Brush Management Articles

1. The article below describes how brush management can increase the potential for greater short term water yields in the Seco Creek watershed.

   Effect of removal of *Juniperus ashei* on evapotranspiration and runoff in the Seco Creek watershed
   W. A. Dugas, R. A. Hicks and P. Wright. 1998.

2. A summary of a technical report by: Richard Conner, Wayne Hamilton, Brad Wilcox. With input from: Neal Wilkins, David K. Langford, Todd Snelgrove. 2009.

   Restoring Native Texas Rangelands for Increased Water Yield: Executive Summary

3. The article below concludes that the most likely sources of water for live oak and Ashe juniper is soil water and a limited supply of water stored in near-surface fractured rock layers.

   Energy balance and water use in a subtropical karst woodland on the Edwards Plateau, Texas
   J.L. Heilman, K.J. McInnes, J.F. Kjelgaard, M. Keith Owens, S. Schwinning. 2009.

4. The two articles below discuss the interception and evaporation of precipitation from juniper canopies in the Texas Hill Country area. The results showed that nearly 1 inch of rain had to fall before an appreciable amount of water actually reached the ground surface beneath the tree.

   Evaporation and interception water loss from juniper communities on the Kerr Wildlife Management Area
   M. Keith Owens, Robert K. Lyons. 2004.

   Evaporation and interception water loss from juniper communities on the Edwards Aquifer Recharge Area
   M. Keith Owens, Robert K. Lyons. 2004.

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Effect of removal of *Juniperus ashei* on evapotranspiration and runoff in the Seco Creek watershed

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Abstract. The water balance of a watershed may be affected by replacing deep-rooted woody species with shallow-rooted herbaceous vegetation. The objective of this study was to measure the effect of removing an individual species of tree, *Juniperus ashei* (Bucch.), on the runoff (RO) and evapotranspiration (ET) from two adjacent, unreplicated 15-ha areas (termed untreated and treated) in northeast Uvalde County, Texas, U.S.A. Daily ET from the two areas, measured from 1991 through 1995 using the Bowen ratio–energy balance method, varied from near 0 to 6 mm/d. All *J. ashei* taller than 0.5 m were cut with a chain saw in the treated area in September 1992. During both the pretreatment period (prior to September 1992) and the posttreatment period, the slope of treated ET as a function of untreated ET was ~1, suggesting that for the entire period of measurements, brush removal had no significant effect on ET. Average daily ET from the area to be treated was 0.05 mm/d lower than that from the untreated area during the 2-year pretreatment period, while it was 0.12 mm/d lower during the 3-year posttreatment period. The ET difference (untreated minus treated) was 0.3 mm/d in the first 2 years following removal of *J. ashei* and decreased thereafter. Removal of *J. ashei* had no consistent effect on RO. Vegetation management increased the potential for greater water yields in the short term from these rangelands by decreasing ET for the first 2 years after imposition of treatment.

1. Introduction

There has been much interest in using vegetation management to increase water yields (runoff and percolation) from rangeland and forest watersheds in the southwestern United States. An option often considered [*Hibbert*, 1983; *Carlson et al.*, 1990; *Jofre and Rambal*, 1993; *Davis*, 1993] is to replace deep-rooted woody species, which may intercept a substantial amount of precipitation [*Eddleman and Miller*, 1991] and have high whole-plant transpiration rates due to high leaf areas [*Angell and Miller*, 1994; *Owens*, 1996], with shallow-rooted herbaceous vegetation that usually intercepts less precipitation and has less leaf area. The amount of increased water yields from these watersheds, if any, resulting from vegetation management depends upon vegetation type or land use [*Dunn and Mackay*, 1995], vegetation treatment type or soils [*Richardson et al.*, 1979], and climate [*Griffen and McCarl*, 1989].

Increasing water yields from the Edwards Aquifer, located in south central Texas, is of interest now because water demands from the aquifer have increased while aquifer storage has remained essentially constant or decreased slightly. This rapidly recharged aquifer extends in an arc from north of Uvalde, Texas, to south of Austin, Texas; is about 250 km long and varies in width from about 8 to 50 km [*Puente*, 1978]. More than 1.5 million people in the immediate area, substantial areas of irrigated cropland, and the Comal and New Braunfels springs (home to several endangered species) are dependent upon water from this aquifer.

From the 1930s to the 1990s, water pumped annually from aquifer wells increased by 380% (to about 0.6×10^{12} L) [*Brown et al.*, 1992]. Annual aquifer discharge resulting from pumping and natural spring flow (~10^{12} L) has exceeded annual recharge on several occasions in recent years. Annual recharge averages about 0.8×10^{12} L and varies from about 0.05×10^{12} to 3×10^{12} L depending upon precipitation [*Brown et al.*, 1992].

About 150 years ago, early settlers in this area found land that had a good cover of native grasses and forbs, fertile soil, wooded bottom lands, and abundant spring-fed streams [*Weniger*, 1984]. *Juniperus ashei* (Buchh.), often termed mountain cedar or ashe juniper, and other woody brush and tree species occurred mainly on steep slopes and canyons [*Taylor and Smeins*, 1994]. However, reduced number and intensity of wildfires and heavy continuous grazing have contributed, along with other possible factors [*Mayeux et al.*, 1991], to an increase in density and aerial coverage of *J. ashei* and decreased herbaceous plant growth in this area [*Taylor and Smeins*, 1994]. This increased density and aerial coverage of *J. ashei* appear to have reduced aquifer recharge by reducing runoff and percolation [*Owens and Knight*, 1992; *Thurow and Taylor*, 1995] and to have reduced spring and seep flow [*Kelton*, 1975].

The objective of this study was to measure the effect of removing *J. ashei* on runoff (RO) and evapotranspiration (ET) from two similar, adjacent, unreplicated areas located upstream of the Edwards Aquifer recharge zone. Differences in measured water balance components of ET and RO before

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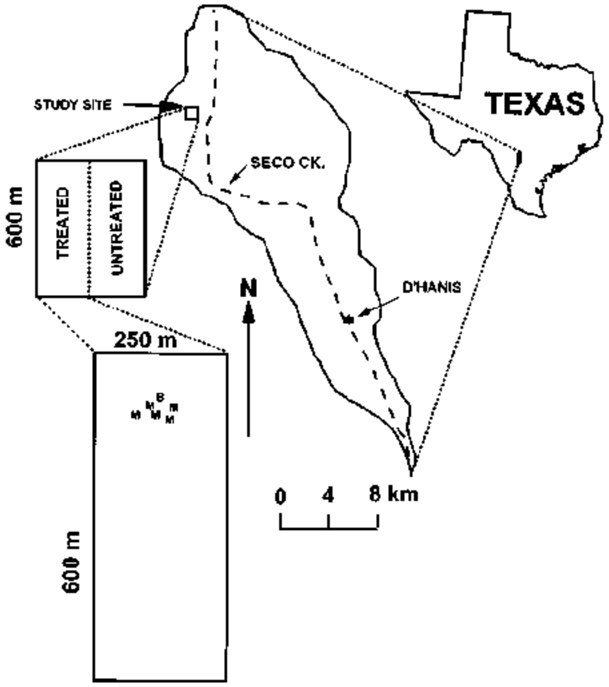

Figure 1. Map of study site. "B" and "M" symbols in treated area represent locations of base and mobile stations, respectively (see text). Base and mobile stations in the untreated area were in similar relative locations. Scale applies to map of Seco Creek watershed.

and after imposition of the treatment were used to interpret the effects of vegetation management on water yield increases and thus on potential for enhanced aquifer recharge from these rangelands.

2. Methods

2.1. Study Site

This study was conducted from 1991 through 1995 on two similar, adjacent, unreplicated areas (Figure 1) in northeast Uvalde County, Texas, U.S.A. (29°35′ N, 99°27′ W; elevation of 450 m), about 70 km west of San Antonio. Both areas were on a south facing hillside that had a slope of less than 10%. The "treated" area (Figure 1) was about 600 m (north-south) by 250 m (east-west) and had all *J. ashei* taller than 0.5 m cut with a chain saw in September 1992. The "untreated" area had no land management treatment imposed and had surface conditions that were similar to those of the surrounding area. Cut stems in the treated area were left lying on the ground. The period before September 16, 1992, the date upon which the majority of *J. ashei* in the treated area was cut, was termed the pretreatment period, while the period after September 16, 1992, was defined as the posttreatment period. Low-intensity grazing (approximately 1 head per 10 hectares per year) was initiated on the study site in early 1993.

Long-term average annual precipitation for this site is about 700 mm (Table 1), with maxima in May and September. Wind direction is predominantly south to southeast from March through October, and long-term average daily temperatures vary from about 10°C in the winter to 30°C in the summer. Estimated annual lake evaporation rate is about 2000 mm. The freeze-free period, about 230 days, begins about March 25 [*National Oceanic and Atmospheric Administration* (*NOAA*), 1978, 1985].

Soils at the study site, which are typical of much of the land in the upper portion of the Seco Creek watershed, belong to the Rockland-Real-Eckrant association (Lithic Haplustolls and Typic Calciustolls) *U.S. Department of Agriculture, Soil Conservation Service* (*USDA-SCS*), *and Texas Agricultural Experiment Station* (*TAES*), 1970]. They are shallow to very shallow; are gravelly, loamy, and clayey with 35 to 85% coarse fragments; are underlain at 0.1–0.5 m by indurated, fractured, limestone bedrock; occur on bench-like topography with limestone rock outcrops of the Glen Rose Formation; are well drained; have a low water-holding capacity; and have a high erosion potential. At this study site, surface soil depth varied from <1 to about 150 mm.

2.2. Vegetation

The point centered–quarter method [*Cottam and Curtis*, 1956] was used to estimate tree and shrub density. Ten points, spaced 30 m apart, were sampled in 1991 and 1994 on four north-south transects (two per area). Distance, maximum and minimum canopy diameter, and height were measured for the nearest shrub and tree in each quarter at each point.

Herbaceous standing crop measurements were made periodically during each year using two methods. Once or twice per year, standing crop by species was calculated from measurements and visual observations along a fixed 30-m transect in each area [*USDA*, 1975, sections 600 and 700].

Beginning in the spring of 1993, herbaceous standing crop also was measured about monthly from March through October in both areas by hand clipping vegetation in nine randomly positioned 0.2- to 1-m^2 quadrats (quadrat size depended upon the amount of vegetation at the sample point). Vegetation from quadrats was separated into live and dead components, then dried and weighed.

2.3. Evapotranspiration

Direct measurement of ET can be made using micrometeorological techniques (e.g., Bowen ratio–energy balance (BREB) and eddy correlation). Direct measurement of ET

Table 1. Monthly Precipitation Totals (mm) at the Study Site Throughout the Study Period, and Long-Term Average from Hondo, Texas

	1991	1992	1993	1994	1995	Hondo Average
January	64	94	32	80	12	44
February	23	134	57	50	9	56
March	13	191	79	104	67	38
April	67	79	19	48	62	70
May	152	174	200	81	161	93
June	96	188	104	54	112	69
July	91	78	1	50	16	42
August	17	55	0	40	41	62
September	286	30	109	51	263	99
October	46	28	13	84	28	76
November	66	141	19	70	53	36
December	240	50	6	110	36	38
Annual	1161	1242	639	822	860	723

For March through October, precipitation totals at the site are an average of four rain gauges, and for other months they are from the base station in the treated area (see text).

allows one to quantify the effect of land management on a water balance component that is a large fraction of precipitation [*Lane et al*., 1984; *Carlson et al*., 1990; *Gay*, 1993] and for which differences may be more detectable.

In this study, ET from each area was measured using the BREB method [*Tanner*, 1960] that often has been used for ET measurements from natural ecosystems [*McNaughton and Black*, 1973; *Gay and Fritschen*, 1979; *Price and Black*, 1990]. The method, which requires adequate fetch (i.e., uniform upwind surface conditions) and assumes equality of the transfer coefficients for heat and water, is accurate [*Tanner*, 1960; *Blad and Rosenberg*, 1974], spatially representative [*LeClerc and Thurtell*, 1990; *Schuepp et al*., 1990], and appropriate for continuous, extended measurements at remote locations [*Malek et al*., 1990; *Dugas and Mayeux*, 1991; *Dugas et al*., 1996].

Instrumentation and methods used in this study have been described by *Tanner et al*. [1987] and *Dugas et al*. [1996], and are similar to those used by *Pitacco et al*. [1992] and *Smith et al*. [1992]. Bowen ratios measured using this type of instrumentation have been shown to be similar to those from other types of equipment for irrigated wheat [*Dugas et al*., 1991] and grassland [*Fritschen et al*., 1992], and to those calculated from lysimeter measurements above bare soil and from eddy correlation measurements above *Prosopis glandulosa* rangeland [*Dugas*, 1992].

In this study, BREB measurements were made from about March 1 through mid-October of 1991 through 1995. Measurements were not made in the winter (November–February) because ET rates were low (average daily lake evaporation rate during this period is less than 3 mm/d, and average measured ET in October was less 1 mm/d) and access to the site was restricted.

Two sets of instrumentation were used in each area. One was at a stationary base station while the other was at one of five mobile locations in each area (Figure 1). Instrumentation at the mobile station in each area was moved, about every 6 weeks, to one of the randomly positioned locations that were 30–100 m south of the base station (Figure 1). The base station in the untreated area was about 300 m east of the treated base station.

Given the size of the treated area (Figure 1) and predominant wind directions, fetch was adequate [*Heilman et al*., 1989]. During the summer, wind directions are from 90° to 180° more than 75% of the time [*Larkin and Bomar*, 1983], and fetch in the treated area, after removal of *J. ashei*, thus was typically greater than 200 m and should have been more than adequate to ensure representative measurements from the instrumentation in the treated area, especially given the turbulent nature of wind flow over this rough surface and the relatively similar conditions in the treated and untreated areas, even after imposition of the treatment. Fetch was greater in the untreated area given the similarity of surrounding conditions, especially because southwesterly and westerly winds are uncommon at this site.

The two sets of instrumentation for each area provided a means of quantifying the ET spatial variability, although results from *Dugas and Mayeux* [1991], *Blanford and Stannard* [1991], *Fritschen and Qian* [1992], and this study (see below) suggest that the variation of ET over rangelands as measured at these heights by the BREB method is small because these measurements are a spatial integration of upwind fluxes [*LeClerc and Thurtell*, 1990; *Schuepp et al*., 1990].

For each set of instrumentation, ET was calculated [*Tanner*, 1960] for every half-hour from 5:30 A.M. to 8:00 P.M. central standard time (CST) from measurements of net radiation, soil heat flux, and gradients of temperature and humidity. Daily ET was calculated as the sum of 30-min ET values from 5:30 A.M. to 8:00 P.M. CST assuming ET was equal to zero at night (i.e., from 8:00 P.M. to 5:30 A.M. CST). The average of the two daily ET values for each area was used.

Half-hour averages of net radiation were measured for each station ($n = 4$) with a REBS model Q*6 net radiometer (REBS, Seattle, Washington) mounted at 3.3 m above the soil and 3 m away from the vertical station mast. When mounted at this height, the lower radiometer sensor received about 90% of the flux from a circle with a diameter of 20 m [*Reifsnyder*, 1967]. Thus these sensors were integrating over a large ground area. All net radiometers were simultaneously calibrated against a laboratory standard above a uniform grass surface prior to each year of measurements. Sensor sensitivities did not change.

Half-hour averages of soil heat flux were calculated from measurements at the base station in each area by four REBS model HFT-1 heat flux plates at 50 mm and from energy storage above the plates. Plates were buried under and between shrubs and grass plants. Factory plate sensitivities, confirmed before deployment to the field, were used. Storage was calculated from soil temperature measurements at 17 and 34 mm above the plates at three locations and from soil heat capacity. Heat capacity was calculated from weekly soil water measurements made gravimetrically in 1991 and 1992, and made in 1992 through 1995 using a Troxler model Sentry 200 soil moisture capacitance probe (Troxler Electronics Laboratory, Research Triangle, North Carolina) that was calibrated against gravimetric samples in each area on seven dates in 1992. Surface soil heat flux at the base station in each area was used for flux calculations for the mobile station.

Temperature and humidity gradients were measured at each station between two arms that were separated by 2 m. Lower arms were about 3.0 m above the soil.

Half-hour Bowen ratios in this study were evaluated for rejection using two criteria [*Ohmura*, 1982]: (1) Was the direction of heat or moisture flux opposite to the sign of temperature or humidity gradient, respectively, and (2) Was the Bowen ratio approximately -1.0? For half-hour periods when Bowen ratios were rejected because either of these criteria was met, ET values were linearly interpolated. Interpolation generally was required for only a few half hours in the early morning and/or early evening when ET was low and did not have a large effect on daily ET calculations.

Bowen ratios were not available from all stations on all days because of sensor problems (e.g., broken thermocouples). If more than 15 half-hour Bowen ratios were missing during the middle of the day, the entire day's data for that station were deleted from the analyses. On average, 18 daily ET measurements were deleted each year.

2.4. Runoff and Precipitation

Runoff is often a small fraction of seasonal or annual precipitation [*Laurenroth and Sims*, 1976; *Wilcox et al*., 1989; *Carlson et al*., 1990] and is highly dependent upon antecedent precipitation. Therefore it is sometimes difficult to discern land management treatment effects on RO because one is looking for a small difference in small numbers that are highly variable. To compare RO from two paired, unreplicated watersheds, one must be careful to select hydrologically similar

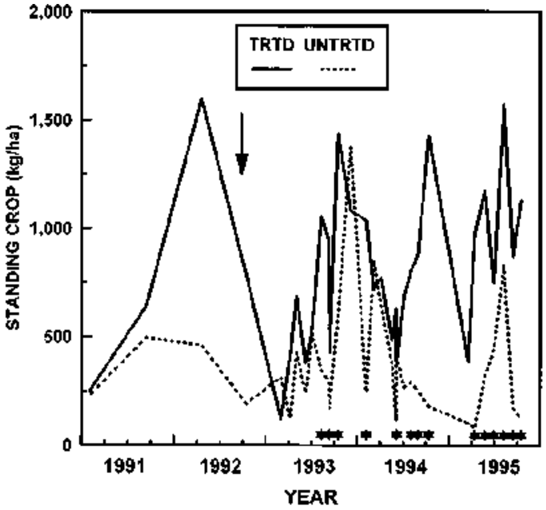

Figure 2. Average standing crop (live and dead) of herbaceous vegetation on treated and untreated areas in 1991 through 1995. Arrow denotes time of removal of *J. ashei*. Stars denote significantly different averages ($P > 0.05$).

watersheds and make RO measurements for a sufficiently long period in both watersheds before and after imposition of a treatment to ensure the relationship of RO from the two watersheds has been adequately characterized.

In September 1991, one 0.6-m-tall H-flume (Plasti-Fab, Tualatin, Oregon), attached to a 1.8-m-long approach section, was installed in each area for measurement of surface runoff from a 5.5-ha watershed in the treated area and a 3.6-ha watershed in the untreated area. The area of each watershed was determined from topographic maps developed from a survey in December 1990. Flume water height was measured year round using a Druck model PDCR 950 pressure transducer (Druck, Inc., Danbury, Connecticut). Factory sensitivities of transducers were verified in the laboratory. One-minute averages of flume water height were measured during flow events, which were infrequent and discrete, using a Campbell Scientific model CR10 data logger (Campbell Scientific, Inc., Logan, Utah). Water height was converted to volumetric discharge using published engineering tables for this flume design. Total RO for each discrete event (typically less than a few hours) was calculated from 1-min volumetric discharges.

Half-hour totals of precipitation were measured at two locations per area from March through October and at the base station in the treated area year round.

2.5. Statistical Techniques

Effects of removing *J. ashei* on ET were determined using regression techniques [*Clausen and Spooner*, 1993; *Davis*, 1993]. Regression analyses of ET for the two areas were conducted for the pretreatment and posttreatment periods. Statistical differences in slopes between the two periods (untreated ET as a function of treated ET) were used to test the effect of vegetation management.

3. Results and Discussion

3.1. Precipitation

Growing season (March through October) precipitation, averaged for the four rain gauges (Table 1), was above the average (549 mm) in 1991 (768 mm), 1992 (812), and 1995 (750) and was slightly below average in 1993 (525) and 1994 (512).

There were small differences in monthly precipitation totals (March–October) between the four rain gauges at the study site. The range of monthly totals across the four gauges averaged 15% of measured precipitation, while the range of growing season totals averaged 10% of total growing season precipitation. The coefficient of variation of growing season precipitation totals for each year across the four locations varied from 4 to 7%. There were no systematic differences between the four gauges. Thus precipitation differences were small across the site and did not cause differences in ET or RO.

3.2. Tree and Shrub Characteristics

J. ashei was the dominant tree at the study site, with minor amounts of live oak (*Quercus virginiana* (Mill.)). In 1991, *J. ashei* density was about 10% lower on the area to be treated. In 1994, *J. ashei* density was 980 trees/ha in the untreated area and 146 trees/ha in the treated area. In 1994 the *J. ashei* in the treated area were almost exclusively <1 m tall, i.e., short trees that were not cut in 1992. In the untreated area in 1994, average *J. ashei* height was 2.9 m, and average canopy ground area, assuming canopies were circular [*Hicks and Dugas*, 1998], was 8 m^2/tree, indicating that about 80% of the total ground area in the untreated area was covered by *J. ashei* canopy. The canopy leaf area index (LAI) of individual *J. ashei* trees was near 10 [*Hicks and Dugas*, 1998]. Dominant shrubs in both areas were agarito (*Berberis trifoliolata* (Moric.)) and Texas persimmon (*Diosporos texana* (Scheele)).

3.3. Herbaceous Standing Crop

Dominant grasses at this site (with the 5-year average standing crop in kilograms per hectare) were perennial threeawn (*Aristida longiseta* (Steud.), 1852), Texas grama (*Bouteloua rigidiseta* (Steud.) Hitchc., 718), little bluestem (*Schizachyrium scoparium* (Michx.) Nash, 439), Nealy grama (*Bouteloua uniflora* (Vasey), 298), and side oats grama (*Bouteloua curtipendula* (Michx.) Torr., 284).

Owing primarily to timing and amounts of precipitation (Table 1), herbaceous standing crop was highly variable in the two areas throughout the study (Figure 2). The large standing crop value in early 1992 in the treated area is associated with the uncertainty of standing crop measurements made using a visual method. Statistically significant differences determined using analysis of variance ($P > 0.05$) between herbaceous standing crop on the two areas were primarily in 1994 and 1995. Beginning in early 1994, standing crop in the treated area was always greater. The increase in standing crop in the treated area in 1994 and 1995 was a result of increased availability of light and water for herbaceous plants due to the removal of *J. ashei*. The generally similar standing crop values in the two areas in 1993 and early 1994 were due to the low growing season precipitation totals that occurred in 1993 (Table 1) and the extended period (>12 months) it took needles to drop from dead stems of *J. ashei* that were lying on the ground following treatment. In the middle of 1994, when almost all needles had dropped from the stems, herbaceous growth upward through the dead stems increased dramatically. Large increases of herbaceous standing crop in the treated area following removal of *J. ashei* could reduce ET differences between the two areas [*Dugas and Mayeux*, 1991].

3.4. Evapotranspiration

Within each area, ET from the base and mobile stations was within about 5% of each other for both the pretreatment and posttreatment periods (Table 2). The similarity of ET from the base and mobile stations within each area supports our use of ET from one station when necessary. Averages in Table 2 were calculated for days when ET measurements were available from both stations in an area, and thus the number of days used in each average differed across areas. Slopes from linear regression (base ET as a function of mobile ET), without an intercept, were 0.95 (pretreatment period) and 0.95 (posttreatment period) for the treated area and 0.89 (pretreatment period) and 0.96 (posttreatment period) for the untreated area.

Daily ET from the two areas varied from near 0 to 6 mm/d (Figure 3). During both periods the slope of ET in the untreated area as a function of ET from the treated area was ~1. Slopes were not significantly different during the two periods, suggesting that for the entire period of measurements, brush removal had no significant effect on ET. During the pretreatment period the average daily ET from the two areas differed by 0.05 mm/d (treated, 1.91 mm/d; untreated, 1.96 mm/d). The larger ET from the untreated area during the pretreatment period versus that from the treated area may have been due to the slightly higher density of *J. ashei* in this area.

During the posttreatment period the slope was increased only by about 1% and the average ET from the treated area was 0.12 mm/d lower (treated, 1.62 mm/d; untreated, 1.74 mm/d). Therefore, for the 3 years, net ET decreased by 0.07 mm/d in the treated area in association with the removal of *J. ashei*. (Note that the average ET rates shown for each area above are different from those in Table 2 because the numbers of days used in calculating the two averages were different; daily ET measurements were needed for both stations in an area for Table 2 but only from one station in each area for the above averages.) The decrease in average ET in the posttreatment period in both areas versus that from the pretreatment period was caused by the lower precipitation (Table 1).

While removal of *J. ashei* had little effect on ET over the entire posttreatment period, the ratio of total ET to total precipitation for the period of March through October in each year was affected immediately after imposition of the treatment (Figure 4). The ratio was essentially equal in the two areas during 1991 (Figure 4) and prior to September in 1992 (results not shown). The difference in the ratio for the two areas was greatest in 1993 (this is equivalent to an average ET difference of 0.3 mm/d) because of reduced leaf area in the treated area associated with *J. ashei* removal. Differences of ET decreased in 1994 (0.10 mm/d) and 1995 (−0.06 mm/d) because of increased herbaceous and *J. ashei* leaf area in the treated area.

Table 2. Average Daily Evapotranspiration for Base and Mobile Stations in Treated and Untreated Areas in Pretreatment and Posttreatment Periods

	Treated		Untreated	
Period	Base	Mobile	Base	Mobile
Pretreatment	1.88	1.98	2.16	2.31
Posttreatment	1.55	1.63	1.70	1.64

The number of days used for calculating the average was equal for two stations in an area and a period but was not equal across areas or periods. Evapotranspiration values are in millimeters per day.

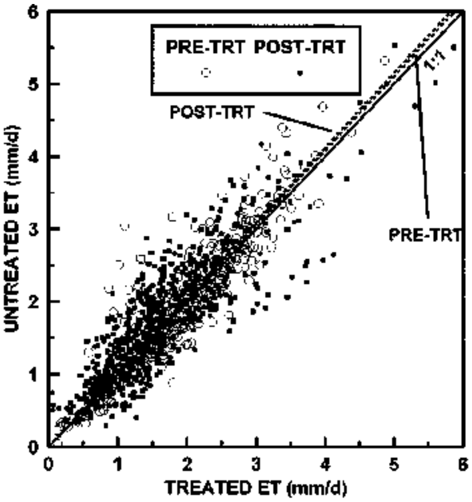

Figure 3. Average daily evapotranspiration (ET) from the untreated area versus average daily ET from the treated area during the pretreatment and posttreatment periods. The 1:1 line and linear regression lines (without intercept) for pretreatment and posttreatment periods are shown. Slopes (with standard errors) from linear regression (untreated ET as a function of treated ET) are: 1.02 (0.01) for the pretreatment period and 1.03 (0.01) for the posttreatment period.

The ET:precipitation ratio varied from less than 55 to over 75% for the 5 years of this study (Figure 4). The ratio increased with decreasing precipitation, i.e., a smaller percentage of precipitation left the site via ET as precipitation increased, and as expected, water yield increased with increasing precipitation.

The equality of ET from the two areas prior to removal of *J. ashei* also is reflected in the cumulative ET difference between

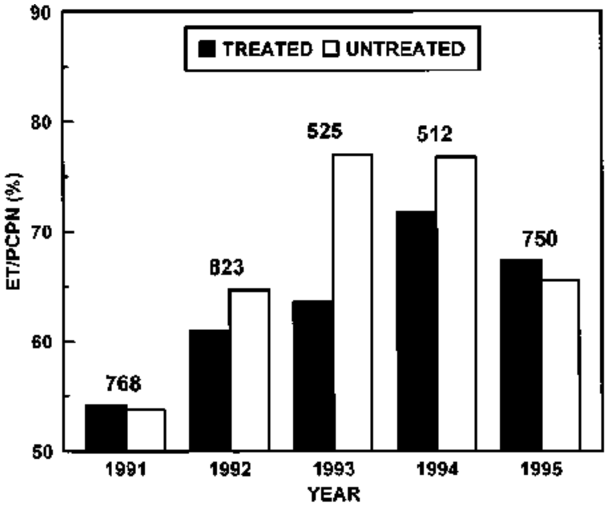

Figure 4. Ratio of total evapotranspiration (ET) and precipitation (PCPN) from March through October for treated and untreated areas for 1991 through 1995. Values above each set of bars are total precipitation (in millimeters) from March through October. *J. ashei* trees were removed from the treated area in September 1992.

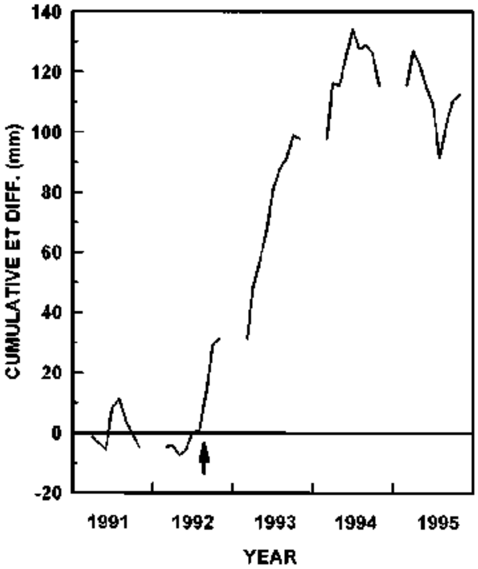

Figure 5. Cumulative difference (untreated minus treated) of total monthly evapotranspiration (ET) from March through October for 1991 through 1995. Arrow denotes time of removal of *J. ashei*. Breaks in lines are during winter when ET was not measured.

the two areas (Figure 5). The difference was approximately equal to zero during the pretreatment period but increased substantially immediately subsequent to *J. ashei* removal in September 1992. This positive cumulative ET difference, which represents a greater water yield (runoff and percolation) from the treated site, increased steadily until mid-1994, when it ceased increasing likely because of greater transpiration by plants in the treated area associated with increased leaf area, as evidenced by the increased herbaceous standing crop (Figure 2), and likely because of increased leaf area and increased transpiration rate per unit leaf area [*Fleck et al.*, 1996] of woody plants after removal of *J. ashei.*

The average ET difference from September 1992 through August 1994 (i.e. the 2 years following imposition of the treatment) was 0.3 mm/d. This is equivalent to an increase in water yield of 1.2×10^6 L per hectare of land cleared per year. This suggests that a considerable area of land would need to be treated to have a large effect on the aquifer water balance. The cumulative ET differences decreased slightly after August 1994. Nevertheless, this short-term (2 years) increase in water yield does offer some potential for increasing aquifer recharge associated with land management, especially if the land is managed to reduce increases in leaf area after treatment.

Also, these ET differences between the two areas reflect, we believe, the lower end of differences one might measure in this area following imposition of this treatment because (1) the herbaceous vegetation response (and thus transpiration) in the treated area in this study was greater than would normally be experienced because of the low grazing pressure and the minimal soil disturbance caused by hand-cutting *J. ashei* as compared to what would have occurred if vegetation had been removed by more traditional mechanical methods, and (2) we did not remove other woody plants that, because they were a large fraction of total leaf area in the treated area following treatment, likely were significant contributors to transpiration in the treated area.

3.5. Runoff

Large precipitation events during the pretreatment period allowed us to demonstrate a consistent, linear relationship between runoff from each watershed (Figure 6). Therefore the two watersheds were hydrologically similar before the *J. ashei* was removed from the treated area.

Only two substantial runoff events occurred in the 3 years subsequent to removal of *J. ashei* and they produced conflicting results (Figure 6). The first of these events (May 1993) showed a 26% increase in runoff from the treated watershed. However, a large runoff event in 1995 showed a substantial decrease in runoff from the treated area. The 1993 runoff result was probably atypical because at this time the treated area did not have a good cover of bunch grasses on account of the short time since removal of *J. ashei*. The 1995 event reflects, we believe, the expected long-term pattern wherein runoff is decreased from lands having bunch grasses versus those with a heavy cover of *J. ashei.*

Regardless, for the relatively small watersheds at this site, runoff is only about 5% of seasonal precipitation and occurs only when precipitation intensity is high. Thus, using differences in RO before and after imposition of a treatment to examine effects of vegetation management in these two areas produced inconclusive results.

4. Conclusions

The following conclusions can be drawn from this research:

1. Evapotranspiration (ET) rates from March through October on these rangelands average about 1.8 mm/d.
2. Averaged over the 5 years of this study, precipitation was partitioned between ET (65%), soil storage and percolation (30%), and runoff (5%).

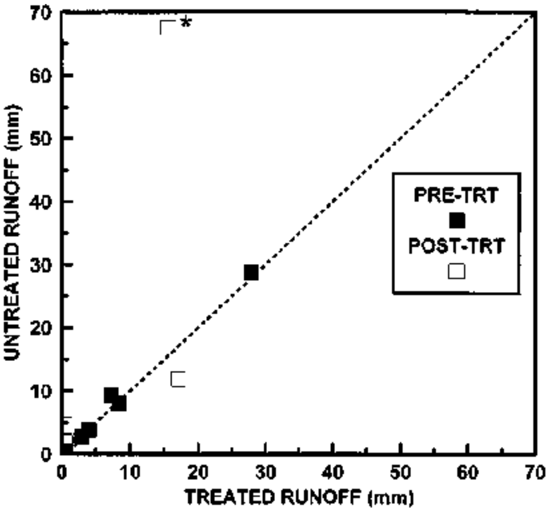

Figure 6. Runoff from watersheds in untreated and treated areas during pretreatment and posttreatment periods. Each point is one runoff event. The runoff data point from the untreated area for the posttreatment period with an asterisk was estimated using precipitation totals and watershed area because of sensor malfunction and water heights that were greater than H-flume height. The 1:1 line is shown.

3. For the 3 years following removal of *J. ashei*, ET was reduced in the treated area by an average of 0.07 mm/d. The ET difference reached a maximum 2 years after treatment and decreased thereafter.

These results are most applicable to sites with similar characteristics, namely, those with a highly permeable soil with low water-holding capacity. Sites with less permeable soils and with soils having a larger water-holding capacity would likely show less difference in ET because of a more rapid and vigorous herbaceous response following treatment [e.g., *Dugas and Mayeux*, 1991] due to more water stored in the soil for a longer period.

In the current study, potential water yields were increased associated with vegetation management due to reduction of ET only during the first 2 years following treatment. After 3 years, water yield increases decreased. The duration and magnitude of increased water yields could possibly be lengthened if treated areas were managed to reduce leaf area increases of remaining vegetation following brush removal.

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References

Angell, R. F., and R. F. Miller, Simulation of leaf conductance and transpiration in *Juniperus occidentallis*, *For. Sci*., *40*, 5–17, 1994.

Blad, B. L., and N. J. Rosenberg, Lysimetric calibration of the Bowen ratio–energy balance method for evapotranspiration estimation in the central Great Plains, *J. Appl. Meteorol*., *13*, 227–236, 1974.

Blanford, J., and D. Stannard, Spatial variability of energy fluxes at Walnut Gulch, in *Proceedings*, *10th American Meteorological Society Conference on Biometeorology and Aerobiology*, pp. 158–160, Am. Meteorol. Soc., Boston, Mass., 1991.

Brown, D. S., B. L. Petri, and G. M. Nalley, Compilation of hydrologic data for the Edwards Aquifer, San Antonio area, Texas, 1991, with 1934–1991 summary, *Bull. 51*, Edwards Underground Water District, San Antonio, Tex., 1992.

Carlson, D. H., T. L. Thurow, R. W. Knight, and R. K. Heitschmidt, Effect of honey mesquite on the water balance of Texas Rolling Plains rangeland, *J. Range Manage*., *43*, 491–496, 1990.

Clausen, J. C., and J. Spooner, Paired watershed study design, *9/1993*; *841-F-93-009*, Off. of Water, U.S. Environ. Prot. Agency, Washington, D.C., 1993.

Cottam, G., and J. T. Curtis, The use of distance measures in phytosociological sampling, *Ecology*, *37*, 451–460, 1956.

Davis, E. A., Chaparral control in mosaic pattern increased streamflow and mitigated nitrate loss in Arizona, *Water Resour. Bull*., *29*, 391–399, 1993.

Dugas, W. A., Bowen ratio and eddy correlation measurements for bare soil, sorghum, and rangeland, *Wetter Leben*, *44*, 3–16, 1992.

Dugas, W. A., and H. S. Mayeux, Jr., Evaporation from rangeland with and without honey mesquite, *J. Range Manage*., *44*, 161–170, 1991.

Dugas, W. A., L. J. Fritschen, L. W. Gay, A. A. Held, A. D. Matthias, D. C. Reicosky, P. Steduto, and J. L. Steiner, Bowen ratio, eddy correlation, and portable chamber measurements from irrigated spring wheat. *Agric. For. Meteorol*., *56*, 1–20, 1991.

Dugas, W. A., R. A. Hicks, and R. Gibbens, Structure and function of C_3 and C_4 Chihuahuan desert plant communities, II, Energy balance components. *J. Arid. Environ*., *33*, 63–79, 1996.

Dunn, S. M., and R. Mackay, Spatial variation in evapotranspiration and the influence of land use on catchment hydrology, *J. Hydrol*., *171*, 49–73, 1995.

Eddleman, L. E., and P. M. Miller, Potential impacts of western juniper on the hydrologic cycle, in *Proceedings—Symposium on Ecology and Management of Riparian Shrub Communities*, pp. 176–180, Intermountain Res. Stn., U.S. For. Serv., Ogden, Utah, 1991.

Fleck, I., D. Grau, M. Sanjose, and D. Vidal, Carbon isotope discrimination in *Quercus ilex* resprouts after fire and tree-fell, *Oecologia*, *105*, 286–292, 1996.

Fritschen, L. J., and P. Qian, Variation in energy balance components from six sites in a native prairie for three years, *J. Geophys. Res*., *97*, 18,651–18,661, 1992.

Fritschen, L. J., P. Qian, E. T. Kanemasu, D. Nie, E. A. Smith, J. B. Stewart, S. B. Verma, and M. L. Wesley, Comparisons of surface flux measurement systems used in FIFE 1989, *J. Geophys. Res*., *97*, 18,697–18,713, 1992.

Gay, L. W., Evaporation measurements for catchment scale water balances, in *Proceedings of the First International Seminar of Watershed Management*, pp. 68–86, Univ. of Sonora, Hermosillo, Sonora, Mexico, 1993.

Gay, L. W., and L. J. Fritschen, An energy budget analysis of water use by saltcedar, *Water Resour. Res*., *15*, 1589–1592, 1979.

Griffen, R. C., and B. A. McCarl, Brushland management for increased water yield in Texas, *Water Resour. Res*., *25*, 175–186, 1989.

Heilman, J. L., C. L. Brittin, and C. M. U. Neale, Fetch requirements for Bowen ratio measurements of latent and sensible heat fluxes, *Agric. For. Meteorol*., *44*, 261–273, 1989.

Hibbert, A. R., Water yield improvement potential by vegetation management on western rangelands, *Water Resour. Bull*., *19*, 375–381, 1983.

Hicks, R. A., and W. A. Dugas, Estimating Ashe Juniper leaf area from tree and stem characteristics, *J. Range Manage*., in press, 1998.

Jofre, R., and S. Rambal, How tree cover influences the water balance of Mediterranean rangelands, *Ecology*, *74*, 570–582, 1993.

Kelton, E., The story of Rocky Creek, *Practicing Nutritionist*, *9*, 1–5, 1975.

Lane, L. J., E. M. Romney, and T. E. Hakonson, Water balance calculations and net production of perennial vegetation in the northern Mojave Desert, *J. Range Manage*., *37*, 12–18, 1984.

Larkin, T. J., and G. W. Bomar, Climate atlas of Texas, *LP-192*, Tex. Dep. of Water Resour., Austin, 1983.

Laurenroth, W. K., and P. L. Sims, Evapotranspiration from a shortgrass prairie subjected to water and nitrogen treatments, *Water Resour. Res*., *12*, 437–442, 1976.

LeClerc, M. Y., and G. W. Thurtell, Footprint prediction of scalar fluxes using a Markovian analysis, *Boundary Layer Meteorol*., *52*, 247–258, 1990.

Malek, E., G. E. Bingham, and G. D. McCurdy, Evapotranspiration from the margin and moist playa of a closed desert valley, *J. Hydrol*., *120*, 15–34, 1990.

Mayeux, H. S., H. B. Johnson, and H. W. Polley, Global change and vegetation dynamics, in *Noxious Range Weeds*, edited by L. F. James, pp. 62–74, Westview, Boulder, Colo., 1991.

McNaughton, K. G., and T. A. Black, A study of evapotranspiration from douglas fir forest using the energy balance approach, *Water Resour. Res*., *9*, 1579–1590, 1973.

National Oceanic and Atmospheric Administration (NOAA), *Climatography of the United States*, *No. 20*, Natl. Clim. Data Cent., Asheville, N. C., 1978.

National Oceanic and Atmospheric Administration (NOAA), Climatic summaries for selected sites, 1951–1980, Texas, in *Climatography of the United States*, *No. 20*, Natl. Clim. Data Cent., Asheville, N. C., 1985.

Ohmura, A., Objective criteria for rejecting data for Bowen ratio flux calculations, *J. Appl. Meteorol*., *21*, 595–598, 1982.

Owens, M. K., The role of leaf and canopy level gas exchange in the replacement of *Quercus virginiana* (Fagaceae) by *Juniperus ashei* (Cupressaceae) in semiarid savannas, *Am. J. Bot*., *83*, 617–623, 1996.

Owens, M. K., and R. W. Knight, Water use on rangelands, in *Water for South Texas*, *TAES CPR 5043-5046*, pp. 1–7, Tex. Agric. Exp. Stn., College Station, 1992.

Pitacco, A., N. Gallinaro, and C. Guilivo, Evaluation of actual evapotranspiration of a *Quercus ilex* L. stand by the Bowen ratio–energy balance method, *Vegetatio*, *99–100*, 163–168, 1992.

Price, D. T., and T. A. Black, Effects of short-term variation in weather on diurnal canopy CO_2 flux and evapotranspiration of a juvenile Douglas-fir stand, *Agric. For. Meteorol*., *50*, 139–158, 1990.

Puente, C., Method of Estimating Recharge to the Edwards Aquifer in the San Antonio Area, Texas, *U.S. Geol. Surv. Water Resour. Invest. Rep., 78-10*, 38 pp., 1978.

Reifsnyder, W., Radiation geometry in the measurement and interpretation of radiation balance, *Agric. Meteorol.*, *4*, 255–265, 1967.

Richardson, C. W., E. Burnett, and R. W. Bovey, Hydrologic effects of brush control on Texas rangelands, *Trans. ASAE*, *22*, 315–319, 1979.

Schuepp, P. H., M. Y. Leclerc, J. I. MacPherson, and R. L. Desjardins, Footprint prediction of scalar fluxes from analytical solutions of the diffusion equation, *Boundary Layer Meteorol.*, *50*, 355–373, 1990.

Smith, E. A., W. L. Crosson, and B. D. Tanner, Estimation of surface heat and moisture fluxes over a prairie grassland, 1, In situ energy budget measurements incorporating a cooled mirror dew point hygrometer, *J. Geophys. Res.*, *97*, 18,557–18,582, 1992.

Tanner, B. D., J. P. Greene, and G. E. Bingham, A Bowen ratio design for long term measurements, *ASAE Tech. Pap. 87-2503*, Am. Soc. Agric. Eng., 6 pp., St. Joseph, Mich., 1987.

Tanner, C. B., Energy balance approach to evapotranspiration from crops, *Soil Sci. Soc. Am. Proc.*, *24*, 1–9, 1960.

Taylor, C. A., Jr., and F. E. Smeins, A history of land use of the Edwards Plateau and its effect on the native vegetation, *Juniper Symposium Proceedings*, *TAES Tech. Rep. 94-2*, pp. 1–8, Tex. A&M Univ. Res. Stn., Sonora, Tex., 1994.

Thurow, T. L., and C. A. Taylor Jr., Juniper effects on the water yield of central Texas rangelands, in *Water for Texas: Research Leads the Way*, *Proceedings of the 24th Water for Texas Conference*, pp. 657–665, Tex. Water Resour. Inst., Tex. A&M Univ., College Station, 1995.

U.S. Department of Agriculture (USDA), *NRCS National Rangeland Handbook*, Washington, D. C., 1975.

U.S. Department of Agriculture, Soil Conservation Service (USDA-SCS) and Texas Agricultural Experiment Station (TAES), Soil survey of Uvalde County, Texas, 1970.

Weniger, D., *The Explorer's Texas: The Lands and the Waters*, 224 pp., Eakin, Austin, Tex., 1984.

Wilcox, B. P., C. L. Hanson, J. R. Wight, and W. H. Blackburn, Sagebrush rangeland hydrology and evaluation of the SPUR hydrology model, *Water Resour. Bull.*, *25*, 653–666, 1989.

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Restoring Native Texas Rangelands for Increased Water Yield: Executive Summary


Canyon Lake. Photo credit: Edward Jackson ©2008

Performance of water catchments and the land-based water cycle is heavily influenced by vegetation and the management of that vegetation. Vegetation in south central Texas has undergone significant change over time, shifting from a grassland-dominated savanna to a heavily wooded landscape. This is due to the invasion of Ashe juniper (sometimes called "cedar") in the Edwards Plateau and mesquite in the South Texas Plains. This transformation to woodland may have reduced water available for recharge and streamflow. Woody plant invasion can be reversed through rangeland restoration. Initial costs, however, are generally more than a landowner can justify when considering livestock production alone.

Under certain circumstances, additional water yield results from rangeland restoration. As is suggested by several studies, there may be opportunities for creating incentive-based programs that lead to additional water yield through rangeland restoration.


Photo credit: Zereshk ©2008

Texas Hill Country, just north of Garner State Park.

With sponsorship from the Texas Wildlife Association Foundation, a team of Texas A&M University scientists have conducted a technical evaluation of land-based water conservation practices and their potential for water yield in south central Texas. The purpose of this evaluation was to determine the feasibility of rangeland restoration for increasing water yield. This team identified areas in south central Texas suitable for rangeland restoration programs. This report is a summary of their findings.

TEXAS A&M | Institute of Renewable Natural Resources

A summary of a technical report by:
Richard Conner
Wayne Hamilton
Brad Wilcox

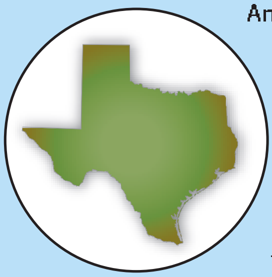
With input from:
Neal Wilkins
David K. Langford
Todd Snelgrove

TWAF

Background

The South Central Texas Regional Water Planning Group, also known as Region L, is one of 16 regional water planning groups across the state. These groups identify water needs, assess potential water supplies, and recommend strategies for meeting those needs for the Texas Water Development Board. It includes over 20 counties and the seventh largest city in the United States—San Antonio. The population of this area was about 2.0 million in 2000 and is projected to grow to about 4.3 million by 2060. Obviously, securing adequate supplies of fresh water for Region L is a mounting concern. Total water use (municipal, industrial, and agricultural uses) in the region was approximately 896,000-acre feet/year (an acre-foot is about 325,000 gallons) in 2000 and is projected to increase by 43 percent to 1.28 million acre-feet/year by 2060 (SCTRWPG 2006). Nearly 80 percent of the region's fresh water is obtained from underground aquifers—primarily the Edwards and the Carrizo-Wilcox. Due to the high demand placed on these aquifers, the amount of water withdrawn exceeds recharge. Thus the need to increase water available for recharge and streamflow is essential.

LAND STEWARDSHIP LANGUAGE IN THE TEXAS CODE



Anyone seeking to officially fund and implement land stewardship programs can now find authorization in our state law. Senate Bill 3 of the 2007 Session of the Texas Legislature amended Article 2, Section 2.02, Subchapter A, Chapter 1 of the Texas Water Code by adding Section 1.004. In this section, our leaders note the benefits of voluntary land stewardship and define the term. It reads:

> **Sec. 1.004. FINDINGS AND POLICY REGARDING LAND STEWARDSHIP.**
>
> **(a)** *The legislature finds that voluntary land stewardship enhances the efficiency and effectiveness of this state's watersheds by helping to increase surface water and groundwater supplies, resulting in a benefit to the natural resources of this state and to the general public. It is therefore the policy of this state to encourage voluntary land stewardship as a significant water management tool.*
>
> **(b)** *"Land stewardship," as used in this code, is the voluntary practice of managing land to conserve or enhance suitable landscapes and the ecosystem values of the land. Land stewardship includes land and habitat management, wildlife conservation, and watershed protection. Land stewardship practices include runoff reduction, prescribed burning, managed grazing, brush management, erosion management, reseeding with native plant species, riparian management and restoration, and spring and creek-bank protection, all of which benefit the water resources of this state.*

With this language, the Texas Legislature officially recognized voluntary land stewardship practices as a means to improve water quality and quantity, opening the door for the development of effective land conservation/management programs designed to benefit water resources.

Influence of Woody Species on the Water Cycle

The two major natural areas of Region L are the Edwards Plateau and the South Texas Plains. Prior to European settlement in the 1800s, the Edwards Plateau and South Texas Plains were dominated by grassland. In the absence of fire and the presence of overgrazing, Ashe juniper has invaded large areas of the Edwards Plateau, and mesquite and mixed brush have overtaken much of the South Texas Plains. There is some evidence that rangelands dominated by these woody shrubs and trees may not yield as much water as rangelands dominated by grasses and herbaceous vegetation. A significant amount of research has been performed that addresses this issue at several scales.

EDWARDS PLATEAU—Research within the Edwards Plateau has focused on the water use of Ashe juniper at the individual tree level. A single, mature juniper tree can transpire approximately 550 gallons per day (Owens and Ansley 1997). In addition, as much as 40% of the precipitation that falls on a juniper tree is intercepted by the canopy and lost to evaporation (Owens et al. 2006). As a consequence, in an area that receives approximately 29.5 inches of annual rainfall, a mature juniper tree will intercept and transpire nearly all of the available water falling within its canopy.

How much water yield?

An additional acre-foot can be gained for every 5 to 8 acres of brush converted to native rangeland in the Edwards Plateau and for every 15 to 30 acres converted in the South Texas Plains.

Based on this, available water can be negatively impacted in regions where extensive juniper cover exists. However, this does not take into account the difference in water usage between juniper and the grasses and other vegetation that would replace it when restored.

Studies conducted at the stand scale have compared the differences in water usage between rangeland grasses and Ashe juniper. These studies show that in areas cleared of juniper, evapotranspiration rates (water lost to the atmosphere through evaporation and use by plants) were 1.6 inches/acre/year less than areas with intact juniper (Dugas et al. 1998).

There are several anecdotal accounts of springs drying following encroachment by juniper. Studies at the small catchment scale that focus on catchments with springs have shown increases in spring discharge following the removal of juniper. In some instances this occurred even when precipitation was below average following juniper removal. These studies estimate that 1.6 to 1.8 inches/acre/year of additional water were made available after restoration of rangelands (Wright 1996, Huang et al. 2006).

Photo credit: Texas Parks and Wildlife Department ©2008

Balcones Escarpment.

Although there have been no large-scale experiments conducted that look at the landscape-scale impacts of juniper encroachment on streamflow, confidence is increasing that restoring rangelands on the Edwards Plateau will increase streamflow and recharge at the small catchment scale.

Photo credit: William Vann ©2008

Based on current research, the best estimate is that converting 5 to 8 acres of juniper to rangeland would result in an approximate increase in recharge and streamflow of 1 acre-foot of water per year.

SOUTH TEXAS PLAINS— Compared to the Edwards Plateau, there has been little effort to study the influence of woody plants on recharge in the South Texas Plains. In studies that have been conducted, there has been evidence that rangeland restoration increases recharge. One field study indicated that there was no recharge on plots with dense shrub cover and 0.9 inches/acre/year of recharge on plots with grass cover (Weltz and Blackburn 1995). On the basis of this study, it can be concluded that recharge is limited on sites dominated by brush and that recharge can be increased if dense shrub cover is converted to grassland. Studies in other regions of Texas dominated by brush have yielded similar results.

Recent work using hydrologic modeling focuses on the strong influence of climate, soils, and vegetation on recharge in Texas. Based on these simulations, it is estimated that recharge for the South Texas Plains is less than 0.2 to 0.4 inches/acre/year (Keese et al. 2005). Further investigation shows that the recharge rate declined by a factor of 2 to 30 times when vegetative cover was included in the model rather than focusing solely on climate and soil texture (Keese et al. 2005). This suggests that rangeland restoration on sandy soils where water has a chance to make it past the root zone may have a strong effect on recharge in the South Texas Plains.

All of the available research in the South Texas Plains suggests that little, if any, recharge occurs in the presence of dense shrub cover. However, both hydrologic modeling and fieldwork suggest that when rangeland grasses are restored, recharge will be higher—especially on sandy soils. ***On the basis of current research, best estimates are that 15 to 30 acres of south central Texas brushland restored to rangeland would yield 1 acre-foot of water per year.***

RANGELAND RESTORATION

Rangelands comprise 60 percent (90 million acres) of Texas land. In addition to supporting livestock production and providing habitat for native wildlife, they serve as the state's largest watershed.

The precipitation that falls on Texas rangeland is a major source of surface flow and aquifer recharge. The management of rangelands can have major impacts on the water available to Texas. Healthy rangelands provide high-quality drinking water, promote recharge, conserve soil, filter overland flow of water, provide forage for livestock, and provide wildlife habitat (Hays et al. 1998). Over the last century, encroachment of woody species across much of Texas' rangelands has degraded many of these services.

Rangeland restoration programs strive to reverse this trend. Through the use of sound management practices, woody species on Texas rangelands can be controlled, and rangelands can be restored.

There are many benefits to rangeland restoration including increased forage for livestock production. This allows the opportunity to increase stocking rates and ultimately increase revenue for landowners. Rangeland restoration can enhance wildlife habitat, thus enhancing hunting opportunities—a major source of income for Texas landowners.

Healthy rangelands provide a tremendous public benefit to Texans. Wise stewardship of this resource will have positive impacts on Texas for many generations—the greatest of which is a plentiful and clean supply of fresh water.

Saving the water and the soil must start where the first raindrop falls.
—Lyndon B. Johnson, 1947

Rangeland Restoration Techniques and Brush Management

The vast differences in terrain and vegetation between the Edwards Plateau and South Texas Plains require different approaches to rangeland restoration and brush management. Costs for both regions are highly variable based on a number of factors including size and density of the target brush species; the type, rock content, and slope of soil in which the target species is growing; whether the target species sprouts re-growth from root buds; and whether cost-effective herbicides are available for controlling the target species.

EDWARDS PLATEAU—Within the Edwards Plateau, Ashe juniper is the primary species targeted for brush management and subsequent restoration of rangelands. Ashe juniper is a non-sprouting species; i.e., juniper will die when all of the aboveground green material is removed. There are three primary methods used for controlling Ashe juniper—mechanical, prescribed fire, and biological. There are limited chemical treatments for the control of Ashe juniper.

Mechanical treatments involve the use of large equipment such as a bulldozer or skid steer loader that physically removes the aboveground portion of the juniper. Costs are variable, but based on current market

$ How much does it cost?

Assuming rangeland restoration practices are effective for at least 10 years, the cost to produce an additional acre-foot of water in the Edwards Plateau would be $40 to $180 depending on the method. Likewise, over the Carrizo-Wilcox Aquifer in south central Texas, the range is $100 to $300 per additional acre-foot.

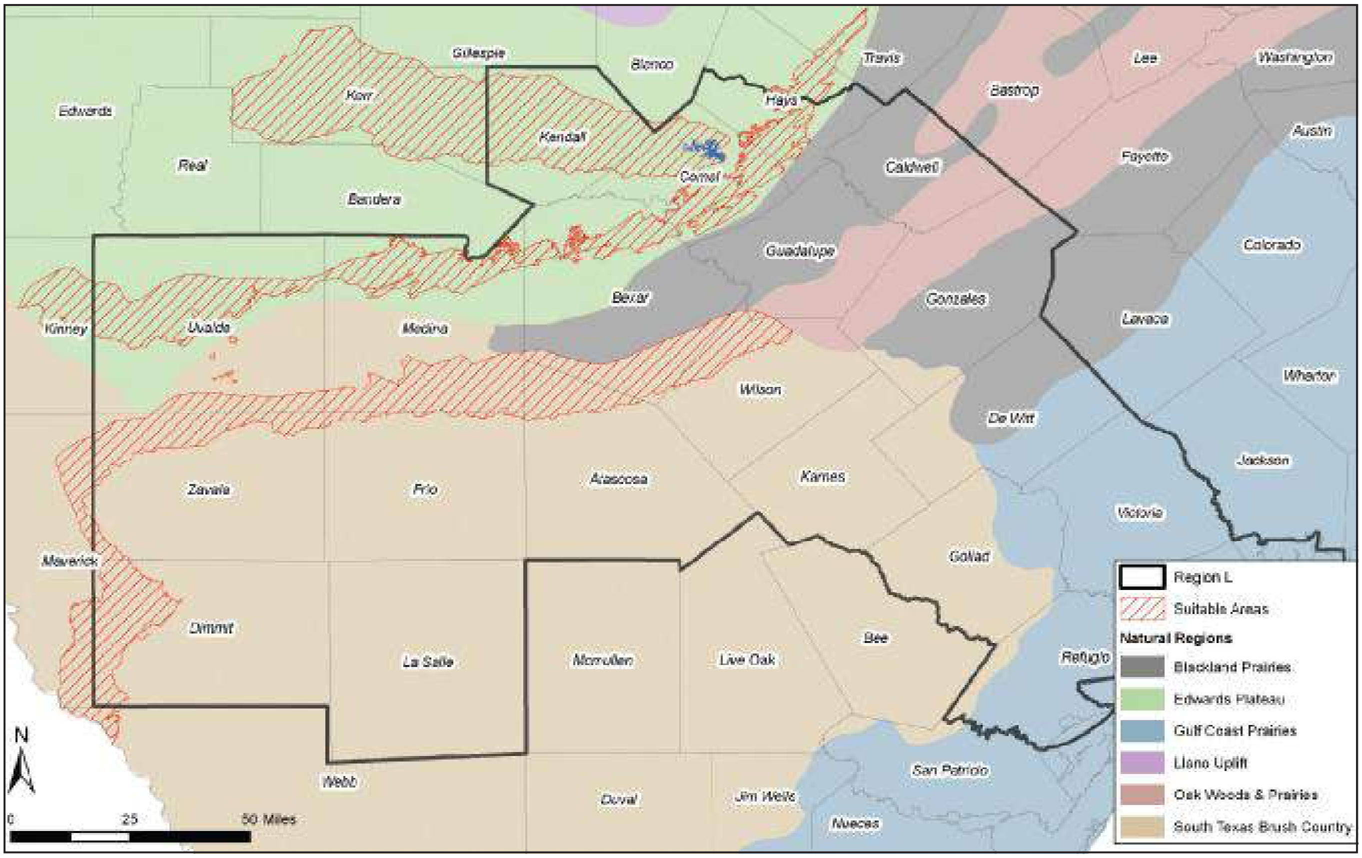
rates, they range from $75 to $400/acre (Pestman 2007). Perhaps the most economically effective treatment for juniper control is prescribed fire. Prescribed fire can be combined with other high-cost initial practices such as mechanical brush control to enhance or maintain brush control benefits for many years. Costs are variable, but based on current market rates, they can range from $3 to $8/acre. Biological control of Ashe juniper can also be achieved through the use of goats. Goats will browse on the young saplings of both juniper and hardwoods. When concentrated in high densities and rotated through pastures, they represent an effective means of controlling woody brush.

SOUTH TEXAS PLAINS—The South Texas Plains are the heart of the Texas "Brush Country," and no other region in Texas has seen more widespread implementation of brush management practices. Brush stands in this region are often mixtures of more than 15 species such as mesquite, acacia, and prickly pear. Most brush species in this region will re-sprout after treatment, which causes significant management challenges. The primary methods of controlling brush in the South Texas Plains are mechanical, chemical, and prescribed fire (Hamilton et al. 2004).

Mechanical methods that involve the use of a root plow, bull dozer, or chaining are highly variable depending on density and target species. These methods range from $30 to $250/acre based on current market rates (Pestman 2007). Due to the re-sprouting nature of most target species in the South Texas Plains, chemical methods represent a cost- effective method for controlling brush and maintaining range conditions. Based on current market rates, costs for chemical control methods range from $20 to $120/acre. Prescribed burning can be combined with other initial practices such as mechanical brush control to enhance or maintain brush control benefits for many years. Costs are variable, but based on current market rates, they range from $3 to $8/acre.

Where does rangeland restoration work?

Water yield resulting from rangeland restoration is likely to be effective only on sites receiving at least 18 inches of annual rainfall and having geology and soil characteristics leading to rapid runoff and infiltration (Hibbert 1983, Seyfreid et al. 2005, Wilcox et al. 2006).



Aquifer recharge zones and river basins within Region L suitable for rangeland restoration efforts to increase water yield based on vegetative cover, geology, and soil characteristics.

Cost of other methods?

The cost of additional water yield through rangeland restoration compares favorably to other methods of acquiring additional available water. For example, municipal conservation efforts cost $50 to $200/acre-foot, and seawater desalination costs $619/acre-foot (SCTRWPG 2006).

Rangeland Restoration and Water

Areas within Region L with the greatest potential for increasing recharge through brush management and rangeland restoration are those areas where deep drainage (water movement beyond the root zone) can occur. This characteristic is found where soils are shallow and overlie relatively permeable bedrock. The Edwards Plateau region is a prime example of this type of situation. It has considerably more "flowing water" than would be expected for a semiarid climate (about 27.5 inches of precipitation per year). The explanation lies in the karst geology—a substrate of fractured limestone that allows rapid flow of water to the subsurface. Other soil types that may enable deep drainage are sandy soils—like those found in the Carrizo-Wilcox Aquifer recharge zone. Large areas of Region L exhibit these characteristics and support vast expanses of brush that provide opportunities for increasing water yield through rangeland restoration.

Based on current research within the Edwards Plateau, the best estimate is that the conversion of Ashe juniper woodlands into grassland-dominated savannas (woody cover < 10%) would result in an average increase in water yield (streamflow and recharge) of approximately 1.5 to 2.4 inches/acre/year. Thus, for every 5 to 8 acres of Ashe juniper converted to open savannas, an additional acre-foot of water would become available for recharge and streamflow. Current research within the south central Texas shrublands indicates that average recharge on sandy soils could be increased by shrub control from 0.4 to 0.8 inches/acre/year. This translates to an additional acre-foot of water for every 15 to 30 acres of brush cleared. For example, if recharge rates were at the lowest estimated level (0.4 inches/acre/year), restoring 200,000 acres of rangeland over the Carrizzo-Wilcox recharge zone would increase recharge by about 5,000 acre-feet/year. Based on average annual water consumption, an acre-foot is enough water to satisfy the needs of five Texans for an entire year.

The cost-effectiveness of implementing a brush management program for increasing recharge and streamflow cannot be assessed strictly on the basis of the initial cost of rangeland restoration. For example, if a rangeland restoration program is limited to the initial practice, re-growth of brush will eventually occur to the point that there will no longer be any increase in groundwater recharge. Alternatively, by using follow-up brush control practices after the initial treatment to control brush re-growth, the increased groundwater recharge gained from the initial brush control practice can be maintained for many more years into the future. Fortunately, follow-up range management practices, like prescribed fire, are relatively inexpensive. Therefore, rangeland restoration programs consisting of an initial treatment plus appropriate maintenance practices at 3- to 6-year intervals after the initial practice can result in maintaining range condition and the resulting increase in ground water recharge for many years into the future.

For example, clearing juniper on the Edwards Plateau ranges from $100 to $400 per acre. On average, this yields an increase in recharge of approximately 0.167 acre-feet per year. The results of extending the years of reduced brush cover, and the subsequent increased groundwater recharge, on the cost per acre-foot of added groundwater recharge are illustrated in Table 1. The cost estimates are obtained by taking the per-acre cost of the restoration practice, or cost of a program consisting of an initial restoration plus follow-up practices, and dividing it by 0.167. This yields the estimated

	YEARS BRUSH CONTROL EFFECTIVE			
	Brush Control Cost/Acre	**1 Year**	**5 Years**	**10 Years**
	COST/ACRE-FOOT/YEAR OF ADDED WATER			
EDWARDS PLATEAU	$70	$419	$83	$41
	$150	$898	$179	$89
	$200	$1,197	$239	$119
	$300	$1,796	$359	$179
CARRIZO-WILCOX	$35	$1,060	$212	$106
	$50	$1,515	$303	$151
	$75	$2,272	$454	$227
	$100	$3030	$606	$303

Table 1. Cost per acre-foot of added water for selected control costs and effective duration of brush control practice within the Edwards Plateau and Carrizon-Wilcox Aquifer.

cost per acre-foot of added groundwater recharge resulting from brush control if the program is effective for only one year. Results for several alternative levels of brush control costs are detailed in Table 1. The third and fourth columns of Table 1 illustrate the per-acre-foot costs of added groundwater recharge resulting from brush control if the brush control practice, or program, is effective for a period of five and ten years, respectively.

If rangeland restoration programs were implemented that require participating landowners to maintain range conditions with 5 percent woody cover for a period of 10 years, then the costs per acre-foot of added groundwater recharge would be expected to range between $40 and $180 per acre-foot in the Edwards Plateau and between $100 and $300 per acre-foot in the Carrizo-Wilcox Aquifer recharge zone. It should be noted that the estimates of added groundwater recharge costs are based on the highly variable costs of the brush control practices and/or programs. Additionally, there are many other factors that would impact the ultimate costs, including landowner participation rates, proper implementation and maintenance of brush management, and availability of cost-share funding.

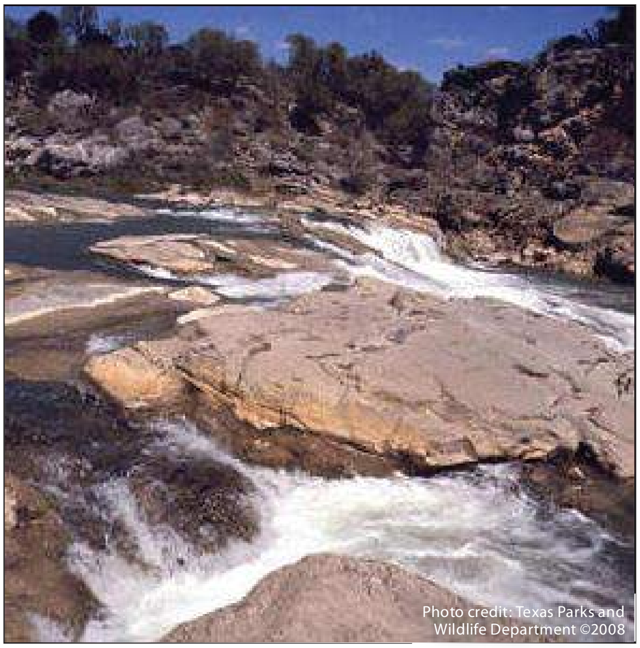
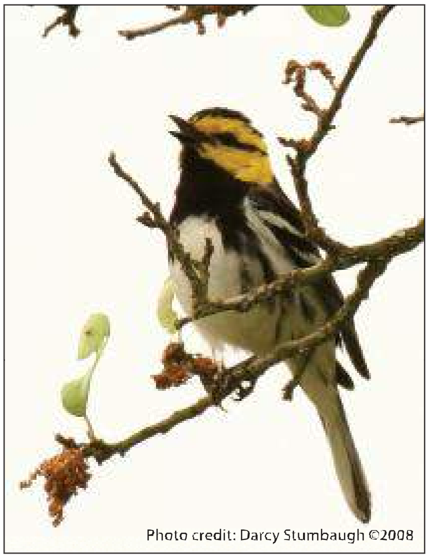


Photo credit: Texas Parks and Wildlife Department ©2008

Pedernales River.

Incentive-Based Programs

Rangeland restoration is generally recognized to be a long-term investment that often requires a large monetary investment with benefits extending several years into the future. Landowner benefits are based on expected increases in returns from livestock and wildlife enterprises (Conner and Bach 2000). Even after benefits are realized, they may not be enough to cover the costs of clearing and maintenance activities. Landowners who receive cost-share funding will realize a profit from their investment more quickly regardless of the cost of clearing if they are reimbursed for a portion of restoration expenses. In addition, studies have shown that when cost-share funds are available, landowner participation rates increase (Olenick et al. 2004). An incentive-based program that shares the cost of rangeland restoration with the landowner could provide opportunities for increasing water yield.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Golden-cheeked warbler.

Endangered Species Management

A rangeland restoration program, if implemented, would need to account for endangered species habitat. Within Region L, the golden-cheeked warbler, a federally listed endangered bird, inhabits mature oak-juniper woodlands. This habitat would not be a candidate for rangeland restoration efforts. Impacts to the Black-capped vireo, another federally listed endangered bird, would also have to be considered. Any juniper removal performed in areas that have the potential for becoming black-capped vireo habitat would have to be done selectively and followed with prescribed fire to enhance that potential. Any brush clearing should be conducted by a certified brush management contractor who has received training on how to recognize and work around endangered species habitat.


Photo credit: Michael Male ©2008

Black-capped vireo.

Where do we go from here?

Additional work should be performed to determine the number of acres suitable for rangeland restoration efforts to increase water yield. In addition, studies should be conducted that assess the impact of incentive-based programs on landowner participation. When combined, these two efforts will give a better estimate of expected water yield from rangeland restoration.

Conclusion

Over the next several decades, Region L will continue to face an ever-increasing demand for a limited resource—fresh water. Based on the research available, there is a better understanding of the influence of vegetation and vegetation management on the performance of water catchments and the land-based water cycle. Land-based water conservation practices, specifically rangeland restoration, offer great promise for augmenting fresh water supplies in the Edwards Plateau and South Texas Plains of Texas. With long-term costs per acre-foot of added water ranging from $40 to $180 for the Edwards Plateau and $100 to $300 for the South Texas Plains, brush management represents a cost-effective alternative for increasing available water when compared to other water management strategies. In order for a rangeland restoration program to be successful, an incentive-based program that helps defray the high initial landowner costs of brush clearing must be developed. Additional programs should be developed that provide incentives for landowners to maintain rangeland in a manner producing the greatest public benefit, i.e., increased water yield and the other benefits healthy rangelands provide.

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References

Conner, J.R., and J.P. Bach. 2000. Assessing the Economic Feasibility of Brush Control to Enhance Off-Site Water Yield. Chapter 2 in: Brush Management/Water Yield Feasibility Studies for Eight Watersheds in Texas. Final Report to the Texas State Soil & Water Conservation Board. Published by Texas Water Research Institute, College Station Texas. TWRI TR-182.

Dugas, W.A., R.A. Hicks, and P. Wright. 1998. Effect of removal of Juniperus ashei on evapotranspiration and runoff in the Seco Creek watershed. Water Resources Research 34:1499-1506.

Hamilton, W. T., A. McGinty, D. N. Ueckert, C. W. Hanselka, and M. R. Lee. 2004. Brush Management: Past, Present, and Future. Texas A&M University Press. 282 pp.

Hays, K.B., B.J. Leister, B.S. Rector, and L.D. White, 1998. Rangeland Watersheds: The Major Source of Water for Texans. Texas Agricultural Extension Service, Water for Texans Series-RLEM No. 1, College Station, Texas. http://texnat.tamu.edu/water/water4texans.htm.

Hibbert, A.R. 1983. Water yield improvement potential by vegetation management on western rangelands. Water Resources Bulletin 19: 375-381.
Huang, Y., B.P. Wilcox, L. Stern, and H. Perotto-Baldivieso. 2006. Springs on rangelands: Runoff dynamics and influence of woody plant cover. Hydrological Processes 20:3277-3288.

Keese, K.E., B.R. Scanlon, and R.C. Reedy. 2005. Assessing controls on diffuse groundwater recharge using unsaturated flow modeling. Water Resources Research 41:W06010, doi:06010.01029/02004WR003841.

Olenick, K.L., J.R. Conner, R.N. Wilkins, U.P. Kreuter, and W.T. Hamilton. 2004. Economic implications of brush treatments to improve water yield in two Texas watersheds. J. of Range Mgt. 57: 337-345.

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

Owens, M.K. and R.J. Ansley. 1997. Growth and ecophysiology of Ashe and redberry juniper. Proc. 1997 Juniper Symposium. San Angelo, TX. TAES Tech. Rep. 97-1.

Pestman: Pest Management Options and Related Investment Analysis System for Forage Lands. TAES project #405048 (under development), Wayne T. Hamilton, PI.

Seyfried, M.S., and B.P. Wilcox. 2006. Soil water storage and rooting depth: key factors controlling recharge on rangelands. Hydrological Processes 20: 3261-3275.

South Central Texas Regional Water Planning Group (SCTRWPG). 2006. 2006 Regional Water Plan, Volume 1: Executive Summary and Regional Water Plan. San Antonio. San Antonio River Authority, http://www.twdb.state.tx.us/RWPG/main-docs/2006RWPindex.asp.

Weltz, M.A., and W.H. Blackburn. 1995. Water budget for south Texas rangelands. Journal of Range Management 48:45-52.

Wilcox, B.P., M.K. Owens, W.A. Dugas, D.N. Ueckert, and C.R. Hart. 2006. Shrubs, streamflow, and the paradox of scale. Hydrological Processes 20:3245-3259.

Wright, P.N. 1996. *Spring enhancement in the Seco Creek water quality demonstration project.* Annual Project Report, Seco Creek Water Quality Demonstration Project. Temple, TX: U.S. Department of Agriculture-Natural Resources Conservation Service.

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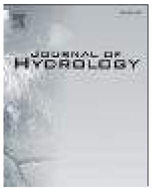

Energy balance and water use in a subtropical karst woodland on the Edwards Plateau, Texas

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SUMMARY

Woody encroachment into karst grasslands and savannas is presumed to reduce water availability and aquifer recharge, in part, because deep roots extract large quantities of water from perennial sources within the fractured bedrock underlying shallow soils. If true, energy balance partitioning and transpiration in woody ecosystems should be decoupled to an extent from rainfall, and sensitivity of the energy balance and evapotranspiration (ET) to rainfall and water deficits should be dampened. We evaluated responses of energy and water vapor fluxes to rainfall and water deficits in a live oak (*Quercus virginiana*)-Ashe juniper (*Juniperus ashei*) woodland on the karst Edwards Plateau, TX, USA, over a 2-year period using eddy covariance measurements of the turbulent fluxes. Total ET during the two years was 1416 mm, 92% of total rainfall. We observed large and rapid reductions in λE and increases in H during drying cycles, and high correlation between ET and soil water content in the upper 20 cm of the root zone. In most cases, ET declined at the same time as soil water content, indicating that the woodland relied heavily on water from recent rainfall events, rather than antecedent water. We found no evidence that deep roots were extracting significant amounts of water from a perennially stable supply of water. Excavations at the woodland site revealed a rock layer at 20 cm below the soil surface, with a dense root mat above the rock and penetration of relatively few roots into the rock through cracks and fissures. Thus, the most likely sources of water for trees were soil water and a limited supply of water stored in near-surface fractured rock layers.

Introduction

Woody plant encroachment into arid and semi-arid grasslands and savannas is occurring worldwide (Archer et al., 2001; Van Auken, 2000), with potentially significant consequences for hydrology and biogeochemical cycling (Houghton et al., 1999; Baldocchi et al., 2004; Engel et al., 2005). The hydrologic impact of woody encroachment is particularly worrisome in karst landscapes because karst aquifers provide 25% of freshwater supplies for human consumption worldwide and 40% in the US (White et al., 1995). Karsts are landscapes formed from dissolution of soluble rocks, mainly limestone and dolomite. They generally have well-developed underground drainage systems, and strong interactions between surface and groundwater flow (Bonacci et al., 2009).

There is a wide-spread perception that woody encroachment, especially in karst landscapes, has significant negative effects on water yield (e.g. Tennesen, 2008). However, reality may be more complicated. A conceptual model by Huxman et al. (2005) laid out criteria for impacts of woody encroachment on water yield. According to this framework, a reduction in streamflow is predicted in semi-arid uplands only if there is potential for rapid subsurface flow. Even though this condition may be characteristic of karst, it is by no means ubiquitous (Wilcox et al., 2005; Schwinning, 2008). For example, in the stepped landform of the Edwards Plateau largely unbroken rock layers close to the surface all but prevent downward fracture flow and deep root formation (Wilcox et al., 2007).

To date, perceptions of woodland ecohydrology on the Edwards Plateau have been shaped by studies conducted in the fault zone of the Balcones Escarpment. In this narrow zone along the eastern edge of the Edwards Plateau, roots of Ashe juniper (*Juniperus ashei* Buckholtz) and live oak (*Quercus virginiana* Miller) were observed in caves to depths of 9 m and 22 m, respectively, tapping into perched water tables (Jackson et al., 1999). Because these deep roots of juniper and oak have larger xylem conduit diameters and hydraulic conductances than shallow roots, they can contribute disproportionally more to water use if they encounter significant sources of water at depth (McElrone et al., 2004). Indeed, Jackson et al. (2000) found that water from depths greater than

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7 m was the source for 24% of growing season water used by a juniper whose roots had access to water in a cave. Pockman et al. (2008) reported that during prolonged drought, water uptake from deep roots of juniper accounted for as much as 60% of total daily transpiration. At night, hydraulic redistribution from deep to shallow soil maintained water flow through the roots. Using stable isotopes for tracing water sources, McCole and Stern (2007) concluded that juniper shifts its water use from predominately deep sources during the warm and dry summers to shallow sources during the cool and wet winters.

Recently, other studies conducted at sites lacking shallow caves in the stepped landform of the Edwards Plateau (Wilcox et al., 2007) have by contrast found no indication of water uptake from perched water tables (Schwinning, 2008; Eggemeyer and Schwinning, 2009). These studies concluded, based on stable isotope evidence, that water sources for juniper, oak and normally deep-rooted honey mesquite (*Prosopis glandulosa*) on the Plateau are largely shallow and unstable. Here we report on a study coming to the same conclusion based on measurements of energy balance and water vapor fluxes of a live oak-Ashe juniper woodland on the Plateau.

The surface energy balance is key to understanding how woody encroachment affects ecohydrology of Plateau ecosystems because water use is controlled by available energy and its partitioning between latent and sensible heat. If deep roots of woody species on the Plateau are exploiting a more stable supply of water than what is available to grasses, energy balance partitioning and transpiration in woody ecosystems should be decoupled to an extent from rainfall, and sensitivity of the energy balance and ET to rainfall and water deficits should be dampened.

Methodology

Site description

The Edwards Plateau, commonly referred to as the Texas Hill Country, is a 93,000 km^2 karst ecoregion that historically was vegetated by prairie grasses and live oaks (*Q. virginiana*) (Barnes et al., 2000). Chronic overgrazing by livestock, and suppression of wildfires has increased areal densities of woody species like Ashe juniper. Soils on the Plateau are generally shallow, and rainfall in excess of the soil's ability to retain is rapidly transported underground to aquifers, either through rapid subsurface flow through extensively fractured rock or through runoff into streams and rivers that connect with sinkholes and other recharge features. The Edwards-Trinity Aquifer is the only source of drinking water for over 2 million people residing primarily in the Austin-San Antonio corridor on the eastern edge of the Plateau. The recharge zone of the aquifer is characterized by highly faulted and fractured limestone, some of which outcrops at the surface. The aquifer is listed by the Karst Waters Institute as one of the ten most endangered karst systems in the world. The Plateau is also home to a number of threatened and endangered plant and animal species, many of them endemic, and at least 40 unique aquatic species live in the Edwards aquifer (Riskind and Diamond, 1986). Rainfall on the Plateau is highly variable, ranging from an annual average of 860 mm in the eastern portion of the Plateau to 380 mm in the west. Summers are usually warm and dry with sporadic rainfall, while winters are cool with frequent rainfall.

Energy balance measurements were made in a live oak-Ashe juniper with a continuous interlocking canopy. The woodland is on the Freeman Ranch, a 1700 ha research area near San Marcos, Texas, USA (Fig. 1) operated by Texas State University-San Marcos. The entire ranch is on the Edwards Aquifer recharge zone. Both species of trees in the woodland are evergreen, but live oak replaces its leaves more frequently than juniper. Most of the Ashe juniper is multi-stemmed, with an estimated areal density of 2850 stems ha^{-1}. At the site, mean diameter at breast height (*dbh*) and basal area for juniper are 0.08 m and 18.4 m^2 ha^{-1}, respectively. Mean *dbh* and basal area of live oak are 0.17 m and 23.5 m^2 ha^{-1}, respectively, and nearly all of the oak have single trunks. Areal density of above-ground biomass was estimated to be 5.6 kg m^{-2} for juniper and 5.8 kg m^{-2} for oak, based on the allometric equation of Jenkins et al. (2003). The soil in the woodland is Comfort stony clay, with a ~20-cm deep A horizon lying on fractured indurated limestone bedrock. Excavations showed that both oak and juniper formed dense root mats above the rock (Fig. 2), but some roots penetrated the rock through cracks and fissures.

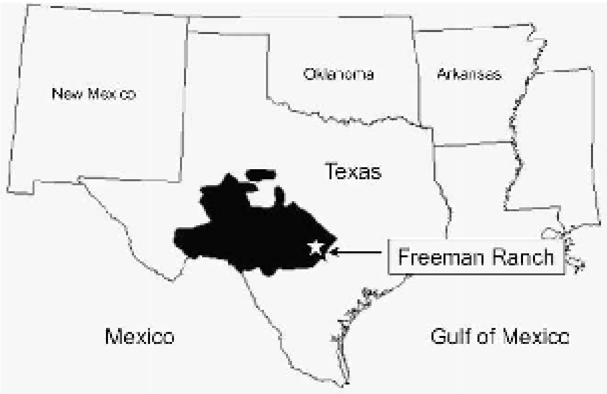

Fig. 1. Location of the Edwards Plateau (shaded) and the Freeman Ranch.

Fig. 2. Photographs of the excavation at the woodland showing rooting patterns above the rock layer that was 20 cm below the surface.

Energy balance measurements

The surface energy balance is described by the equation

$$R_n = H + \lambda E + G + S \tag{1}$$

where R_n is net all-wave radiation, H is sensible heat flux, λE is latent heat flux, G is soil heat flux, and S is storage heat flux. Storage heat flux includes heat storage in above-ground biomass (S_v), and sensible (S_a) and latent (S_λ) heat storage in the canopy air space. Net radiation was measured at a height of 15 m above the soil using a model Q7.1 net radiometer (REBS, Seattle, WA). In addition, we had a Kipp and Zonen CRN1 net radiometer measuring short and longwave components of R_n from late May–mid-September in 2006.

Sensible and latent heat fluxes were determined by tower-based eddy covariance using the equations

$$H = \rho c_p \overline{w'T'_a} \tag{2}$$

and

$$\lambda E = \overline{\lambda w' \rho'_v} \tag{3}$$

where ρ is density of air, c_p is specific heat of air, w is vertical wind speed, T_a is air temperature, λ is latent heat of vaporization, and ρ_v is vapor density. The prime in Eq. (2) denotes the fluctuation from a temporal average (here, 30-min) and the over bar a temporal average. Vertical wind speed and air temperature were measured acoustically using a CSAT-3 sonic anemometer (Campbell Scientific Inc., Logan, UT), while vapor density was measured using a LI-7500 open path infrared gas analyzer (LI-COR Inc., Lincoln, NE). The Schotanus et al. (1983) humidity correction was applied to sonic anemometer-derived H. The anemometer and open-path gas analyzer were placed at the same elevations as the net radiometer, and outputs sampled at 10 Hz. The gas analyzer was calibrated periodically using a span gas of known CO_2 concentration and a dewpoint generator (LI-610, LI-COR).

Soil heat flux (G) was determined by soil heat flux plates and calorimetry (Liebethal et al., 2005) using the equation

$$G = G_z + C_s \frac{\Delta T_s}{\Delta t} Z \tag{4}$$

where G_z is heat flux measured at depth z, C_s is soil heat capacity, T_s is average soil temperature above the heat flux plates, and t is time. Heat flux was measured at a depth of 5 cm at three locations at each site using heat flux transducers (HFT-3, REBS), and soil temperatures above the transducers were measured by thermocouple thermometry. Heat capacity was calculated from

$$C_s = \rho_b c_m + \rho_w \theta c_m \tag{5}$$

where ρ_b is soil bulk density, c_m is specific heat of the soil minerals, ρ_w is density of water, c_w is specific heat of water, and θ is volumetric water content, Water content was estimated by EC-10 capacitance sensors (Decagon, Pullman, WA).

Heat storage flux in the woodland biomass (S_v) was determined by calorimetry using the equation

$$S_v = m_v c_v \frac{\Delta T_v}{\Delta t} \tag{6}$$

where m_v is areal density of above-ground biomass, c_v is specific heat of vegetation, T_v is biomass temperature, and t is time. Biomass was estimated from measurements of diameter at breast height (*dbh*) using an allometric equation for a juniper-oak-mesquite woodland published by Jenkins et al. (2003). The *dbh* was obtained from stem (trunk) diameter measurements on all trees in 100 m^2 subplots along a 200 m transect in the woodland. Specific heat was estimated as 70% of the specific heat of water (Thom, 1975), and layer-weighted air temperature was used as a surrogate for T_v, following Oliphant et al. (2004). Air temperatures were measured at heights of 0.5, 2, 5, 8 and 15 m above the soil using ventilated HMP35A temperature–humidity probes (Vaisala, Woburn, MA). Blanken et al. (1997) found that heat storage in leaves contributed <5% to total heat storage, and this was confirmed by Oliphant et al. (2004). We therefore neglected that contribution to S_v.

Sensible heat storage in the canopy air-space (S_a) was calculated as described by Oliphant et al. (2004) using the equation

$$S_a = \rho c_p \sum_{i=1}^{n} \frac{\Delta T_a}{\Delta t} \Delta z_i \tag{7}$$

where T_a is the air temperature of layer i as measured by the HMP35A, and Δz_i is layer thickness. Similarly, latent heat storage (S_λ) was calculated as

$$S_\lambda = \lambda \sum_{i=1}^{n} \frac{\Delta \rho_v}{\Delta t} \Delta z_i \tag{8}$$

where ρ_v was determined from HMP35A measurements of relative humidity and air temperature.

Supporting measurements

A number of other meteorological, and soil measurements were made. Global irradiance (R_s) was measured with a pyranometer (LI-200, LI-COR) and rainfall with a tipping-bucket rain gauge (Texas Electronics, Inc., Dallas, TX, USA). Volumetric soil water content at depth intervals 0–0.10, and 0.10–0.20 m was measured continuously using capacitance sensors (EC-10, Decagon, Inc., Pullman, WA, USA) with three sensors installed at each depth interval. We encountered rock at depths greater than 0.2 m, so no water content sensors were installed beyond that depth.

Data processing and gap filling

All fluxes were calculated as 30-min averages. Eddy covariance calculations included spike removal, 'natural wind' coordinate rotation (Lee et al., 2004), and adjustments for variations in air density due to water vapor (Webb et al., 1980; Ham and Heilman, 2003). A friction velocity (u^*) filter was used to reject data obtained when turbulence was low (u^*) less than a threshold value). We used a u^* threshold of 0.15 m s^{-1}, which was determined as the value above which further increases in u^* had little effect on flux calculations (Hastings et al., 2005). Gaps in meteorological data and turbulent fluxes were filled using the on-line tools of Reichstein (http://www.bgc-jena.mpg.de/bgc-mdi/html/eddyproc/index.html).

Energy balance closure

Energy balance closure is a requirement of the first law of thermodynamics, but it is seldom achieved due to systematic underestimation of the turbulent fluxes by eddy covariance, as discussed by Wilson et al. (2002). They examined energy balance closure across 22 sites in FLUXNET and reported that slopes of regressions of $\lambda E + H$ against $R_n - G - S$ for all sites and years ranged from 0.53 to 0.99 with a mean of 0.79. We achieved energy balance closure of 0.93 ($H + \lambda E = 0.93$ ($R_n - G - S$) $- 1.4$, $r^2 = 0.94$) over the two years, based on 30-min averages of the fluxes. We then forced energy balance closure using a Bowen ratio conservation approach discussed by Twine et al. (2000) and used by Oliphant et al. (2004), Scott et al. (2004), Barr et al. (2006), Steinwand et al. (2006), and Kosugi et al. (2007), among others. We multiplied both H and λE by the ratio of ($R_n - G - S$) to ($H + \lambda E$), thus preserving the Bowen ratio ($H/\lambda E$) measured by eddy covariance without favoring sensible or latent heat in the apportionment of the missing energy (Steinwand et al., 2006).

Results and discussion

Environmental conditions

Microclimatic conditions for 2005 and 2006 are shown in Fig. 3. The woodland received 6.0 GJ m^{-2} of solar radiation in 2005, and 6.1 GJ m^{-2} in 2006. Total rainfall in 2005 was 795 mm, while the total in 2006 was 744 mm. Both totals were below the annual mean of 858 mm. Total rainfall during the last 3 months of 2004 was 382 mm, 182 mm above the annual mean for those months, so that soil water storage was fully charged at the beginning of 2005. An additional 278 mm of rainfall occurred during the first 3 months of 2005, with rainfall occurring on 30 days during this period. In contrast, only 44 mm of rain fell during the last 3 months of 2005, resulting in low soil water content at the beginning of 2006. Also, total rainfall during the first three months of 2006 was only 129 mm, much lower that what occurred during the same time period in the previous year. There were several pronounced drying cycles during each year during which little or no rainfall occurred, most notably between days 154 (3 June) and 187 (6 July) in 2005, and days 187 (6 July) and 247 (4 September) in 2006. Mean annual air temperatures and vapor pressure deficits (VPD) were 19.1 °C and 0.72 kPa, respectively, in 2005, and 19.8 °C and 0.85 kPa in 2006. Reference evaporation, calculated using the method of Allen et al. (1994), was slightly higher in 2006 (875 mm vs. 851 mm in 2005).

Net radiation

Seasonal fluctuations in R_n are shown in Fig. 4. The highest daily total recorded during the 2-year period was 20.9 MJ m^{-2}, while the lowest was 0.6 MJ m^{-2}. The annual total averaged 4.0 GJ m^{-2}, with <1% difference between years. During the four months in spring and summer of 2006 when components of R_n were measured by the CRN1 radiometer, midday albedo averaged 0.10, and the emitted longwave component of R_n averaged 464 W m^{-2}. Maximum and minimum outgoing longwave recorded during this period were 578 and 300 W m^{-2}, respectively. We did not observe any

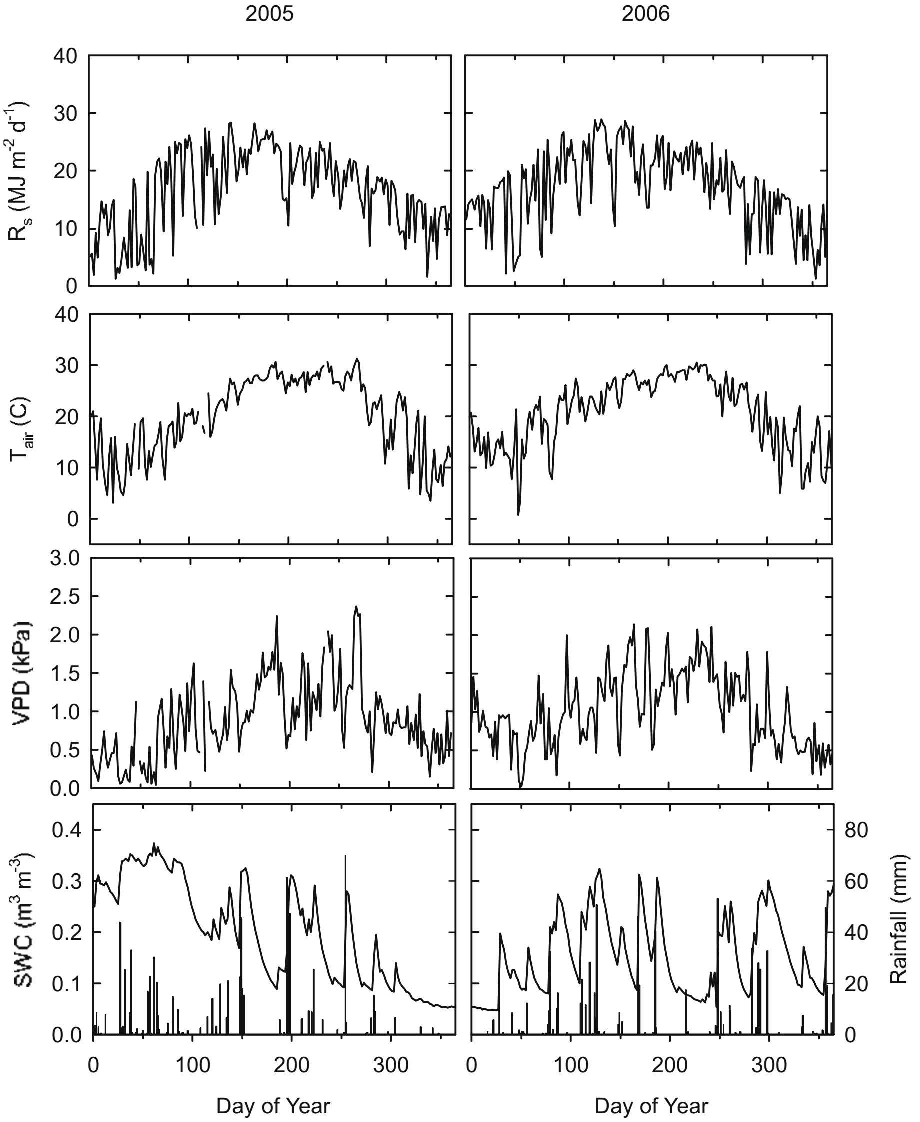

Fig. 3. Seasonal variation in global irradiance (R_s); average daily air temperature (T_{air}); vapor pressure deficit (VPD); soil water content in the upper 20 cm (SWC); and daily totals of rainfall (bars) in 2005 and 2006.

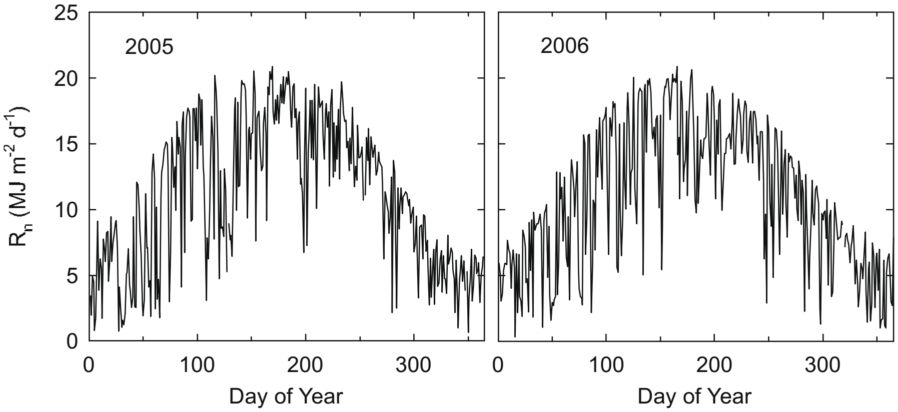

Fig. 4. Seasonal variations in net radiation (R_n) in 2005 and 2006.

consistent reductions in R_n during periods of water deficit that might have occurred due to changes in albedo or increases in canopy temperature.

Storage heat fluxes

On most days, diurnal fluctuations of G and S were of similar magnitude, with peak gains and losses in G lagging those in S by 4–6 h. However, on sunny days following cloudy days, there were large gains in S during the morning that considerably exceeded those in G. Seasonal changes in storage heat flux were dominated by G, as shown by the monthly averages of daily totals in Fig. 5. Averages of S were an order of magnitude lower than G because at night the canopy essentially lost all of the heat it gained during the daytime. Soil warming in spring and summer resulted in a heat gain and net downward transfer of G, and soil cooling in autumn and winter resulted in a heat loss and net upward transfer of G. In 2005, maximum heat storage in the soil occurred in June at the time of peak solar radiation and maximum soil surface temperatures. However, in 2006 maximum G occurred in August during a prolonged period without rain.

Cumulative heat loss in the woodland reached its peak in early spring, and cumulative heat gain in late summer (Fig. 6), 1/4 cycle out of phase with net radiation, as expected. The end of year deficits were similar to those found by Oliphant et al. (2004) for a deciduous forest in Indiana, USA, and are attributed to actual year-to-year variations, methodology, and unmeasured components.

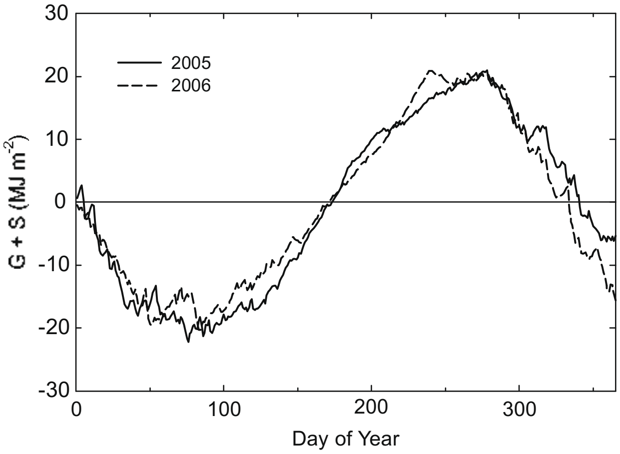

Fig. 6. Cumulative sum of soil heat flux (G) and storage heat flux in the canopy in 2005 and 2006.

Sensible and latent heat flux, and evaporation

Seasonal changes in λE and H, shown in Fig. 7(a–d), tracked changes in R_n, VPD and soil water content (Figs. 3 and 4). There were large reductions in λE when the soil dried, accompanied by increases in H. After forcing energy balance closure, peak values

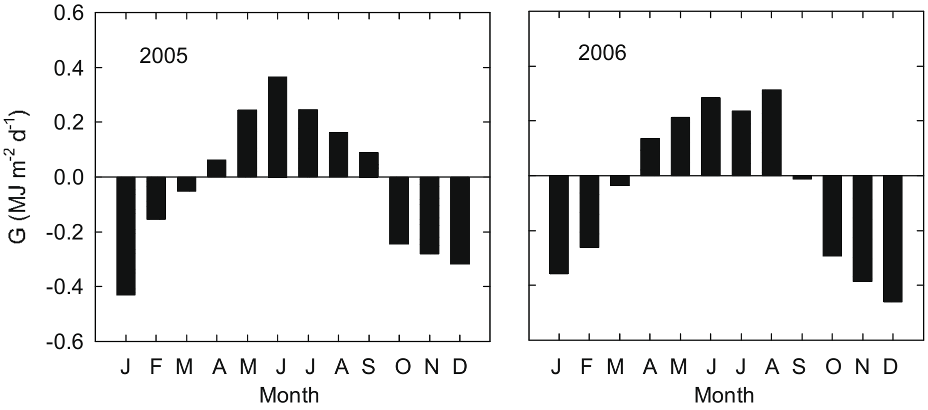

Fig. 5. Monthly averages of daily soil heat flux (G) in 2005 and 2006. Positive values denote a heat gain and negative values a loss.

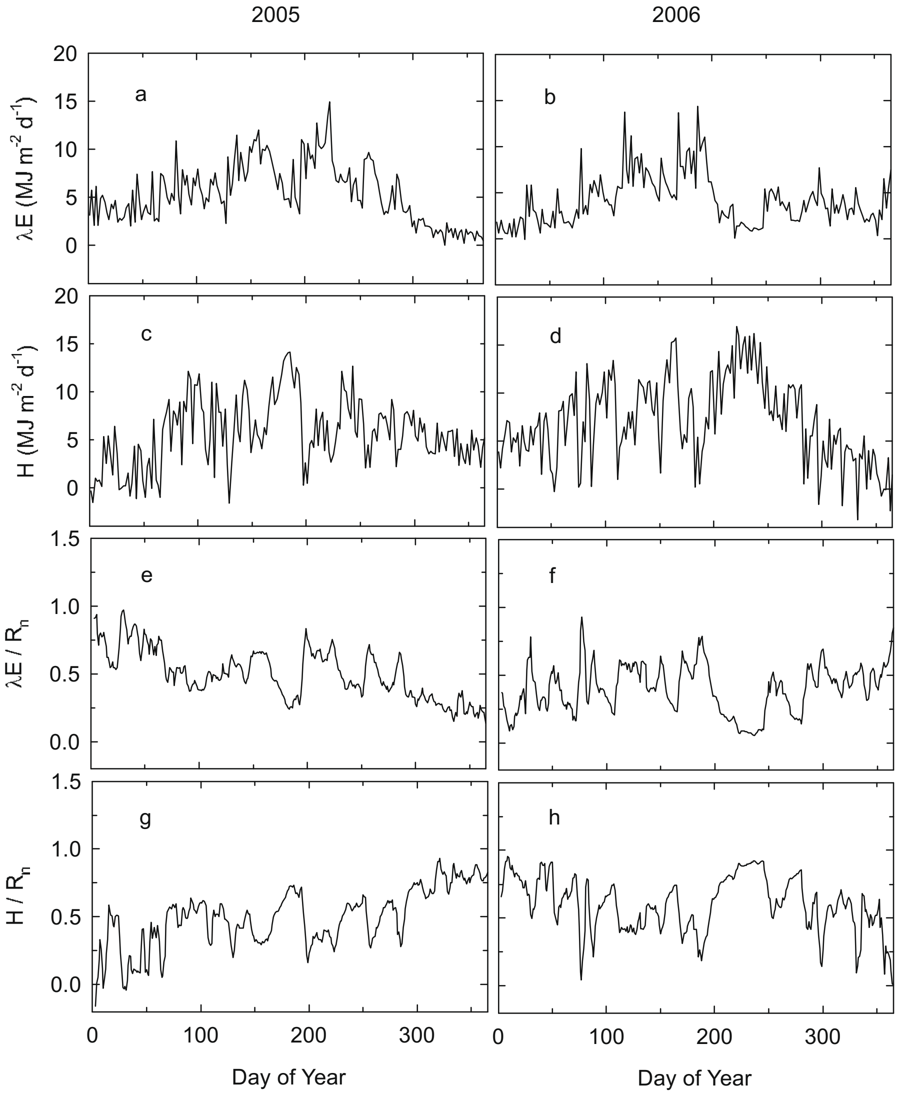

Fig. 7. Seasonal variations in latent (λE) and sensible (H) heat fluxes (a–d); and 5-d running averages of the ratio of daily totals of λE and H to net radiation (R_n) (e–h) in 2005 and 2006.

of λE and H in 2005 were 14.9 MJ m^{-2} d^{-1} (6.1 mm d^{-1} of evaporation) and 15.4 MJ m^{-2} d^{-1}, respectively, and 14.3 (5.8 mm d^{-1}) and 16.9 MJ m^{-2} d^{-1} in 2006. In 2005, there was a gradual decrease in λE as a percentage of available energy that was associated with declining water availability, with λER_n dropping from near 1 at the beginning of the year to 0.14 at the end (Fig. 7e). Sensible heat loss accounted for 82% of R_n at the end of 2005 (Fig. 7g). Similar trends were not observed in 2006, but like 2005, there were large reductions in λER_n and increases in H/R_n during drying cycles (Fig. 7f, and h). During the most severe dry period, λE dropped to 4% of R_n while H rose to 94%.

In 2005, turbulent fluxes were divided almost equally between λE and H (each ~2 GJ m^{-2} year^{-1}) (Fig. 8). For the first 9 months of that year, Bowen ratios ($\beta = H/\lambda E$) based on daily totals of H and λE were <1 on the majority of the days, and cumulative λE exceeded H. There were periods of water deficit during this time when β reached values as high as 4.8 (Fig. 9). During the last three months, β increased to values as high as 14.4 because rainfall and water availability were very low. In 2006, total H was much higher than λE (2.5 GJ m^{-2} year^{-1} vs. 1.5 GJ m^{-2} year^{-1}) because of lower water availability, with β reaching 24 near the end of the extended dry period in late summer (Figs. 8 and 9). Oliphant et al. (2004) observed a much smaller increase in β in the Indiana forest during an unusually dry period. He attributed the small response to the effectiveness of deep roots in extracting water stored in the soil column.

Total ET in 2005, based on forced energy balance closure, was 806 mm, exceeding total rainfall by 11 mm. As mentioned previously, rainfall during the latter part of 2004 was unusually high, so it is likely that water availability in the root zone was very high at the start of 2005. In addition, 302 mm of rain fell during the first 4 months of 2005, and soil water content in the upper 20 cm did not drop below 0.2 m^3 m^{-3} until day 24 May 2005 (day 144). In contrast to 2005, total E in 2006 was 610 mm, 34 mm below total annual rainfall. Forcing energy balance closure increased estimates of E by 97 mm in 2005, and 119 mm in 2006.

We found that ET at our woodland site was highly responsive to rainfall, and during drying cycles, highly correlated with soil water content in the upper 20 cm (Figs. 10 and 11). ET in Figs. 10 and 11 was normalized by reference ET (ETo) to minimize impact of day-to-day changes in microclimate (irradiance, VPD, etc.). In most cases, ET started to decrease at the same time as soil water content, and the response was nearly linear (Fig. 11b,c,e,f). This suggests insufficient root water uptake from the bedrock to sustain transpiration as soil water in the upper 20 cm was depleted. ET rates and slopes of the ET vs. water content relationships were lower in 2006 than in 2005, indicating there was less water available in the root zone at onset of drying cycles. There were some periods when ET

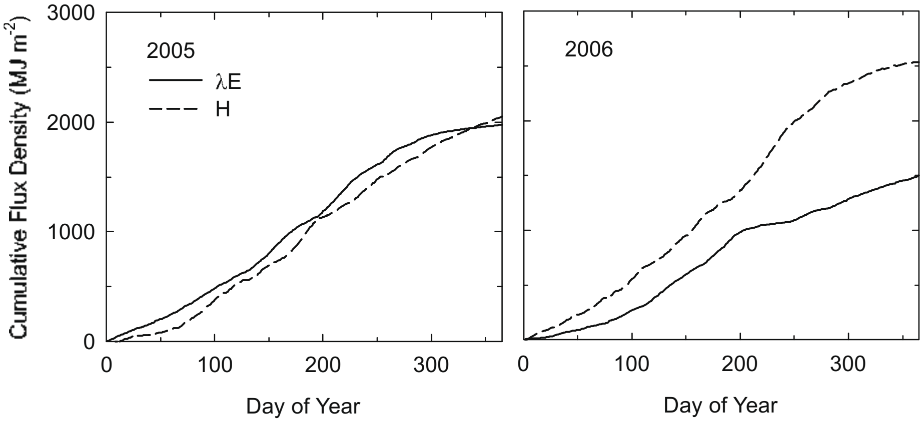

Fig. 8. Cumulative latent (λE) and sensible (H) heat fluxes in 2005 and 2006.

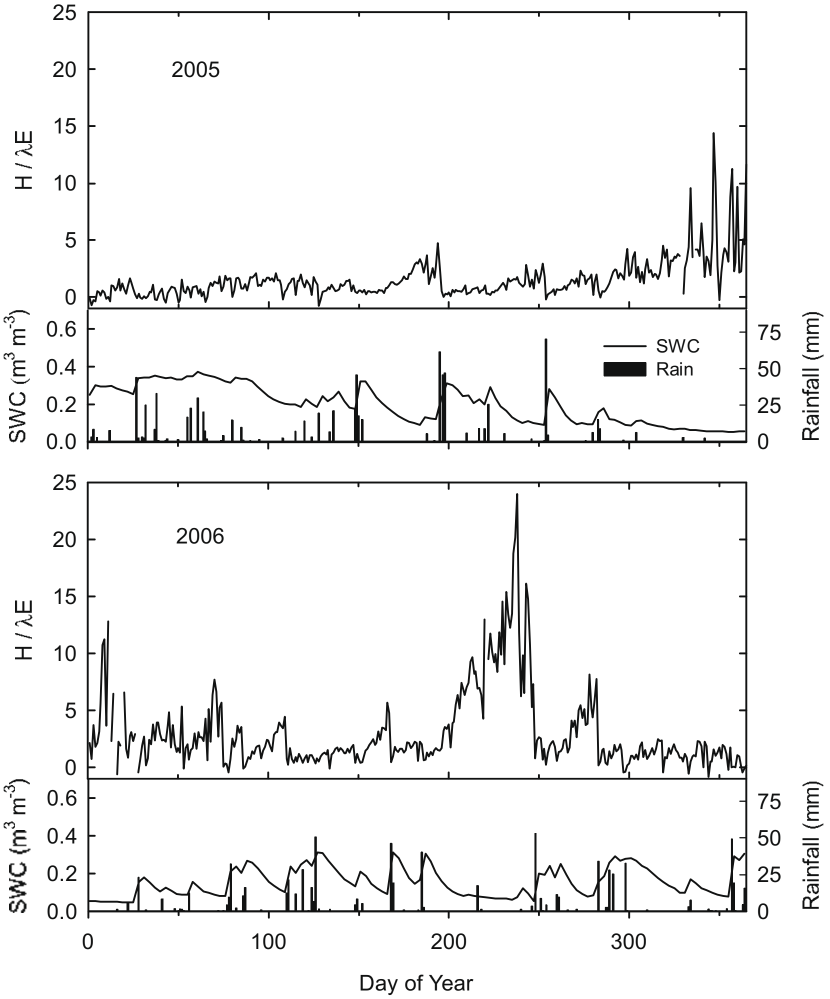

Fig. 9. Seasonal variations in the Bowen ratio calculated using daily totals of sensible (H) and latent (λE) heat fluxes. Also shown are soil water content (SWC) in the upper 20 cm and daily totals of rainfall.

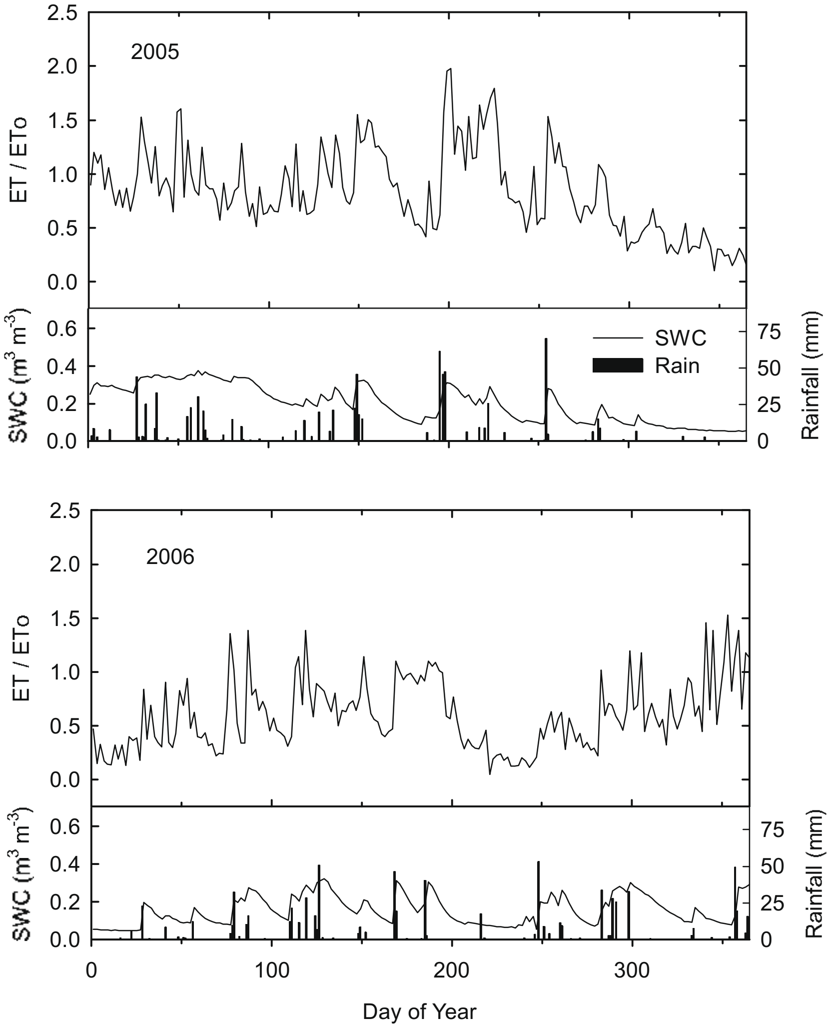

Fig. 10. Seasonal variations in evapotranspiration (ET), normalized by reference evapotranspiration (ETo). Also shown are soil water content (SWC) in the upper 20 cm and daily totals of rainfall.

response was delayed, and ET declined exponentially with soil water content (Fig. 11a and d). For example, ET during the most severe dry period (6 July–4 September 2006, days 187–247) did not begin to decline until 5 days after soil water content started to drop. This suggests a greater contribution from roots in the bedrock in meeting the evaporative demand than at other times. Apparently, rainfall that occurred prior to onset of this drying cycle was more effective in replenishing the root zone than similar rainfall events preceding other drying cycles. Cumulative ET during two of the most severe dry periods (days 154–187 in 2005, and days 187–247 in 2006) was 106 and 89 mm, respectively, which exceeded the water storage capacity of the 20 cm deep soil profile, estimated to be 70 mm. This indicates that roots did extract some water from the bedrock during drought. However, these water sources were ephemeral and depletable, just like the soil layer above.

The energy balance and ET responses of the woodland to rainfall and water deficits showed little evidence of a decoupling of transpiration from recent rainfall, as would be expected if deep roots were providing significant amounts of water from stable sources in the bedrock. Instead, our observations support the conclusions of Schwinning (2008), that water sources for oak and juniper on the Plateau are generally shallow and unstable. While deep roots can extract water from perennial sources such as perched water tables and cave streams in the narrow geographical range where these features exist (Jackson et al., 2000), the implication by Tennesen (2008) that this is the norm on the Edwards Plateau, and is responsible for large-scale depletion of surface and groundwater, is quite likely a gross overstatement.

Summary and conclusions

We examined energy balance partitioning and water use in a live oak-Ashe juniper woodland on the karst Edwards Plateau over a 2-year period (2005 and 2006), with a focus on response to rainfall and water deficits. We found large differences in total ET between years, and in partitioning of available energy between H and λE, due to differences in water availability. On an annual basis, turbulent fluxes in 2005 were divided almost equally between λE and H, whereas in 2006, λE was only 60% of H because overall water availability was lower than in the previous year. Total ET over the two years, based on forced energy balance closure, was 1416 mm, 92% of total rainfall. We observed large and rapid reductions in ET (λE) and increases in H during drying cycles, and high correlation between ET and near surface soil water content,

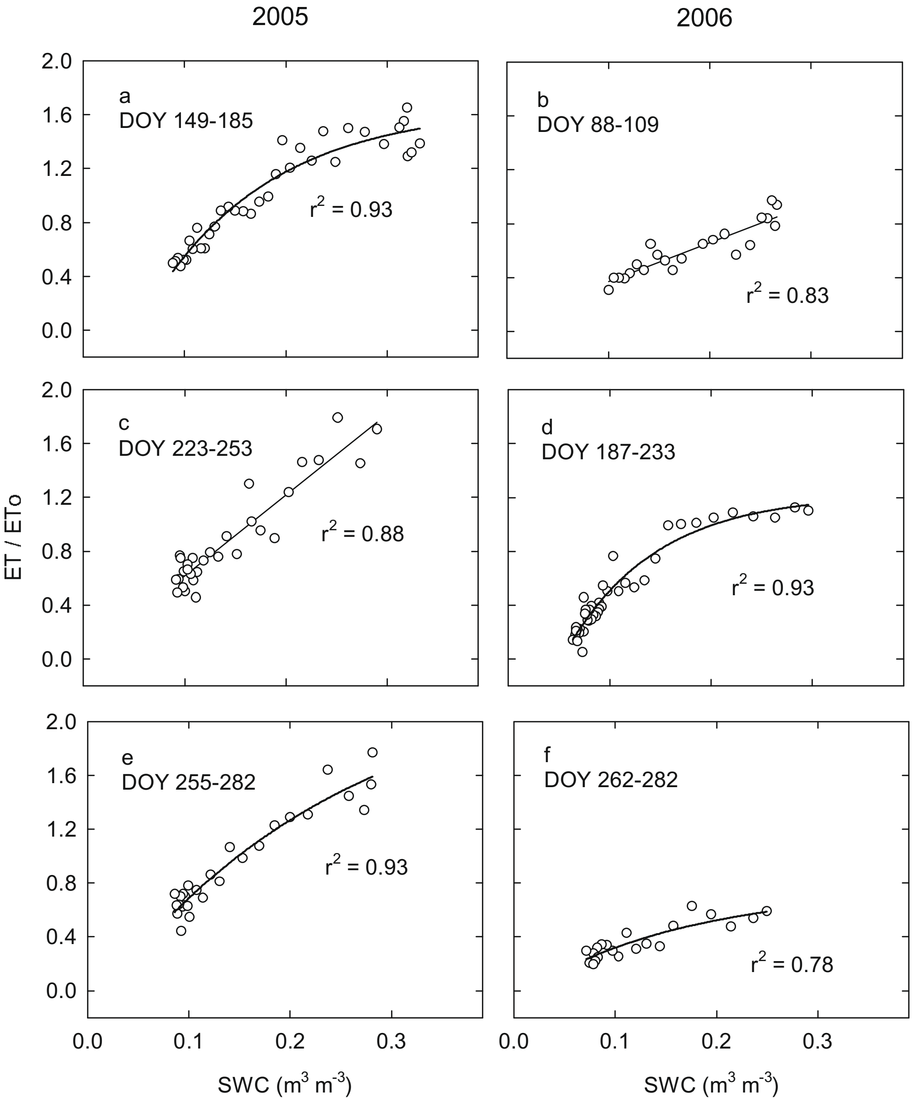

Fig. 11. Response of evapotranspiration (ET), normalized by reference evapotranspiration (ETo), to soil water content (SWC) in the upper 20 cm of the root zone during drying cycles in 2005 and 2006, identified by the first and last day of year (DOY) of the drying period.

indicating that the woodland relied heavily on water from recent rainfall events, rather than antecedent water.

The woodland we studied was on the Edwards Aquifer recharge zone where the limestone bedrock is highly fractured and infiltration rates are high. It has long been assumed that woody species on the Plateau withdraw substantial amounts of water stored deep within the fractured bedrock which otherwise would find its way into the aquifer. This assumption has been used, in part, to justify removal of juniper and other species to increase water availability (Jones and Gregory, 2008). Our results cast doubt on that assertion, indicating instead that the water storage capacity of the root zone is limited, with little evidence that deep roots extract significant amounts of water from a more stable supply of water than what is available to shallow roots. Because storage capacity of the fractured bedrock is low, deep roots likely experience a hydraulic environment similar to that in shallow soil, fast recharge followed by rapid depletion. As a result, transpiration and partitioning of available energy between latent and sensible heat fluxes are closely coupled to rainfall.

Acknowledgements

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References

Archer, S., Boutton, T.W., Hibbard, K.A., 2001. Trees in grasslands: biogeochemical consequences of woody plant expansion. In: Schulze, E.D., Heimann, M., Harrison, S., Holland, E., Lloyd, J., Prentice, I., Schimel, D. (Eds.), Global Biogeochemical Cycles in the Climate System. Academic Press, pp. 115–138.

Allen, R.G., Smith, M., Perrier, A., Pereira, L.S., 1994. An update for the calculation of reference evapotranspiration. ICID Bull. 43, 35–92.

Baldocchi, D.D., Xu, L., Kiang, N., 2004. How plant functional-type, weather, seasonal drought, and soil physical properties alter water and energy fluxes of an oak–grass savanna and an annual grassland. Agric. For. Meteorol. 123, 13–39.

Barnes, P.W., Liang, S.-Y., Jessup, K.E., Ruiseco, L.E., Phillips, P.L., Reagan, S.J., 2000. Soils, topography and vegetation of the Freeman Ranch, Freeman Ranch Publication Series No. 1, Southwest Texas State University Press

Barr, A.G., Morgenstern, K., Black, T.A., McCaughey, J.N., Nezic, Z., 2006. Surface energy balance closure by the eddy-covariance method above three boreal woodland stands and implications for the measurement of the CO_2 flux. Agric. For. Meteorol. 140, 322–337.

Blanken, P.D., Black, T.A., Yang, P.C., Neumann, H.H., Nesic, Z., Staebler, R., den Hartog, G., Novak, M.D., Lee, X., 1997. Energy balance and canopy conductance of a boreal aspen forest: partitioning overstory and understory components. J. Geophys. Res. 102, 28915–28927.

Bonacci, O., Pipan, T., Culver, D.C., 2009. A framework for karst ecohydrology. Environ. Geol. 56, 891–900.

Eggemeyer, K.D., Schwinning, S., 2009. Biogeography of woody encroachment: why is mesquite excluded from shallow soils? Ecohydrology 2, 81–87.

Engel, V., Jobbágy, E.G., Stieglitz, M., Williams, M., Jackson, R.B., 2005. Hydrological consequences of Eucalyptus afforestation in the Argentine Pampas. Water Resour. Res. 41, W10409. doi:10.1029/2004WR003671.

Ham, J.M., Heilman, J.L., 2003. Experimental test of density and energy-balance corrections on CO_2 flux as measured using open-path eddy covariance. Agron. J. 95, 1393–1403.

Hastings, S.J., Oechel, W.C., Muhlia-Melo, A., 2005. Diurnal, seasonal and annual variation in the net ecosystem CO_2 exchange of a desert shrub community (Sarcocaulescent) in Baja California, Mexico. Global Change Biol. 11, 927–939.

Houghton, R.A., Hackler, J.L., Lawrence, K.T., 1999. The US carbon budget: contributions from land-use change. Science 285, 574–578.

Huxman, T.E., Wilcox, B.P., Breshears, D.D., Scott, R.L., Snyder, K.A., Small, E.E., Hultine, K., Pockman, W.T., Jackson, R.B., 2005. Ecohydrological implications of woody plant encroachment. Ecology 86, 308–319.

Jackson, R.B., Moore, L.A., Hoffmann, W.A., Pockman, W.T., Linder, C.R., 1999. Ecosystem rooting depth determined with caves and DNA. Proc. Natl. Acad. Sci. USA 96, 11387–11392.

Jackson, R.B., Sperry, J.S., Dawson, T.E., 2000. Root water uptake and transport: using physiological processes in global predictions. Trends Plant Sci. 5, 482–488.

Jenkins, J.C., Chojnacky, D.C., Heath, L.S., Birdsey, R.A., 2003. National-scale biomass estimators for United States tree species. Woodland Sci. 49, 12–35.

Jones, C.A., Gregory, L., 2008. Effects of brush management on water resources. Technical Report TR-338, Texas Water Resources Institute, Texas A&M AgriLife.

Kosugi, Y., Takanashi, S., Tanaka, H., Ohkubo, S., Tani, M., Yano, M., Katayama, T., 2007. Evapotranspiration over a Japanese cypress woodland. I. Eddy covariance fluxes and surface conductance characteristics for 3 years. J. Hydrol. 337, 269–283.

Lee, X., Finnigan, J., Paw U, K.T., 2004. Coordinate systems and flux bias error. In: Lee, X., Massman, W., Law, B. (Eds.), Handbook of Micrometeorology, A Guide for Surface Flux Measurement and Analysis. Kluwer Academic Publisher, pp. 33–66.

Liebethal, C., Huwe, B., Foken, T., 2005. Sensitivity analysis for two ground heat flux calculation approaches. Agric. For. Meteorol. 132, 253–262.

McCole, A.A., Stern, L.A., 2007. Seasonal water use patterns of *Juniperus ashei* on the Edwards Plateau, Texas, based on stable isotopes in water. J. Hydrol. 342, 238–248.

McElrone, A.J., Pockman, W.T., Martinez-Vilalta, J., Jackson, R.B., 2004. Variation in xylem structure and function in stems and roots of trees to 20 m depth. New Phytol. 163, 507–517.

Oliphant, A.J., Grimmond, C.S.B., Zutter, H.N., Schmid, H.P., Su, H.-B., Scott, S.L., Offerle, B., Randolph, J.C., Ehman, J., 2004. Heat storage and energy balance fluxes for a temperate deciduous woodland. Agric. For. Meteorol. 126, 185–201.

Pockman, W.T., McElrone, A.J., Bleby, T.M., Jackson, R.B., 2008. The structure and function of roots of woody species on the Edwards Plateau, Texas, USA. Abstract H34A-02, Joint Assembly of American Geophysical Union, Ft. Lauderdale, FL.

Riskind, D.H., Diamond, D.D., 1986. Plant communities of the Edwards Plateau of Texas, in the Balcones Escarpment. In: Abbott, P.L., Woodruff, C.M., Jr. (Eds.), The Balcones Escarpment. The Walter Geology Library. The University of Texas, Austin, pp. 20–32.

Schotanus, P., Nieuwstadt, F.T.M., De Bruin, H.A.R., 1983. Temperature measurement with a sonic anemometer and its application to heat and moisture fluxes. Boundary-Layer Meteorol. 26, 81–93.

Schwinning, S., 2008. The water relations of two evergreen tree species in a karst savanna. Oecologia, doi:10.1007/s0042-008-1147-2.

Scott, R.L., Edwards, E.A., Shuttleworth, W.J., Huxman, T.E., Watts, C., Goodrich, D.C., 2004. Interannual and seasonal variation in fluxes of water and carbon dioxide from a riparian woodland ecosystem. Agric. For. Meteorol. 122, 65–84.

Steinwand, A.L., Harrington, R.F., Or, D., 2006. Water balance for Great Basin phreatophytes derived from eddy covariance, soil water, and water table measurements. J. Hydrol. 329, 595–605.

Tennesen, M., 2008. When juniper and other woody plants invade, water may retreat. Science 322, 1630–1631.

Thom, A.S., 1975. Momentum, mass and heat exchange of plant communities. In: Monteith, J.L. (Ed.), Vegetation and the Atmosphere 1. Academic Press, New York, pp. 57–109.

Twine, T.E., Kustas, W.P., Norman, J.M., Cook, D.R., House, P.R., Meyers, T.P., Prueger, J.H., Starks, P.J., Wesely, M.L., 2000. Correcting eddy-covariance flux underestimates over a grassland. Agric. For. Meteorol. 103, 279–300.

Van Auken, O.W., 2000. Shrub invasions of North American semiarid grasslands. Annu. Rev. Ecol. S. 31, 197–215.

Webb, E.K., Pearman, G.I., Leuning, R., 1980. Correction of flux measurements for density effects due to heat and water vapour transfer. Quart. J. R. Met. Soc. 106, 85–100.

White, W.B., Culver, D.C., Herman, J.S., Kane, T.C., Mylroie, J.E., 1995. Karst lands. Am. Sci. 83, 450–459.

Wilcox, B.P., Owens, M.K., Knight, R.W., Lyons, R.L., 2005. Do woody plants affect streamflow on semiarid karst rangelands? Ecol. Appl. 15, 127–136.

Wilcox, B.P., Wilding, L.P., Woodruff, C.M., 2007. Soil and topographic controls on runoff generation from stepped landforms in the Edwards Plateau of Central Texas. Geophys. Res. Lett. 34, L24S24. doi:10.1029/2007GL030860.

Wilson, K., Goldstein, A., Falge, E., Aubinet, M., Baldocchi, D., Berbigier, P., Bernhofer, C., Ceulemans, R., Dolman, H., Field, C., Grelle, A., Ibrom, A., Law, B.E., Kowalski, A., Meyeres, T., Moncrieff, J., Monson, R., Oechel, W., Tenhunen, J., Valentini, R., Verma, S., 2002. Energy balance closure at FLUXNET sites. Agric. For. Meteorol. 113, 223–243.

Evaporation and interception water loss from juniper communities on the Kerr Wildlife Management Area

Final Report

by

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and

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To

Upper Guadalupe River Authority

May 10, 2004

Summary

Juniper canopies are ideally structured to intercept rainfall and redirect it to the base of the tree, thus altering the hydrology of the site. The amount of water redirected, and the amount lost to interception and evaporation, may be a significant portion of the annual rainfall. We monitored interception and rainfall partitioning in juniper canopies at the Kerr Wildlife Management Area for 1100 days beginning on 3 October 2000. Over this time span, there were 294 total rain events accumulating a total of 70.5 inches of precipitation. Over 170 of the rainfall events (57% of all storms) were less than 0.1 inches and accumulated only 4.9 inches of rainfall. The six largest storms (2% of the total) accumulated over 14 inches of rain. About 35% of the precipitation falling on juniper trees is intercepted by the canopy of the tree and evaporated back to the atmosphere, 5% is intercepted by the litter and duff beneath the tree, and 60% actually reaches the ground surface for either recharge or plant growth. The amount of rainfall intercepted by the canopy is most affected by the intensity and duration of the storm. At high intensities, such as 2.8 inches over a 15 hr period, only 20% is intercepted by the canopy and litter. The remainder is available for either plant growth or aquifer recharge. When rainfall is less intense, such as 0.5 inches over a 19 hour period, 60% (0.3 inch) is intercepted by the tree and litter. Not until nearly 1 inch of rain has fallen does an appreciable amount of water actually reach the ground surface beneath the tree. Nearly 84% of the rainfall events observed over the last several years have been small events of less than 0.5 inches. These events, although common, do not contribute significantly to soil water under juniper trees and are largely ineffective.

Introduction

The density and aerial cover of Ashe juniper (*Juniperus ashei*) in central Texas has increased over the last 200 years. Originally limited to rocky outcrops or areas of low fuel availability, Ashe juniper now covers almost 2.7 million hectares on the Edwards Plateau.

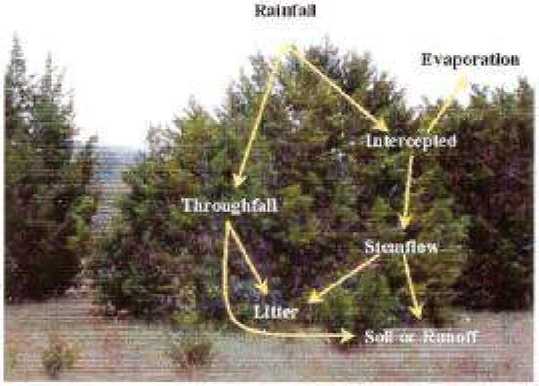

Figure 1. Rain falling on juniper trees can be partitioned to determine evaporative losses.

The impact of juniper trees on the hydrologic budget is hotly debated as water demands from rangelands increase. Understanding both the physiological and physical impact of juniper trees on water availability is crucial; this study investigates the physical impact of juniper trees on the hydrologic budget. The amount of rainfall intercepted by tree canopies and lost to evaporation is species-specific, and may be a function of rainfall intensity (Thurow and Hester 1987, Schowalter 1999, Silva and Rodriguez 2001). When rain falls on a juniper canopy, there are a limited number of things which can happen (Figure 1). The rain can either be intercepted by the juniper canopy or it can fall directly through the canopy to reach the litter layer. The rain that is intercepted can either be evaporated back to the atmosphere or it can flow down the outside of the stem as stemflow. The stemflow water can be further partitioned into water intercepted by the litter layer or water which actually reaches the soil surface. The rain that is not intercepted by the canopy occurs as throughfall and directly reaches the litter layer under the tree. This water is either retained by the litter layer or it can reach the soil surface. It was impractical to follow the rainfall after it reached the soil surface in this study, but it would be available for either plant growth, deep drainage, or overland flow.

Our objectives were to:
1. Determine how rainfall is partitioned within juniper trees at the Kerr Wildlife Management Area, and
2. Determine how rainfall intensity alters the patterns of rainfall partitioning.

Methods

Figure 2. Data collection system and Tree 1 at the KWMA.

Figure 3. Tree 2 at the KWMA.

The Kerr Wildlife Management Area (KWMA; 30.09°N, 99.49°W) was selected as a research site on the Edwards Aquifer Drainage Area. Two mature juniper trees were selected for instrumentation in an ungrazed pasture. The trees were representative of the site and were within 100 feet of each other. The site was established on 3 October 2000 and dismantled 1100 days later.

Each tree was instrumented to collect rainfall, throughfall, stemflow and litter moisture (Figure 4). Rainfall above the canopy (hereafter referred to as bulk rainfall) was measured to the closest 0.01 inch using a tipping bucket rain gauge (Texas Electronics).

Throughfall was collected using a system of four 8-inch funnels connected to a collection tube. As the throughfall was collected, a float in the tube recorded the increasing water level. The change in millivolts was calibrated to record the actual height of the water column. After the rain stopped, the datalogger tripped a solenoid to drain the tube and make it ready for the next rainfall event.

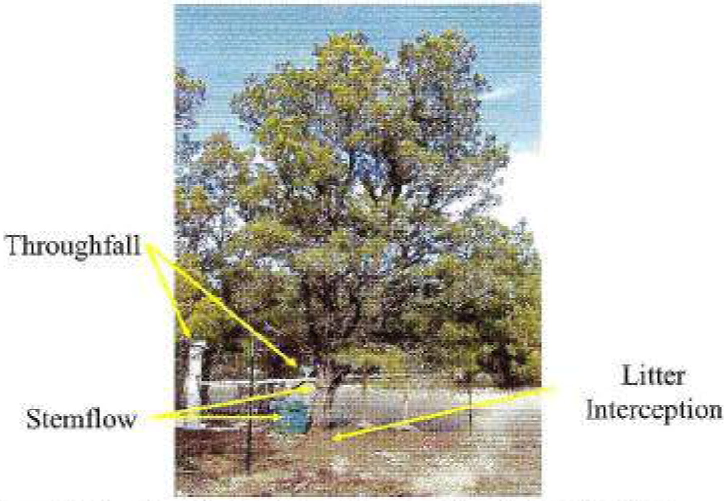

Figure 4. Typical juniper tree showing the data collection equipment.

Litter moisture was measured using water content reflectometers (Campbell Scientific CS615), after they were calibrated to the high organic matter. The amount of litter was determined by measuring litter depth near the base of the tree, mid-way through the canopy, and at the drip line of the canopy on 8 equally spaced transects radiating from the base of each tree. The area of the tree was combined with litter depths to determine the volume of litter under each tree. Bulk density samples were collected to convert from litter volume to litter mass. Additional samples were taken to calibrate the reflectometer probes. For calibration purposes, the litter was oven-dried and weighed to determine the mass of the sample. Ten percent of that mass was then added using distilled water and a measurement was taken using the CS615 probe. This process was repeated to measure from 10% to 80% gravimetric moisture. This whole process was repeated 6 times and a regression was calculated to convert the millivolt reading from the probes to gravimetric litter moisture. Litter moisture was calculated as :

$$\textit{Litter moisture} = -4681.93 + 14416.18 * mV - 14600.62 * mV^2 + 4942.83 * mV^3$$

where mV = millivolt reading from the CS615 probe.

Stemflow was collected by constructing a narrow collar around the base of each tree. The collar collected all of the water which was flowing on the outside of the stem and diverted it to a tipping bucket measuring device. The bucket held 1 L of water before it tipped. The 1 L of water represented about 0.005 inches of rain for an average size juniper tree.

All of this information was collected hourly by an electronic datalogger and downloaded to a computer every second day. The computer then ran a program to check the data for errors and summarized the results, posting the information to a web page at http://uvalde.tamu.edu/intercept.

Canopy interception cannot be measured directly, but must be estimated by subtraction using the formula:

$$\text{Canopy Interception} = \text{Bulk Rainfall} - (\text{Throughfall} + \text{Stemflow})$$

And then the amount of water reaching the soil surface was calculated as :

$$\text{Soil Water} = \text{Bulk Rainfall} - \text{Canopy Interception} - \text{Litter Interception}$$

During the 3-year study, data were collected from over 290 rainfall events. Bulk rainfall was partitioned to canopy interception, evaporation, soil litter interception, and soil moisture, on both a gallons per tree and a percentage basis. Data were analyzed by creating classes of rainfall based on 0.1 inch increments and using curvilinear regression techniques. In addition, the hourly time step of rainfall partitioning for different intensity storms was calculated to determine how rainfall intensity and duration affected interception losses.

Results and Discussion

Tree was 15 feet tall, had a canopy area of 242 square feet, and a litter depth of 1.5 inches. Tree 2 was 14 feet tall, had a canopy area of 220 square feet, and a litter depth of 1.05 inches. These trees are typical of regrowth Ashe juniper after 20-25 years.

Rainfall Distribution

The research site was installed for 1100 days beginning in October 2000. A total of 70.5 inches of rainfall was recorded over this period. It is important to note that this is not the total amount of rainfall received - our equipment could measure only up to 5 inches of rain at a time so larger storms were not used in this report, and equipment malfunction sometimes resulted in missed rainfall. There were 294 individual storms during this interval. When the storms were

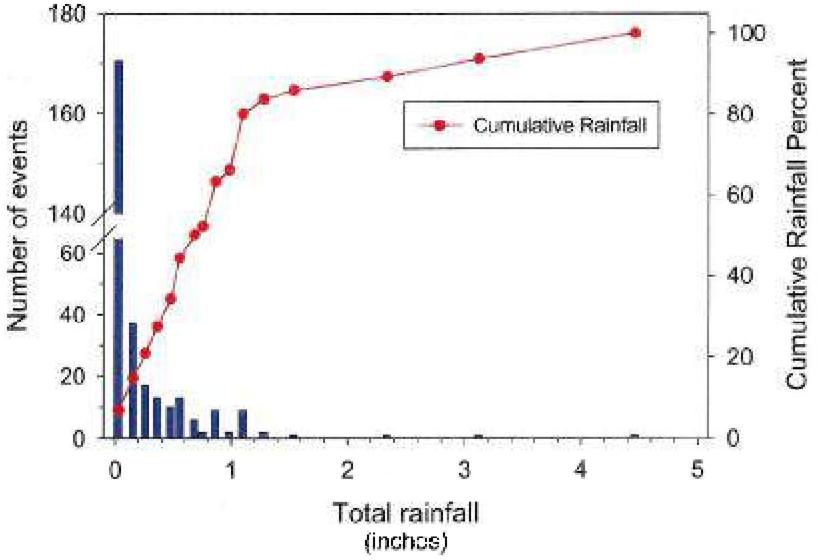

Figure 5. Rainfall frequency histogram (bars) and cumulative rainfall amount (rel line) at the KWMA.

divided into classes, over 170 of the storms delivered less than 0.1 inch, and most (84%) delivered less than 0.5 inches. Although these storms were numerous, they contributed only 6.8% and 34% of the total rainfall, respectively. The relatively few large events delivered most of the rainfall over this period. Storms greater than 1.25 inches were less numerous (6 total), accounting of only 2% of the total number of storms, but they contributed nearly 20% of the total rainfall. This rainfall distribution will have significant impacts on water availability as demonstrated in a later section.

Rainfall Partitioning

Averaged over all storms during the 3 year study, about 58% of the ambient precipitation reached the soil surface beneath juniper trees while the remaining 42% was intercepted and lost to evaporation. The high canopy interception and evaporative loss is due mainly to the large number of small storms which experienced total, or nearly total, interception. The low intensity storms were numerous but contributed little moisture to the soil surface (Figure 6). Most of the precipitation from storms < 0.1 inch was either intercepted by the canopy (96%) or the litter layer (2%) leaving only 2% of the bulk rainfall to reach the soil surface beneath the juniper trees. At the highest rainfall levels, at least 12% of the bulk rainfall was intercepted by the tree canopy. The litter layer became saturated at fairly low levels of rain and absorbed about 7% of the bulk precipitation, leaving about 81% of the bulk rainfall reaching the soil surface.

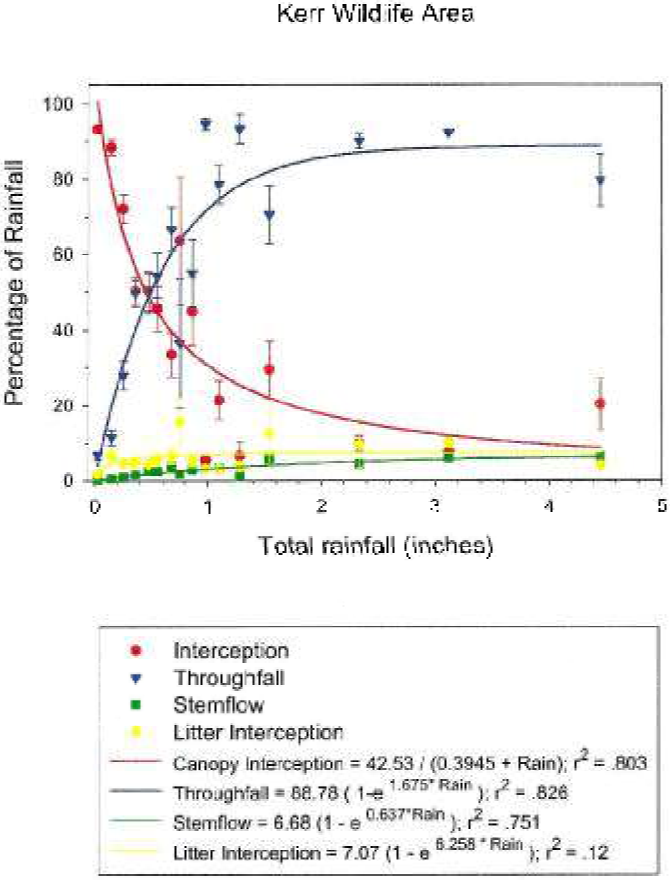

Figure 6. Curvilinear regression analysis of interception, throughfall, stemflow and litter interception within juniper canopies at the Kerr Wildlife Management Area.

As storm size increased, the proportionate amount of water intercepted by the canopy and lost to evaporation decreased (Figure 6). Curvilinear regression analysis demonstrated the high interception loss from small rainfall events. Approximately 50% direct throughfall did not occur until at least 0.4 inches of rain occurred. At this time, about 43% of the rain was intercepted by the canopy, 5.6% was intercepted by the litter and 2% occurred as stemflow. The remaining 50% directly reached the soil surface. At the highest rainfall levels, nearly 88% of the rain directly reached the soil surface as throughfall, nearly 7% was intercepted by the litter layer, 6.7 % occurred as stemflow and 8.7% was intercepted by the canopy. Interception by the litter layer peaked quickly and remained constant after saturation, resulting in a low coefficient of determination for that regression.

Rainfall Partitioning Model

We created a simple model combining average tree size, the frequency distribution of rainfall events, and the regression equations from Figure 6 to calculate the impact of juniper trees on the hydrological budget at each of the 10 research sites. These estimates are based on the solitary trees we measured, although as tree density increases the canopies may influence one another to some extent. We included a range from 20% canopy cover, which would be an open savanna, to 100% canopy cover which represents a cedar break. We made a conservative assumption that all of the bulk rainfall reaches the soil surface in a grassland savanna. When juniper cover was low (20%), the amount of water lost to canopy and litter interception was about 0.2 acre-feet per year, regardless of the site (Figure 7). Intuitively this makes sense because the types of storms and the amount of rainfall should not affect water loss when tree cover is low. As tree cover increased from 20 % to 100%, the amount of water lost to interception increased to an average of 1.05 acre-feet (342,000 gallons) per acre per year. At the KWMA, the pattern of storms resulted in an average canopy interception loss of 0.82 acre feet

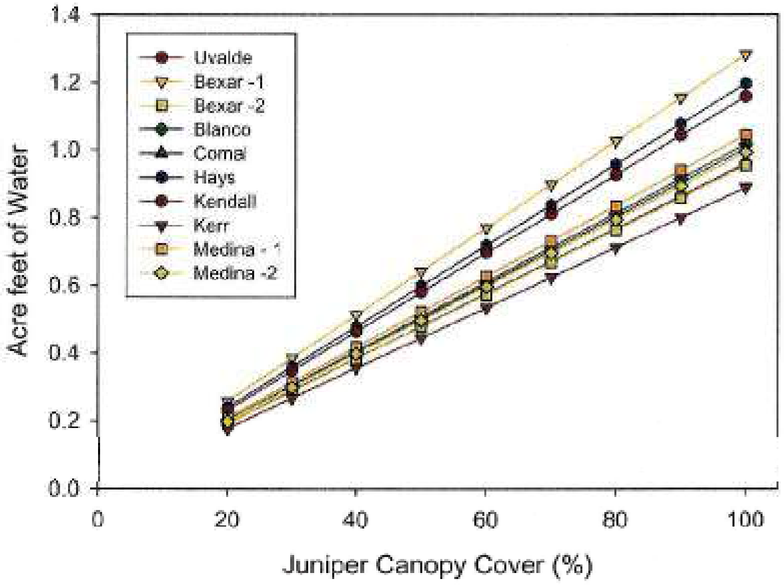

Figure 7. The amount of water (in acre feet) lost to canopy and litter interception for increasing amounts of juniper cover.

per acre of cedar break.

Another use of this model is to determine the amount of water which can be gained into the soil when juniper is removed. For instance, if a cedar break at the KWMA site was reduced by 80%, the expected increase in water at the soil surface would be 0.71 acre-feet per year (231,000 gallons). At this point we cannot determine how much of this water would be available for directly recharging the aquifer; that is the objective of another on-going study. The important point is that removing the juniper will result in a net gain of water to the ecosystem. An additional caveat is that vegetation regrowth will also affect the amount of water intercepted by plant canopies as the site recovers.

Rainfall Intensity and Partitioning within Juniper Canopies

Low Intensity Storms.

Low intensity storms typically deposit < 1 inch of rain over a 24 hour period. During low intensity rainfall events, most of the initial rainfall is intercepted by the canopy and the litter layer. Figure 8 depicts the hourly partitioning of rainfall during a 0.5 inch storm that lasted for 29 hours. During the first 16 hours of the storm, canopy interception and litter interception were the dominant factors. After 0.3 inches of rain accumulated (at hour 17), then throughfall became the dominant factor in partitioning rainfall. Overall stemflow was a negligible factor in low intensity storms. The cumulative partitioning (Figure 9) demonstrates that over 50% of the rain received during this a typical low intensity storm is intercepted by either the tree canopy or the litter layer.

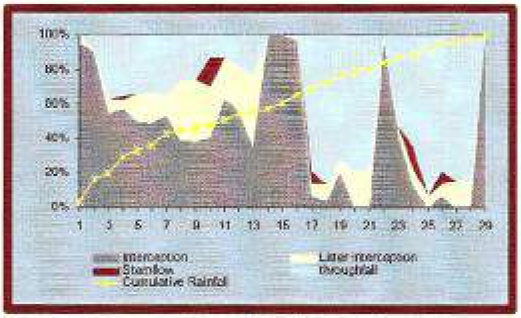

Figure 8. Hourly rainfall partitioning during a 0.5 inch storm that lasted for 19 hours.

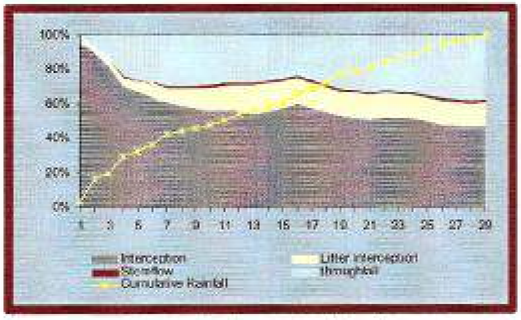

Figure 9. Cumulative partitioning over the entire course of a 0.5 inch storm.

High Intensity Storms.

High intensity storms can deposit 1 inch or more over a very short time period. The hourly pattern of rainfall within high intensity events dictates how rainfall is partitioned within tree canopies. Figures 10 and 11 depict a 2.7 inch storm which began with a light rain over a 16 hour period. The hourly time steps (Figure 10) show that periods of low rainfall typically have higher interception losses and lower throughfall. During the first 0.3 inches of the storm, most of the rainfall was captured by either the canopy or the litter (up to hour 3 in Figure 11), but after that throughfall was the dominant factor. Hours within the storms that had high intensity rainfall (for example hours 6 to 8, and 11 to 13) experienced greater throughfall than other periods.

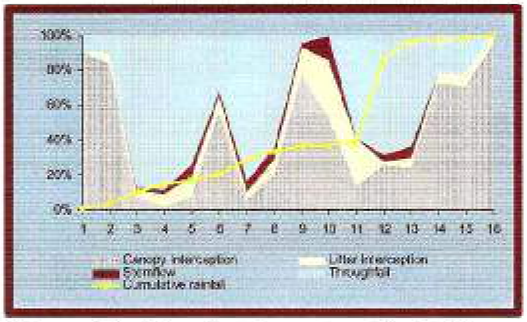

Figure 10. Hourly time step of rainfall partitioning during a 2.7 inch rainfall. The yellow line denotes the cumulative percent rainfall during the storm.

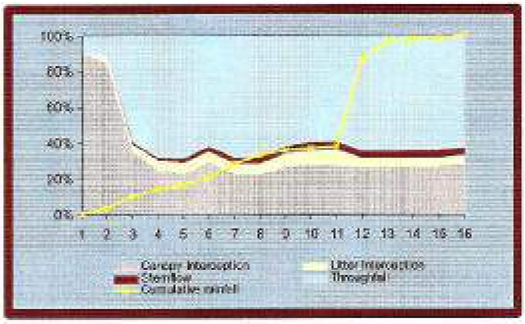

Figure 11. Cumulative rainfall partitioning and rainfall during a 2.7 inch storm.

Stemflow seemed to lag behind the rainfall by about 1 hour. The cumulative partitioning (Figure 11) demonstrates that only about 30% of the bulk rainfall received during a mixed intensity storm is intercepted by the tree canopy or litter layer. This particular storm started rather gently with only 0.3 inches over a 3 hour period, but more intense storms behaved differently.

Conclusions

The loss of water due to the physiological process of transpiration has been demonstrated in previous studies. This study demonstrates the clear impact of the physical presence of Ashe juniper on water resources. Over a 3 year period, nearly 40% of the ambient rainfall failed to reach the soil surface beneath juniper trees across a broad geographic region. This effectively changed the precipitation range from 24-36 inches to 14-22 inches under juniper trees. A simple model demonstrates that as much as 1 acre-foot of water per year can be intercepted by juniper canopies within a cedar break and then be re-evaporated to the atmosphere.

In small rainfall events, all of the precipitation was intercepted by the juniper canopy. The infrequent, high intensity storms supply most of the water to the ground surface beneath these trees. The hourly pattern of precipitation within a storm altered the partitioning of rainfall. Storms beginning with brief intense rainfall intercept less water than storms beginning with lower intensities. Hourly time steps within a storm closely mimicked the patterns observed for similar-sized isolated storms.

Juniper trees clearly altered the hydrologic budget simply through their physical presence. Low intensity rainfall, which could conceivably benefit the local plant community, was entirely intercepted by the juniper trees. High intensity rainfall supplies the most water to the system and was less influenced by juniper canopies. The re-direction of bulk rainfall to the stem of the tree via stemflow may benefit the tree by concentrating water near the root system, or conversely it may serve to funnel water to preferential flowpaths beneath the trees. An on-going study is investigating the fate of the stemflow water.

Citations

Thurow, T.L. and J.W. Hester. 1997. Hydrological Characteristics In: Taylor, C.A. (Ed.). 1997 Juniper Symposium. Texas Agricultural Experiment Station, The Texas A&M Univeristy System. Tech. Rep. 97-1.

Schowalter, T.D. 1999. Throughfall volume and chemistry as affected by precipitation volume, sampling size, and defoliation intensity. Great Basin Nat. 59:79-84.

Silva, I.C. and H.G.Rodriguez 2001. Interception loss, throughfall and stemflow chemistry in pine and oak forests in northeastern Mexico. Tree Physiology 21:1009-113

Evaporation and interception water loss from juniper communities on the Edwards Aquifer Recharge Area

Final Report

by
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February 3, 2004

Summary

Juniper canopies are ideally structured to intercept rainfall and redirect it to the base of the tree, thus altering the hydrology of the site. The amount of water redirected, and the amount lost to interception and evaporation, may be a significant portion of the annual rainfall. We monitored interception and rainfall partitioning in juniper canopies at 10 sites covering a 24 to 36 inch rainfall gradient over a 3 year period. Averaged over all 10 sites and 2700 total rain events, about 35% of the precipitation falling on juniper trees is intercepted by the canopy of the tree and evaporated back to the atmosphere, 5% is intercepted by the litter and duff beneath the tree, and 60% actually reaches the ground surface for either recharge or plant growth. The amount of rainfall intercepted by the canopy is most affected by the intensity and duration of the storm. At high intensities, such as 2.8 inches over a 15 hr period, only 20% is intercepted by the canopy and litter. The remainder is available for either plant growth or aquifer recharge. When rainfall is less intense, such as 0.5 inches over a 19 hour period, 60% (0.3 inch) is intercepted by the tree and litter. Not until nearly 1 inch of rain has fallen does an appreciable amount of water actually reach the ground surface beneath the tree. Nearly 83% of the rainfall events observed over the last several years have been small events of less than 0.5 inches. These events, although common, do not contribute to soil water under juniper trees and are largely ineffective.

Introduction

The density and aerial cover of Ashe juniper (*Juniperus ashei*) in central Texas has increased over the last 200 years. Originally limited to rocky outcrops or areas of low fuel availability, Ashe juniper now covers almost 2.7 million hectares on the Edwards Plateau.

The impact of juniper trees on the hydrologic budget is hotly debated as water demands from rangelands increase. Understanding both the physiological and physical impact of juniper trees on water availability is crucial; this study investigates the physical impact of juniper trees on the hydrologic budget. The amount of rainfall intercepted by tree canopies and lost to evaporation is species-specific, and may be a function of rainfall intensity (Thurow and Hester 1987, Schowalter 1999, Silva and Rodriguez 2001).

When rain falls on a juniper canopy, there are a limited number of things which can happen (Figure 1). The rain can either be intercepted by the juniper canopy or it can fall directly through the canopy to reach the litter layer. The rain that is intercepted can either be evaporated back to the atmosphere or it can flow down the outside of the stem as stemflow. The stemflow water can be further partitioned into water intercepted by the litter layer or water which actually reaches the soil surface. The rain that is not intercepted by the canopy occurs as throughfall and directly reaches

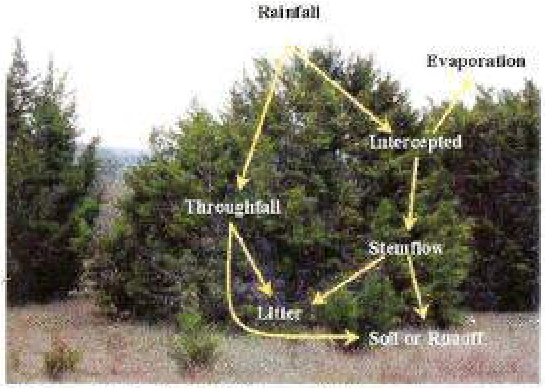

Figure 2. Rain falling on juniper trees can be partitioned to determine evaporative losses.

the litter layer under the tree. This water is either retained by the litter layer or it can reach the soil surface. It was impractical to follow the rainfall after it reached the soil surface in this study, but it would be available for either plant growth, deep drainage, or overland flow.

Our objectives were to:

1. Determine how rainfall is partitioned within juniper trees over a wide geographic region, and
2. Determine how rainfall intensity alters the patterns of rainfall partitioning.

Methods

Ten study sites were selected over a 180 mile range from near Concan, TX to San Marcos, TX (Figure 2). These sites were selected to cover a 24 to 36 inch rainfall gradient from the western to the eastern portion of the study area. At each site, two trees were selected for instrumentation. The trees were representative of the site and were within 100 feet of each other. Site location and the date of establishment for each site is presented in Table 1.

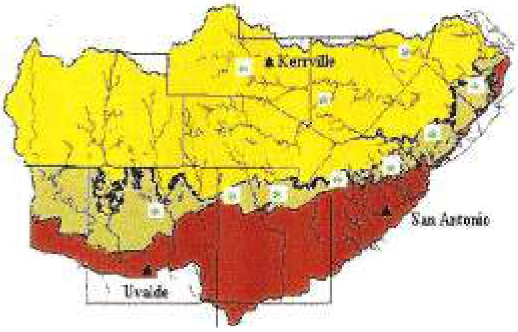

Figure 3. Map depicting the geographic distribution of the 10 study sites.

Table 1. Research site location and establishment date.

County	Latitude	Longitude	Site	Date Established
Uvalde	29.44°	99. 69°	Annandale Ranch	Aug. 7, 2000
Bexar - 1	29.66°	98.78°	Schott Ranch	Sep. 16, 2000
Bexar - 2	29.74°	98.41°	Page Ranch	Nov. 22, 2000
Blanco	30.28°	98.41°	Johnson City	Nov. 16, 2000
Comal	29.86°	98.16°	Pape Ranch	Dec. 15, 2000
Hays	29.94°	98.01°	Freeman Ranch	Sep. 15, 2000
Kendall	29.96°	98.80°	Seidensticker Ranch	Dec. 18, 2000
Kerr	30.09°	99.49°	Kerr Wildlife Management Area	Oct. 3, 2000
Medina -1	25.54°	99.16°	Peters Ranch	Nov. 2, 2000
Medina - 2	29.56°	99.45°	Crosby Ranch	Dec. 19, 2000

Each tree was instrumented to collect rainfall, throughfall, stemflow and litter moisture (Figure 3). Rainfall above the canopy (hereafter referred to as bulk rainfall) was measured to the closest 0.01 inch using a tipping bucket rain gauge (Texas Electronics).

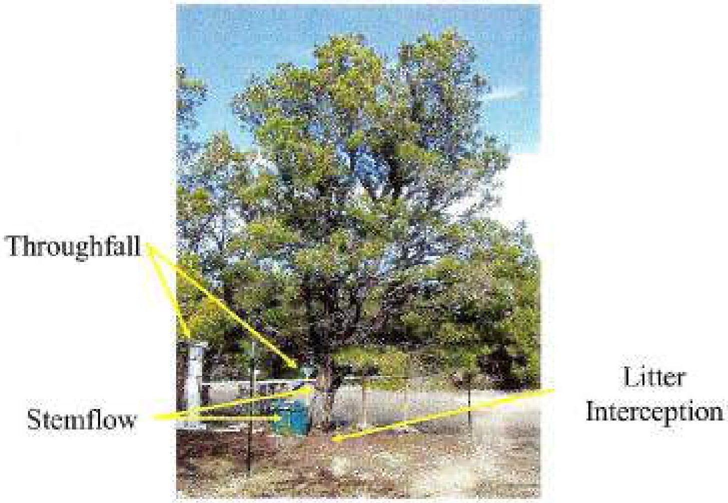

Figure 4. Juniper tree at the Page Ranch in Bexar County showing the data collection equipment.

Throughfall was collected using a system of four 8-inch funnels connected to a collection tube. As the throughfall was collected, a float in the tube recorded the increasing water level. The change in millivolts was calibrated to record the actual height of the water column. After the rain stopped, the datalogger tripped a solenoid to drain the tube and make it ready for the next rainfall event.

Litter moisture was measured using water content reflectometers (Campbell Scientific CS615), after they were calibrated to the high organic matter. The amount of litter was determined by measuring litter depth near the base of the tree, mid-way through the canopy, and at the drip line of the canopy on 8 equally spaced transects radiating from the base of each tree. The area of the tree was combined with litter depths to determine the volume of litter under each tree. Bulk density samples were collected to convert from litter volume to litter mass. Additional samples were taken to calibrate the reflectometer probes. For calibration purposes, the litter was oven-dried and weighed to determine the mass of the sample. Ten percent of that mass was then added using distilled water and a measurement was taken using the CS615 probe. This process was repeated to measure from 10% to 80% gravimetric moisture. This whole process was repeated 6 times and a regression was calculated to convert the millivolt reading from the probes to gravimetric litter moisture. Litter moisture was calculated as :

$$Litter\ moisture = -4681.93 + 14416.18 * mV - 14600.62 * mV^2 + 4942.83 * mV^3$$

where mV = millivolt reading from the CS615 probe.

Stemflow was collected by constructing a narrow collar around the base of each tree. The collar collected all of the water which was flowing on the outside of the stem and diverted it to a tipping bucket measuring device. The bucket held 1 L of water before it tipped. The 1 L of water represented about 0.005 inches of rain for an average size juniper tree.

All of this information was collected hourly by an electronic datalogger and downloaded to a computer every second day. The computer then ran a program to check the data for errors and summarized the results, posting the information to a web page at http://uvalde.tamu.edu/intercept.

Canopy interception cannot be measured directly, but must be estimated by subtraction using the formula:

Canopy Interception = Bulk Rainfall - (Throughfall + Stemflow)

And then the amount of water reaching the soil surface was calculated as :

Soil Water = Bulk Rainfall - Canopy Interception - Litter Interception

During the 3-year study, data were collected from over 2700 rainfall events (over all 10 sites). Bulk rainfall was partitioned to canopy interception, evaporation, soil litter interception, and soil moisture, on both a gallons per tree and a percentage basis. Data were analyzed by creating classes of rainfall based on 0.1 inch increments and using curvilinear regression techniques. In addition, the hourly time step of rainfall partitioning for different intensity storms was calculated to determine how rainfall intensity and duration affected interception losses.

Results and Discussion

Tree size varied over the 10 sites. The average tree was 17.7 feet tall (range of 12.5 to 25 feet) and had a canopy area of 230.3 feet^2 (range of 87.2 to 690 feet^2) (Table 2). Generally, the taller and larger trees were from the eastern portion of the study area while the smaller trees were from the drier Edwards Aquifer drainage area rather than the aquifer recharge area.

Table 2. Tree size and litter amounts for the 10 research sites.

	Tree 1				Tree2			
Site	Height (ft)	Canopy Area (ft^2)	Litter Depth (inches)	Litter Weight (lbs)	Height (ft)	Canopy Area (ft^2)	Litter Depth (inches)	Litter Weight (lbs)
Uvalde	20	125.8	1.03	62.5	20	242.0	1.58	135.0
Bexar - 1	15	159.5	1.33	102.6	23	194.8	1.94	182.1
Bexar - 2	19	216.3	1.6	167.5	19	336.6	0.94	152.3
Blanco	12.5	129.5	0.73	45.5	15	103.5	0.52	30.0
Comal	24	387.8	0.66	141.9	15.5	191.3	0.92	73.1
Hays	25	371.9	2.40	145.7	15	163.7	1.52	130.4
Kendall	24	690.5	0.16	123.9	20.5	361.8	0.87	116.4
Kerr	15	242.0	1.52	177.9	14	220.8	1.05	112.1
Medina - 1	15	126.1	1.32	79.9	14	87.2	1.79	153.6
Medina - 2	14	151.9	0.83	64.5	14	103.6	1.87	71.9

Rainfall Distribution

The research sites were installed for different lengths of time depending on when we could get access to the properties. The Comal county site was instrumented for the shortest length of time (505 days) while the Uvalde county site was in place the longest (1122 days)(Figure 4). During the time the Comal county site was installed, we recorded 158 rainfall events for a total of 46.3 inches. At the Uvalde county site we recorded 355 rainfall events for 88.41 inches of rain. The wettest site was the Hays county site with 126.32 inches of rain in 361 storms. There were no statistical differences between the rainfall frequency histograms for the 10 sites, so the average histogram is presented in Figure 5. Sixty percent of the storms at all the sites were less than 0.1 inch. Although these storms were numerous, they contributed only 5.4% of the total rainfall at each site. Storms greater than 2.5 inches were less numerous, accounting of only 2.7% of the total number of storms, but they contributed over 27% of the total rainfall. This rainfall distribution will have significant impacts on water availability as demonstrated in a later section.

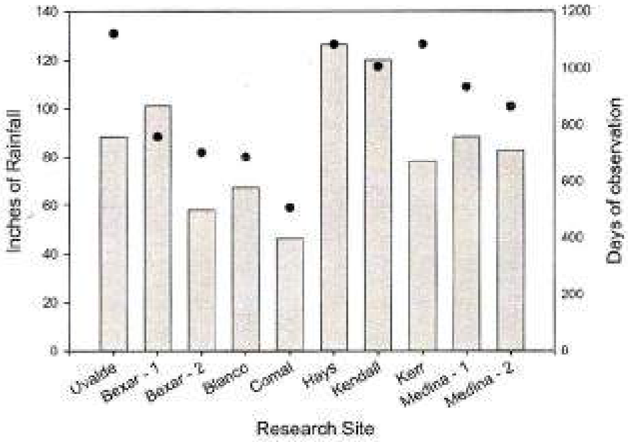

Figure 5. Amount of rain received site (bars) and the length of the observation (Circles) at each site.

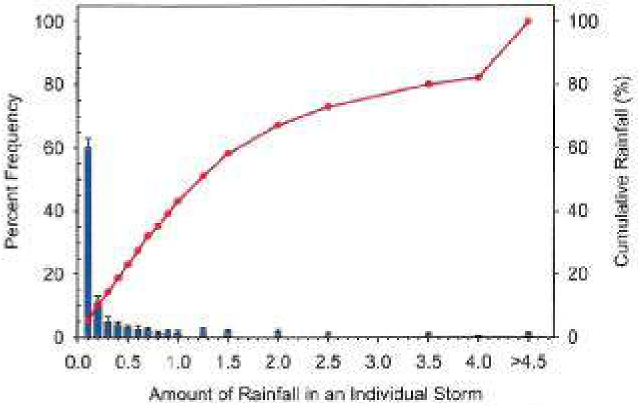

Figure 6. Rainfall frequency histogram (bars) averaged over the 10 research sites and cumulative percent of the rainfall (line) contributed by each frequency class.

Rainfall Partitioning

Averaged over all storms during the 3 year study, about 60% of the ambient precipitation reached the soil surface beneath juniper trees while the remaining 40% was intercepted and lost to evaporation (Figure 6). There were significant differences in the amount of water lost versus that reaching the soil surface among the 10 sites. There was no clear geographic or rainfall impact on the amount of water reaching the soil surface, but rather the differences were probably due to different tree morphology at each site. Actual leaf area was not measured for these trees, but leaf density was not equal according to our observations. The high canopy interception and

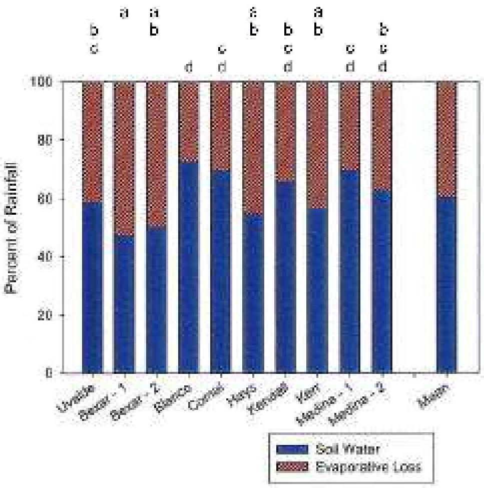

Figure 6. Percent of rainfall lost to evaporation at each of the 10 research sites. Columns with different letters were significantly different.

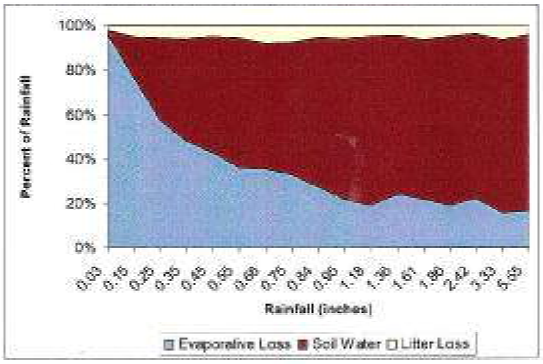

Figure 7. Rainfall partitioning beneath juniper canopies for different amounts of total rainfall.

evaporative loss is due mainly to the large number of small storms which experienced total, or nearly total, interception. The low intensity storms were numerous but contributed little moisture to the soil surface (Figure 7). Most of the precipitation from storms < 0.1 inch was either intercepted by the canopy (96%) or the litter layer (2%) leaving only 2% of the bulk rainfall to reach the soil surface beneath the juniper trees. At the highest rainfall levels, at least 15% of the bulk rainfall was intercepted by the tree canopy. The litter layer became saturated at fairly low levels of rain and absorbed about 5% of the bulk precipitation, leaving about 80% of the bulk rainfall reaching the soil surface.

As storm size increased, the proportionate amount of water intercepted by the canopy and lost to evaporation decreased (Figure 8). Curvilinear regression analysis demonstrated the high interception loss from small rainfall events. Approximately 50% direct throughfall did not occur until at least 0.4 inches of rain occurred. At this time, about 43% of the rain was intercepted by the

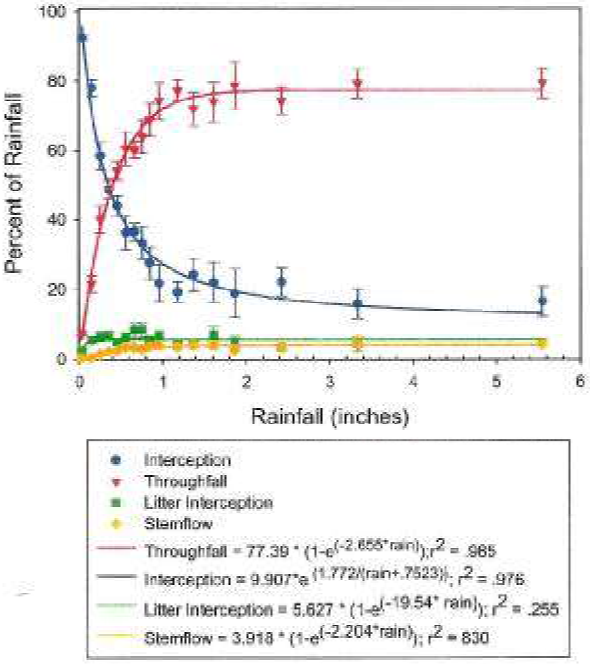

Figure 8. Curvilinear regression analysis of rainfall partitioning within juniper canopies over all 10 research sites.

canopy, 5.6% was intercepted by the litter and 2% occurred as stemflow. The remaining 50% directly reached the soil surface. At the highest rainfall levels, nearly 80% of the rain directly reached the soil surface as throughfall, nearly 5.6% was intercepted by the litter layer, 4 % occurred as stemflow and 10% was intercepted by the canopy. Interception by the litter layer peaked quickly and remained constant after saturation, resulting in a low coefficient of determination for that regression.

Rainfall Partitioning Model

We created a simple model combining average tree size, the frequency distribution of rainfall events, and the regression equations from Figure 8 to calculate the impact of juniper trees on the hydrological budget at each of the 10 research sites. These estimates are based on the solitary trees we measured, although as tree density increases the canopies may influence one another to some extent. We included a range from 20% canopy cover, which would be an open savanna, to 100% canopy cover which represents a cedar break. We made a conservative assumption that all of the bulk rainfall reaches the soil surface in a grassland savanna. When juniper cover was low (20%), the amount of water lost to canopy and litter interception was about 0.2 acre-feet per year (Figure 9), regardless of the site. Intuitively this makes sense because the types of storms and the amount of rainfall should not affect water loss when tree cover is low. As tree cover increased from 20 % to 100%, the amount of water lost to interception increased to an average of 1.05 acre-feet (342,000 gallons) per acre per year. Sites which received the most intense storms (Bexar-1, Hays, and Kendall) had the greatest increase in the amount of water lost to interception. At those sites, approximately 1.2 acre-feet (390,900

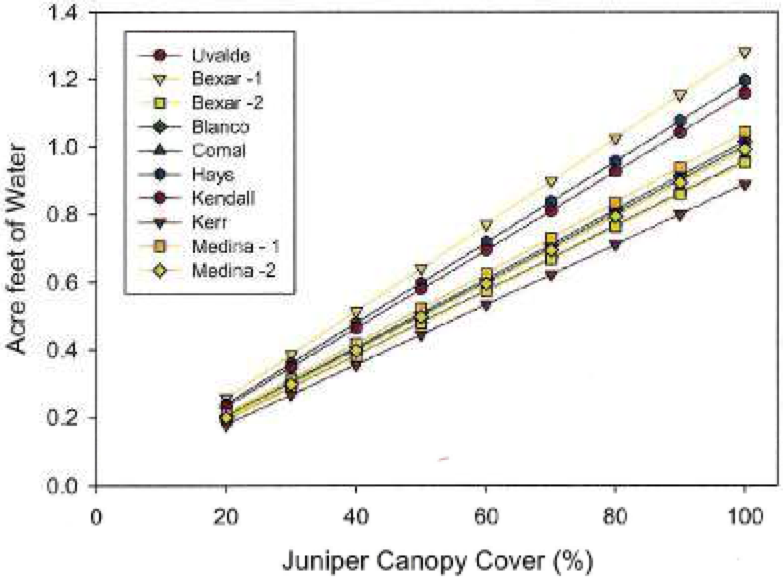

Figure 10. The amount of water (in acre feet) lost to canopy and litter interception for increasing amounts of juniper cover.

gallons) were lost to interception. At drier sites, or at sites with little litter under the trees, the interception loss averaged 0.95 acre-feet per acre (309,500 gallons).

Another use of this model is to determine the amount of water which can be gained into the soil when juniper is removed. For instance, if a cedar break at the Bexar-1 site was treated to remove 80% of the juniper cover, there would be a net gain of 1.02 acre-feet per acre per year (332,300 gallons) which would be available for either plant growth or aquifer recharge. At the Kerr site, if a cedar break was reduced by 80%, the expected increase in water at the soil surface would be only 0.71 acre-feet per year (231,000 gallons). At this point we cannot determine how much of this water would be available for directly recharging the aquifer; that is the objective of another on-going study. The important point is that removing the juniper will result in a net gain of water to the ecosystem. An additional caveat is that vegetation regrowth will also affect the amount of water intercepted by plant canopies as the site recovers.

Rainfall Intensity and Partitioning within Juniper Canopies

Low Intensity Storms.

Low intensity storms typically deposit < 1 inch of rain over a 24 hour period. During low intensity rainfall events, most of the initial rainfall is intercepted by the canopy and the litter layer. Figure 10 depicts the hourly partitioning of rainfall during a 0.5 inch storm that lasted for 29 hours. During the first 16 hours of the storm, canopy interception and litter interception were the dominant factors. After 0.3 inches of rain accumulated (at hour 17), then throughfall became the dominant factor in partitioning rainfall. Overall stemflow was a negligible factor in low intensity storms. The cumulative partitioning (Figure 11) demonstrates that over 50% of the rain received during this a typical low intensity storm is intercepted by either the tree canopy or the litter layer.

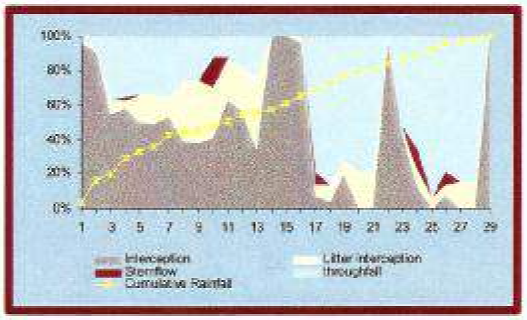

Figure 11. Rainfall partitioning during a 0.5 inch storm that lasted for 19 hours.

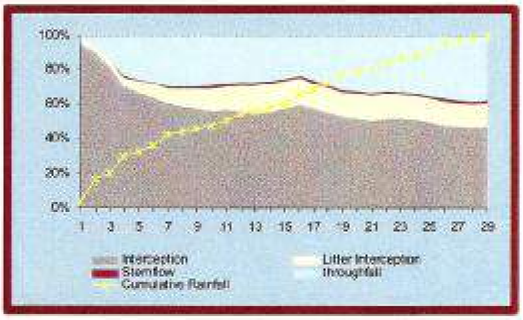

Figure 12. Cumulative partitioning over the entire course of a 0.5 inch storm.

High Intensity Storms.

High intensity storms can deposit 1 inch or more over a very short time period. The hourly pattern of rainfall within high intensity events dictates how rainfall is partitioned within tree canopies. Figures 12 and 13 depict a 2.7 inch storm which began with a light rain over a 16 hour period. The hourly time steps (Figure 12) show that periods of low rainfall typically have higher interception losses and lower throughfall. During the first 0.3 inches of the storm, most of the rainfall was captured by either the canopy or the litter (up to hour 3 in Figure 13), but after that throughfall was the dominant factor. Hours within the storms that had high intensity rainfall (for example hours 6 to 8, and 11 to 13) experienced greater throughfall than other periods.

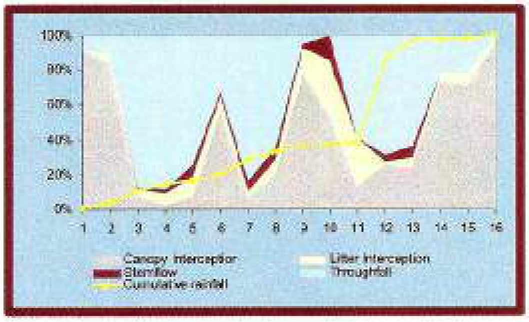

Figure 13. Hourly time step of rainfall partitioning during a 2.7 inch rainfall. The yellow line denotes the cumulative percent rainfall during the storm.

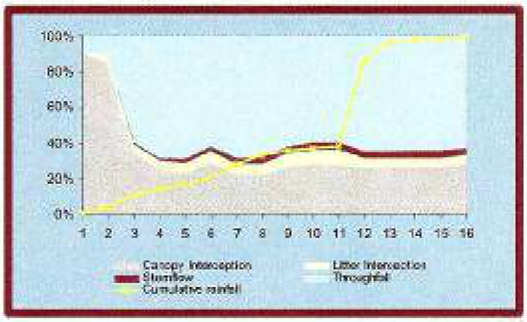

Figure 14. Cumulative rainfall partitioning and rainfall during a 2.7 inch storm.

Stemflow seemed to lag behind the rainfall by about 1 hour. The cumulative partitioning (Figure 13) demonstrates that only about 30% of the bulk rainfall received during a mixed intensity storm is intercepted by the tree canopy or litter layer. This particular storm started rather gently with only 0.3 inches over a 3 hour period, but more intense storms behaved differently.

During a 2.87 inch rainfall over a 15 hour period, the storm began with over 0.3 inches in the first hour. The canopy and litter were quickly saturated and throughfall was dominant early in the storm (Figures 14 and 15). Stemflow still lagged behind the precipitation. During the a 1 hour interval (hour 5 to 6), about 1.15 inches of rain fell. Very little of this rain was intercepted and retained in the canopy because most of it was direct throughfall and significant stemflow occurred. The cumulative partitioning (Figure 15) demonstrates that only about 15% of the rain received during a typical high intensity storm is intercepted by either the tree canopy or the litter layer. Overall, these events have a greater proportion of throughfall than either lower or mixed intensity events.

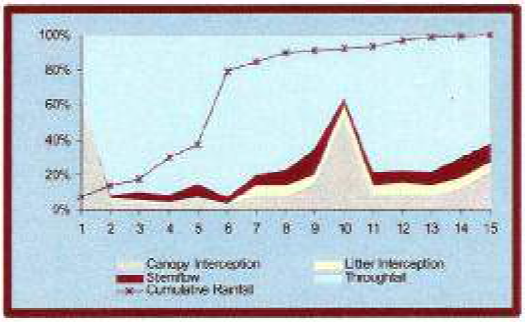

Figure 15. Hourly time step of rainfall partitioning during a 2.87 inch rainstorm.

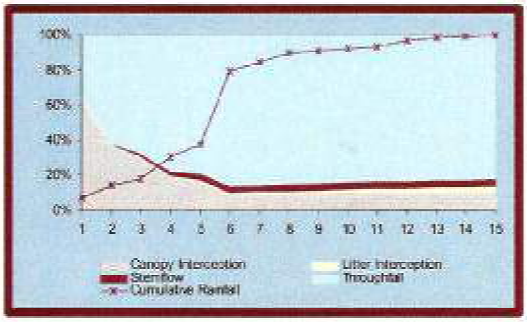

Figure 16. Cumulative rainfall partitioning during a 2.87 inch storm.

Conclusions

The loss of water due to the physiological process of transpiration has been demonstrated in previous studies. This study demonstrates the clear impact of the physical presence of Ashe juniper on water resources. Over a 3 year period, nearly 40% of the ambient rainfall failed to reach the soil surface beneath juniper trees across a broad geographic region. This effectively changed the precipitation range from 24-36 inches to 14-22 inches under juniper trees. A simple model demonstrates that as much as 1 acre-foot of water per year can be intercepted by juniper canopies within a cedar break and then be re-evaporated to the atmosphere.

In small rainfall events, all of the precipitation was intercepted by the juniper canopy. The infrequent, high intensity storms supply most of the water to the ground surface beneath these trees. The hourly pattern of precipitation within a storm altered the partitioning of rainfall. Storms beginning with brief intense rainfall intercept less water than storms beginning with lower intensities. Hourly time steps within a storm closely mimicked the patterns observed for similar-sized isolated storms.

Juniper trees clearly altered the hydrologic budget simply through their physical presence. Low intensity rainfall, which could conceivably benefit the local plant community, was entirely intercepted by the juniper trees. High intensity rainfall supplies the most water to the system and was less influenced by juniper canopies. The re-direction of bulk rainfall to the stem of the tree via stemflow may benefit the tree by concentrating water near the root system, or conversely it may serve to funnel water to preferential flowpaths beneath the trees. An on-going study is investigating the fate of the stemflow water.

Citations

Thurow, T.L. and J.W. Hester. 1997. Hydrological Characteristics In: Taylor, C.A. (Ed.). 1997 Juniper Symposium. Texas Agricultural Experiment Station, The Texas A&M Univeristy System. Tech. Rep. 97-1

Schowalter, T.D. 1999. Throughfall volume and chemistry as affected by precipitation volume, sampling size, and defoliation intensity. Great Basin Nat. 59:79-84.

Silva, I.C. and H.G.Rodriguez 2001. Interception loss, throughfall and stemflow chemistry in pine and oak forests in northeastern Mexico. Tree Physiology 21:1009-113