The 33% canopy interception value for central Oklahoma redcedars (Table 5, El Reno) determined in this study is comparable to that observed by Thurow and Hester (1997) and Owens et al. (2006) for ashe juniper (37 and 35%, respectively) and the 27% value observed by Thurow and Hester (1997) for redberry juniper. Additionally, our estimates of throughfall and stemflow for central Oklahoma redcedars (≈ 50% and 5%, respectively) are comparable to that observed by Owens et al. (2006) for ashe juniper (55% and 5%, respectively). Calculation of effective precipitation (= measured rainfall – canopy interception) indicates that redcedar canopy interception may have more potential impact on runoff, streamflow, and groundwater recharge in the drier portions of the state because of the smaller rainfall events which occur there. In a climatological sense, the effective rainfall at Woodward, OK reflects precipitation measured over a bare surface 300 km further west, while effective rainfall at El Reno reflected bare surface annual rainfall amounts measured 175 km further west. This westward "shift" towards drier conditions was only 33 km for Broken Bow, OK.

Limited resources constrained our measurements of T_r to two trees in two size classes. We acknowledge that the limited number of trees reduces the power of statistical inference; however, this deficiency is somewhat offset by the length of record of continuous and simultaneous measurements of T_r in the two size classes.

Redcedars can use considerable amounts of water, depending upon tree size, time of year, and water availability. The small redcedars of this study (T3 and T4) used 7 L d^{-1} during the summer, whereas the large redcedar (T1) used 196 L d^{-1} during this time. When normalized by leaf area, the data presented herein suggests that during the drought conditions of this study, that from 5 to 9 L of water were transpired per month per meter square of leaf area (average ≈ 7.6 L m^{-2} $month^{-1}$). On an above ground dry mass basis the redcedars used from 11 to 15 L kg^{-1} $month^{-1}$ (average ≈ 12.4 L kg^{-1} $month^{-1}$).

T_r rates (mm d^{-1}) of the individual, isolated trees of this study were compared to reported values from dense stands of redcedars. Awada et al. (2012) reported whole stand T_r of 413 mm (= 1.1 mm d^{-1}) over their one-year study period. The dominant tree class in the stand (average diameter at breast height, DBH, = 0.16m) accounted for 77% of the total stand T_r (318 mm or 0.88 mm d^{-1}), whereas the co-dominant class (DBH = 0.12m) and suppressed class (DBH = 0.08m) accounted for 16 and 7% (66.2 mm or 0.18 mm d^{-1}; 27.8 mm or 0.08 mm d^{-1}), respectively. The largest tree class in their study transpired at a rate 1.7 times less than that observed for the smallest tree (T3) of this study. Redcedar T_r rates measured by Landon et al. (2009) are comparable to that of Awada et al. (2012), and, likewise, are much smaller than that observed for any redcedar in our study. Comparison with the results of Duesterhaus (2008) is less straightforward because those measurements were made using and eddy covariance system, which provides evapotranspiration (E_{Ta}; soil, plant, free water evaporation) rather than T_r. However, assuming that measured $E_{Ta} = T_r$, then T_r of Duesterhaus' study (2.4 mm d^{-1}) is close to that observed for T3 of this study. However, the value observed by Duesterhaus was for an even-aged stand of redcedars of about 50 years old (DBH = 0.11 m, average height = 9 m), whereas T3 was a much younger and smaller tree.

Total annual T_r (in mm) was divided by normal annual precipitation (in mm) to compute T_r as a percentage of total annual rainfall. Values for redcedars in this study were 155, 84, and 63% for T1, T3, and T4, respectively. Values for each size class in the study of Awada et al. (2012) were 77, 16, and 7% for the dominant, co-dominant, and suppressed classes, respectively. The redcedar stand measured by Duesterhaus (2008) used about 105% of the study site's normal annual rainfall, and that for the Landon et al. (2009) study was 64%.

Our observations of T_r in response to change in soil water content and precipitation inputs support the findings of Eggemeyer et al. (2009) who tracked changes in redcedar T_r over a one year time period with regard to soil and atmospheric variables. These authors found that redcedars of approximately the size of T1 in this study, acquired water from soil layers below 90 cm in the winter months, from the 5 – 50 cm depth in the spring and early part of the growing season, but that water extraction from the soil profile progressively moved from the 5 – 50 cm layer to deeper in the profile as the growing season progressed. When soil water content reached its minimum in September, redcedars began to extract water from below 90 cm. These authors also found that the redcedars became less responsive to precipitation events as the growing season progressed.

The relatively shallow-rooted trees at Site 2 (T3, root depth = 0.4 to 0.8 m over the study period; T4, root depth = 0.2 to 0.4 m) showed an increase in T_r from May to June 2011 (Figure 7), but decreased from June to July followed by a slight increase from July to August. Minimum T_r for all trees occurred in December, 2011. Although the water content of the soil profile recharged during the fall and winter months of 2011-2012, T_r remained low for T1 (also lower for T3 and T4) due to low atmospheric demand. Both T3 and T4 exhibited similar T_r rates from December 2011 to the end of the study in June 2012. Neither of these two trees reached the maximum T_r values measured in the summer of 2011, likely due to the lack of precipitation (i.e., available soil water) during the summer of 2012.

The comparisons above show that T_r is quite variable and is not only affected by macro-environmental variables (e.g., rainfall, soil water availability, humidity, etc.) but may also be affected by variations in microclimatic conditions (e.g., open grown vs. closed stand) experienced by each redcedar.

Because redcedar is encroaching into grasslands of the Great Plains, it is instructive to compare redcedar T_r to that of grasses. Although only eight months of data were available for comparison in this study, the E_{Ta} of the native grassland was much lower than T_r of T1 (Figure 7), but similar to that of the two smaller redcedars (T3 and T4) over the months where comparisons could be made. Fairbourn (1982) showed that T_r for range grasses in the High Plains of Wyoming ranged from 53 to 66% (avg. = 59%) as a percentage of E_{Ta}. Assuming this average applies to Southern Great Plains native grasses, average daily maximum T_r of the native grasses measured during our study was about 2.7 mm d^{-1}, or about half the maximum measured for T1 and T3, and about 87% of the maximum T_r measured for T4.

5. Conclusions

Eastern redcedar is among a number of aggressively encroaching plant species (alien or native) world-wide that may negatively impact local and regional water resources. Our findings suggest that red cedar canopies can intercept ≈ 33% of annual precipitation in central Oklahoma, and as much as ≈ 39% in the western (and drier) part of the state. The amount of water transpired by a given redcedar will be a function of tree size, atmospheric demand, and available soil water. The large red cedar in our study transpired 331 L d^{-1} for one day in May 2012, but averaged 132 L d^{-1} over the study period. The smaller red cedars transpired from 0.8 to 2.2 L d^{-1}. The red cedars of our study transpired from 5 to 9 L month^{-1} m^{-2} of leaf area and from 11 to 15 L kg^{-1} of above ground dry mass. Transpiration of our redcedars, growing in open conditions, was much higher than that observed by other researchers conducting their studies in or on dense stands of redcedar. Significant canopy interception of precipitation, coupled with year-round transpiration and transpiration rates as large as or larger than native grasses suggests that increases in red cedar density and areal coverage could affect local water resources through reduced infiltration, reduced runoff to streams, and decreases in ground water recharge rates. The similarity of redcedar and ashe juniper in terms of canopy interception, transpiration, and leaf area characteristics suggests that these two species may be parameterized similarly in hydrologic models used to investigate the impacts of these juniper species on water resources.

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