WATER RESOURCES RESEARCH, VOL. 34, NO. 6, PAGES 1499–1506, JUNE 1998

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 ($\sim 10^{12}$ 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

Paper number 98WR00556.
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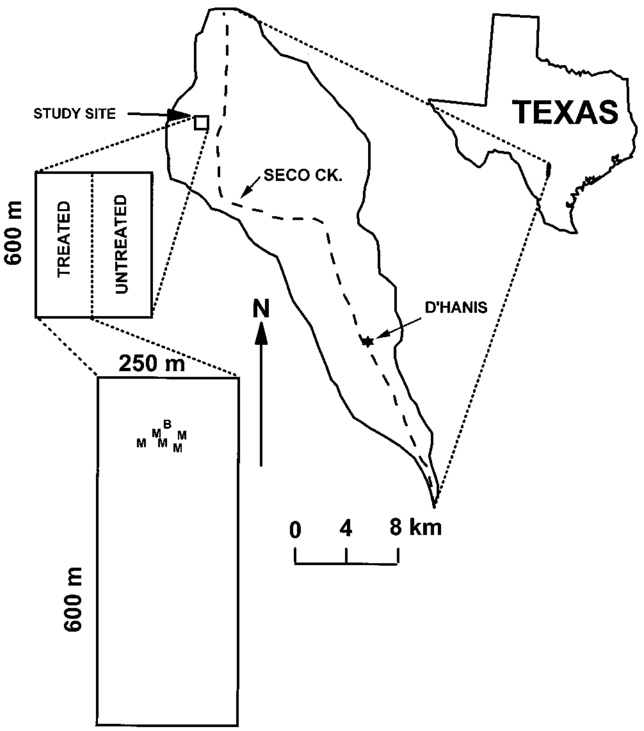

Figure 1. Map of study site. "B" and "M" symbols in treated area represent locations of base and mobile stations, respectively (see text). Base and mobile stations in the untreated area were in similar relative locations. Scale applies to map of Seco Creek watershed.

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

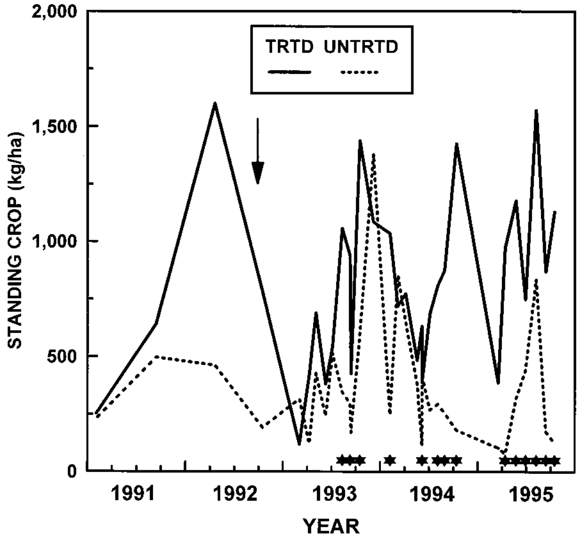

Figure 2. Average standing crop (live and dead) of herbaceous vegetation on treated and untreated areas in 1991 through 1995. Arrow denotes time of removal of *J. ashei*. Stars denote significantly different averages ($P > 0.05$).

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)

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.

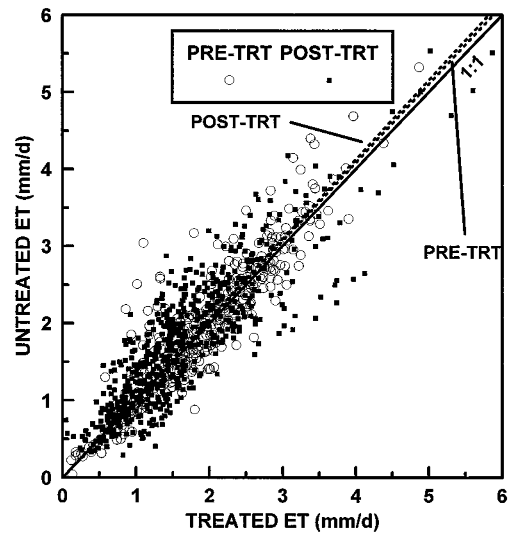

Figure 3. Average daily evapotranspiration (ET) from the untreated area versus average daily ET from the treated area during the pretreatment and posttreatment periods. The 1:1 line and linear regression lines (without intercept) for pretreatment and posttreatment periods are shown. Slopes (with standard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

because of increased herbaceous and *J. ashei* leaf area in the treated area.

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

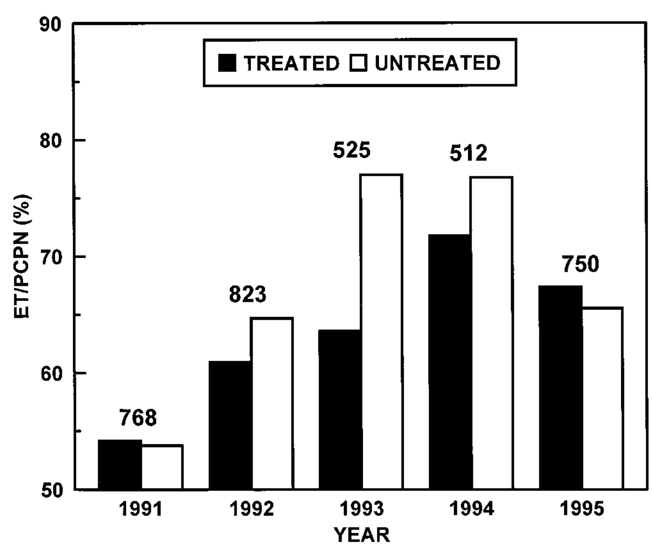

Figure 4. Ratio of total evapotranspiration (ET) and precipitation (PCPN) from March through October for treated and untreated areas for 1991 through 1995. Values above each set of bars are total precipitation (in millimeters) from March through October. *J. ashei* trees were removed from the treated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

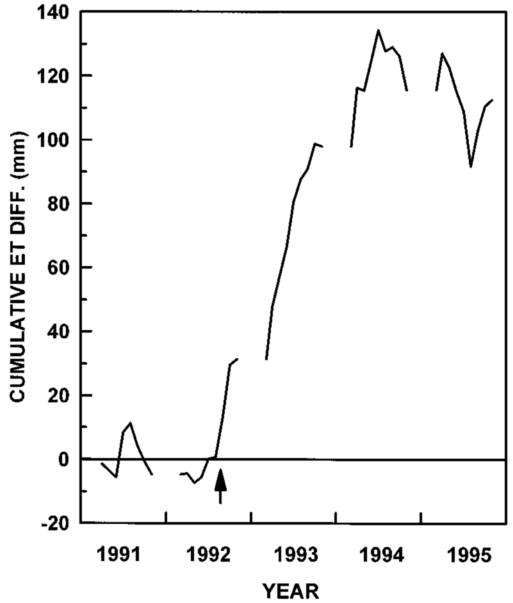

Figure 5. Cumulative difference (untreated minus treated) of total monthly evapotranspiration (ET) from March through October for 1991 through 1995. Arrow denotes time of removal of *J. ashei*. Breaks in lines are during winter when ET was not measured.

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%).

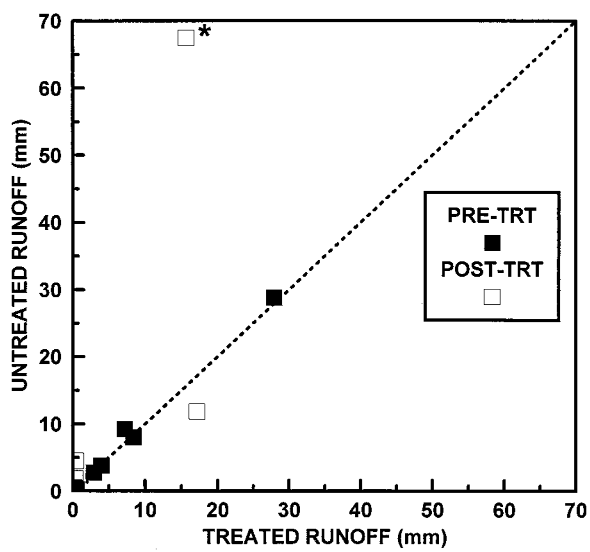

Figure 6. Runoff from watersheds in untreated and treated areas during pretreatment and posttreatment periods. Each point is one runoff event. The runoff data point from the untreated area for the posttreatment period with an asterisk was estimated using precipitation totals and watershed area because 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.

Acknowledgments. We gratefully acknowledge Mark Heuer, J. R. Rodriguez, and Ron Whitis for technical assistance, Melanie Sikes for some of the herbaceous standing crop estimates, NRCS staff for assistance with topographic mapping of the area, and Norman Erskine for assistance with flume installation. This research was partially supported by grant 68-7442-0-91 from Natural Resources Conservation Service to the Texas Agricultural Experiment Station.

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(Received July 24, 1997; revised January 8, 1998;
accepted February 13, 1998.)