doi:10.2489/jswc.64.5.336

Effect of brush control on evapotranspiration in the North Concho River watershed using the eddy covariance technique

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Abstract: This paper reports on a project that was designed to study changes in total water budget with implementation of brush control in two adjacent mesquite-dominated experimental sites, wherein one site received brush control treatment and the other served as an untreated site. The two sites, each consisting of about 80 ha (200 ac), are located within the North Concho River watershed near San Angelo, Texas. Evapotranspiration (*ET*) from the sites was measured with the eddy covariance technique beginning in April 2005. The field data indicated that the measured *ET* at the mesquite-treated site was lower than that of the untreated site during the mesquite growing season (May to October). For instance, the largest difference in *ET* (about 25%) in measured *ET* between the treated and untreated sites was recorded during the peak mesquite growing season in 2008. The higher *ET* measured at the untreated site suggests that there is great potential for increasing water yield by eliminating the water uptake by mesquite trees, through a brush control approach in the North Concho River watershed. For example, based on 952 daily *ET* measurements (from 9:00 a.m. to 6:30 p.m.), the experimental data indicated that during the four-year study, the mesquite-dominated untreated site had a net consumption of over 46 mm (1.8 in) more water than the treated site. In addition, extrapolation of the data set to include all days during the four-year study (1,370 days) indicated that the untreated site had a potential net consumption of about 71 mm (2.8 in) more water compared to the treated site. Truncation of the data set to include measurements obtained during only the months within the mesquite growing season (May to October) indicated that the untreated site had consumed more than 58 mm (2.3 in) more water than the treated site based on 513 daily measurements obtained during the four-year study. Extrapolation of the data set to account for missing values within the growing season (732 days) indicated that water consumption at the untreated site would be expected to potentially exceed that of the treated site by 90 mm (3.5 in) during the growing season months over the four year period.

Key words: brush control—eddy covariance—evapotranspiration—mesquite—North Concho River watershed

Consumptive water use of surface and subsurface waters in the western United States exceeds recharge. This imbalance of supply and demand has led to a significant depletion of aquifers and stream flows throughout much of the region (Bidlake 2000; Thurow et al. 2000). It is believed that if a site is dominated by grass instead of brush, then water yield from rangeland will be significantly greater (Hinnert 1983). Therefore, brush control programs are being considered by policymakers as a way to relieve regional water shortages, based on the belief that improved water yields from suitable range sites will raise groundwater levels and/or increase stream flow in the region thus benefiting off-site water users (Thurow et al. 2000).

In Texas, water supply is a crucial issue because of projected population growth, combined with Texas' vulnerability to drought (Texas Water Development Board 2006). The growing Texas population, and associated municipal and industrial growth, is placing greater demands on the state's water supply. The issue of available water supply becomes particularly acute during times of drought, as recent experience during the drought of the late 1990s to 2001 suggests (Wilcox et al. 2005). Brush in Texas uses about 12.3 billion m^3 (10 million ac ft) of water per year, compared with human usage of 18.5 billion m^3 (15 million ac ft) a year, as estimated by the USDA Natural Resources Conservation Service (Walker et al. 1998). Therefore, brush control will affect water resources by enhancing surface water supplies, the recharge of groundwater aquifers, and spring flows.

Honey mesquite (*Prosopis glandulosa* Torr.), one of the dominant brush species growing in Texas, is known as a high water user. The root system of a mature mesquite tree, consisting of lateral roots and tap roots, makes it possible for it to utilize both shallow and deep soil moisture (Ansley 2005). Mesquite's shallow lateral roots compete for water with grasses, while mesquite's deep tap roots are used to obtain water from the underground water table. This root structure enables the plant to avoid drought (Ansley et al. 1990). Thus, prolonged drought conditions could reduce perennial forage and favor mesquite survival (Warren et al. 1996). In addition, mesquite establishes under a wide range of conditions and withstands repeated top removal, because it is a prolific producer of long-lived seeds that germinate readily after scarification (Laxson et al. 1997). The density and distribution of mesquite have been increasing. The factors that are associated with this increase usually include (1) rangeland management practices, (2) enhanced seed distribution, (3) reduced grass competition as a result of livestock grazing, (4) suppression of naturally occurring fires, and (5) climate changes and increasing atmospheric carbon dioxide (Ansley et al. 2001). The invasion of mesquite has also negatively influenced the density and production of native grasses, which are the principal ground cover and forage for livestock (Tiedemann and Klemmedson 2004).

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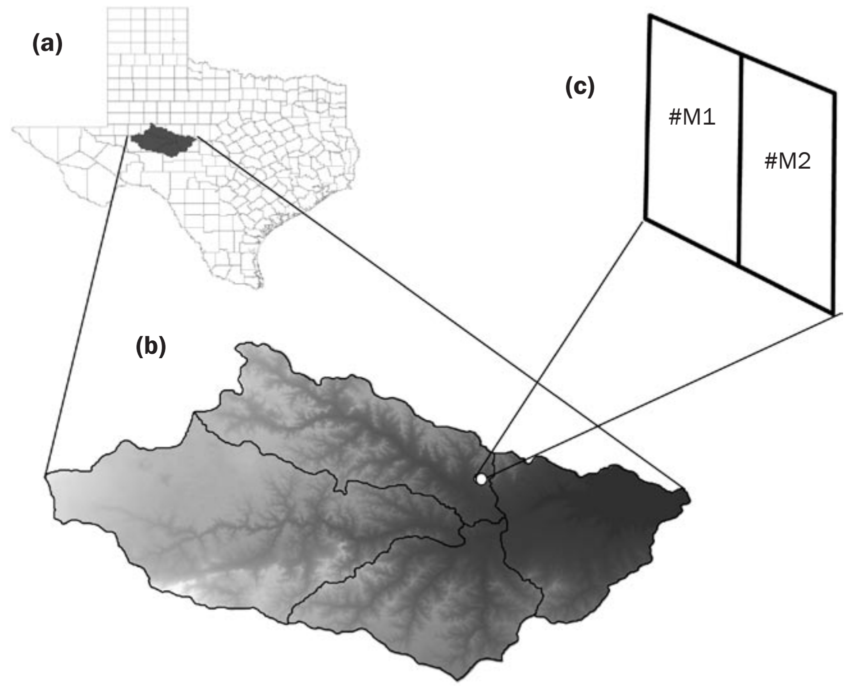
The North Concho River (NCR) watershed, located in West Central Texas, is one of the watersheds in which water resources are affected by growing brush levels. This watershed encompasses more than 380,000 ha (939,000 ac) within Tom Green, Sterling, Glasscock, and Coke Counties. The NCR is dammed to form O.C. Fisher Reservoir, which is a major water supply for the city of San Angelo. However, "more than 130 million mesquite trees and more than 100 million junipers thrive in the watershed," and "the trees' tentacle roots act like straws to suck water from the watershed," according to Johnny Oswald, project manager for the Texas State Soil and Water Conservation Board. Selectively removing these types of trees is, therefore, expected to increase underground water resources for ranchers and farmers and divert more water into the NCR and ultimately into O.C. Fisher Reservoir (Smith 2000).

Studies have shown that brush control can increase surface water flows and ground water recharge through reductions in evapotranspiration (*ET*) and possible interception by resident plants (Griffin and McCarl 1989). In 1998, a study funded by the Texas Water Development Board, was conducted by the Texas State Soil and Water Conservation Board, Texas A&M Research and Extension Center, and the Upper Colorado River Authority on the NCR watershed to determine potential water yields from a comprehensive brush control program. The study estimated that a brush control program in the NCR watershed could improve the water yield of the river by 40.7 million m^3 y^{-1} (33,000 ac ft yr^{-1}), a five-fold increase (Smith 2000).

The rationale for using brush management to increase water yield is based on the premise that shifting vegetation composition from species associated with high *ET* potential (e.g., trees and shrubs), to species with lower *ET* potential (e.g., grasses) will increase the likelihood of water yield from the site in forms such as runoff and/or deep drainage (Thurow et al. 2000). Although evaporation from the soil may increase because of less shading and more air movement, the net result of the conversion to grasses is to reduce water use. Wu et al. (2001) concluded that in semiarid rangelands, *ET* can account for 80% to 95% of the water loss. Thus, changes in woody cover in semiarid rangelands can significantly alter *ET* losses, which in turn will generally increase the amount of water that percolates below the root zone into groundwater.

Figure 1

Location map for the Concho River Basin near San Angelo, Texas. (a) Texas county map with Concho River Basin. (b) Concho River Basin map. (c) Paired mesquite watersheds and station locations (number signs). M1 denotes the treated site; M2 denotes the untreated site.



This study was conducted to evaluate the effect of brush control on the water budget by measuring *ET* from two study sites located in Tom Green County and within the NCR watershed. The main objective of this study was to investigate reductions in *ET* as a result of the removal of mesquite trees, by determining statistically significant differences in *ET* between mesquite-treated and untreated sites. The results of this study are important in that they will provide an estimate of the quantity of water that could be saved by brush control for this and similar locations within the United States.

Materials and Methods

Study Area and Brush Treatment. The study area is located within the southeast portion of the NCR watershed (figures 1a and 1b), near San Angelo, Texas, in a flat mesquite-dominated area with relatively deep soils in northern Tom Green County. Climate in the study area is semiarid. Long-term average annual precipitation is 566 mm (20.9 in), average daily maximum temperature is 25°C (77°F), and average daily minimum temperature is 11°C (51.7°F) (NWS 2008). The study area consists of two adjacent sites, each covering approximately 80 ha (200 ac) (figure 1c). Mesquite is the dominant land cover at these sites, and major land use is a light grazing cow/calf operation. The paired sites are in an area of very low relief with an absence of discernible pathways for surface water flow. Based on a field survey, the mesquite density of the study area was about 4,520 trees ha^{-1} (1,830 trees ac^{-1}).

On June 1, 2002, the herbicides Remedy (triclopyr) and Reclaim (clopyralid) were sprayed over the mesquite trees in one of the sites. The trees were defoliated within two weeks, representing the initiation of the brush treatment phase of the project. There was no land management imposed on the other mesquite-dominated plot (M1), referred to as untreated (M2) in this paper (figure 1c). Photographs of the treated and untreated sites are shown in figures 2a and 2b, respectively, and were taken in June 2008.

Micrometeorological Data Collection Techniques. A 10 m (33 ft) flux tower was established at each site in 2000. The coordinates of the towers were 31°36'20.24" and 100°30'55.84" at the treated site and 31°36'12.16" and 100°30'33.71" at the untreated site. The two towers were equipped with identical instruments. The Bowen Ratio technique was initially employed, intending to obtain approximately three years of pretreatment data to establish the baseline data, which was necessary for application of the paired site approach. However, various complications and failures of instrumentation with the Bowen Ratio system resulted in the collection of less than a complete set of reliable data.

Because of the unreliability in the data collection with the Bowen Ratio technique, a three-dimensional eddy covariance (EC) system (Campbell Scientific, Inc, Logan, Utah) was mounted to the tower for the untreated site in April 2004 and for the treated site in April 2005. The EC technique is based on direct measurements of the product of vertical velocity fluctuations and scalar concentration fluctuations, resulting in an estimate of sensible heat flux (H) and latent heat flux (LE), assuming the mean vertical velocity is negligible (Twine et al. 2000). The EC system, mounted at a height of 8 m (26 ft) above the ground and oriented toward the south to take advantage of the predominant wind direction, measured the surface fluxes above the canopy, which has an average height of about 3 m (10 ft).

According to the eddy covariance theory, the LE (W m^{-2}) is determined as follows:

$$LE = L_v \overline{w'\rho'_v} , \quad (1)$$

where L_v (kJ kg^{-1}) is the latent heat of vaporization for water, w' is the instantaneous deviation of vertical wind speed from the mean, and ρ'_v is the instantaneous deviation of the water vapor density from the mean. The quantity $\overline{w'\rho'_v}$ is the covariance between the vertical wind speed and vapor density.

With the EC technique, vertical wind speed was measured by a three-dimensional sonic anemometer (model CSAT3; Campbell Scientific, Inc), and vapor density was measured by a krypton hygrometer (model KH20; Campbell Scientific, Inc). The fluctuations were sampled at 10 Hz, and the covariance between the vertical wind speed and vapor density was computed every 30 minutes. The measurements were recorded on a datalogger (model CR5000, Campbell Scientific, Inc). The LE was computed using

$$LE = \frac{2{,}400 \times \overline{w'(\ln V_h)'}}{-xk_w} , \quad (2)$$

Figure 2

Study site photographs taken in June 2008. (a) Treated site (M1). (b) Untreated site (M2).

(a)

(b)

where $\ln V_h$ is the natural log of the signal voltage from the hygrometer, x (1.210 cm [0.048 in] for the treated site and 1.295 cm [0.051 in] for the untreated site) is the path length of the hygrometer used in this study, and k_w (0.146 m^3 g^{-1} cm^{-1} [371.27 ft^3 oz^{-1} in^{-1}] for both treated and untreated sites) is the absorption coefficient for water vapor.

Then, the LE was converted to a rate of ET as

$$ET = \frac{LE}{L_v} , \quad (3)$$

Figure 3
Photographs of untreated study site taken (a) sortly after the fire that occurred on January 19, 2006, and (b) during the following growing season on July 8, 2006.

(a)

(b)

where L_v changes with sonic temperature (T_s), which is measured by the 3-D sonic anemometer. The linear regression between the two is

$$L_v = 2{,}500 - 2.359T_s \, , \tag{4}$$

which is from Jones 1983.

In addition, a temperature and relative humidity probe was installed at a height of 1.8 m (5.9 ft) (model HMP45C, Vaisala Inc), and a tipping bucket rain gage was installed at a height of 1.5 m (4.9 ft) (model TE525, Campbell Scientific, Inc) at each site. With the availability of additional funding in March 2008, more sensors were installed at both sites to collect microclimate variables, including net radiation at a height of 5.3 m (17 ft) above the ground (model NRLite; Kipp & Zonen), soil heat flux at a depth of 8 cm (3.2 in) below the ground (model HFT3; REBS Inc), soil moisture at a depth of 2.5 cm (1 in) (model CS615; Campbell Scientific Inc), and soil temperature at depths of 2 cm (0.8 in) and 6 cm (2.4 in) (model TCAV; Campbell Scientific Inc). Through these additional measurements, an energy budget for each study site was established to validate the fluxes measured with the EC technique.

Post-Field Data Processing and Energy Balance Closure Assessment. Before the *ET* data were computed through equations 1 to 4, the following corrections were made to the measured *H* and *LE*: (1) correction of the krypton hygrometer data for ultraviolet absorption by oxygen (van Dijk et al. 2003); (2) correction of the sonic temperature for the effect of moisture (Schotanus et al. 1983); (3) two-dimensional rotations to transform the measured fluxes from the sonic anemometer's coordinates into the natural coordinate system (Kaimal and Finnigan 1994; Lee et al. 2004); and (4) Webb-Pearman-Leuning correction to the water vapor flux for the fluctuations of temperature and water vapor (Webb et al. 1980).

Using the corrected *H* and *LE*, the energy balance closure (*D*) was assessed by

$$D = \frac{H + LE}{R_n - G - S} \, , \tag{5}$$

where R_n is net radiation (W m^{-2}), *G* is soil heat flux (W m^{-2}), and *S* is heat storage in soil (W m^{-2}).

Grass Cover Index. To monitor the changes of the surface grasses during the study period, four 1 m^2 (3.28 ft^2) plots were randomly selected at each of the treated and untreated sites. Within each plot, grass-related data, including percentage of overall grass cover, percentages of dead and live grass, grass height, and species, were recorded and photographed beginning in July 2005. The observed grasses at the study area included Texas winter grass (*Stipa leucotricha*), woolly croton (*Croton capitatus*), wildrye (*Elymus sp.*), pepper weed (*Lepidium virginicum*), paleseed plantain (*Plantago virginica*), and western ragweed (*Ambrosia psilostachya*).

To quantitatively reveal the grass cover collected at the mesquite sites, the Grass Cover Index (*GCI*) was developed as follows for each plot in this study:

$$GCI = OGC \times LGC \times (GH/GH_{max}) , \quad (6)$$

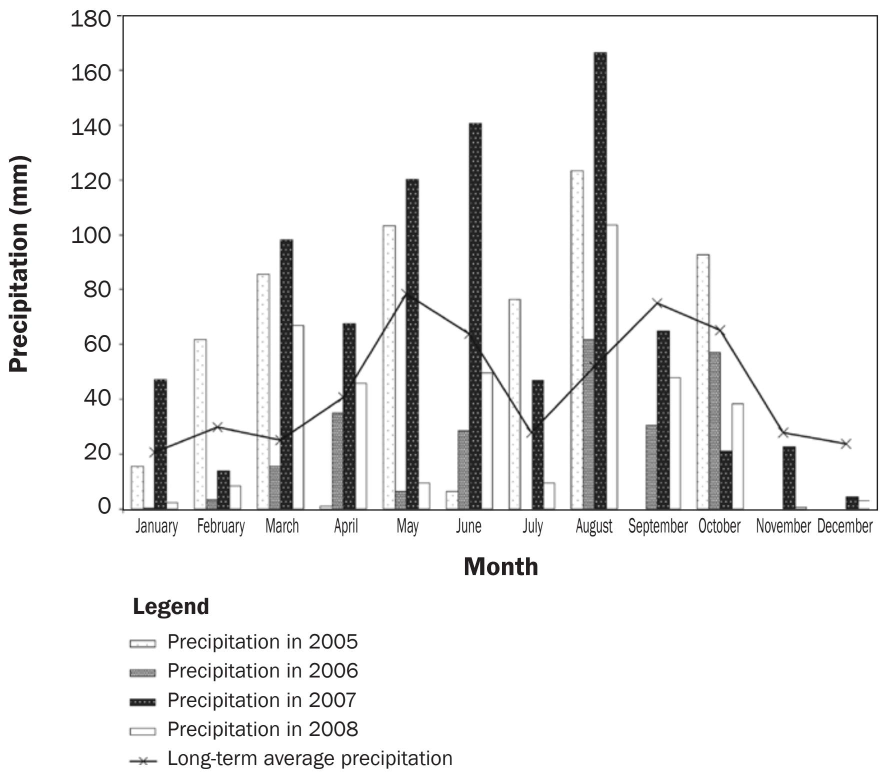
where OGC is the percentage of overall grass cover, LGC is the percentage of live grass cover, GH is grass height, and GH_{max} is maximum grass height during the entire survey period. Therefore, GH/GH_{max} is scaled from 0 to 1. The *GCI* for each site was presented as the average of the four plots.

In addition, several mesquite trees randomly selected within the study area were photographed along with the grass survey to monitor growing stages of the trees.

Data Quality Control Procedures. Although great effort was taken to assure the quality of the data, incidents led to interruptions in the consistency of data collection. For example, during a severe drought, the untreated site was burned by a quickly spreading fire on January 19, 2006. As a result of the fire, winter grass cover was destroyed, and approximately 90% to 95% of the mesquite trees were partially affected. Some of the EC equipment, including battery and wires, was also damaged, resulting in a loss of 24 days of data. However, due to the resilience of mesquite trees and the relatively short duration of the fire, the mesquite root systems along with above-ground biomass were not completely destroyed. Figure 3a shows a picture of a portion of the untreated site right after the fire on January 19, 2006; while figure 3b shows a picture taken of the same location during the following growing season on July 8, 2006. Regrowth of leaves and tree branches of the affected trees occurred during the next growing season (i.e., July 2006). However, the ground surface grass cover was much less compared to the same area in 2005. For instance, the average overall grass cover of the four plots at the untreated site was about 100% in July 2005 but dropped to 40% in July 2006. This slow regrowth of grass cover was due to drought conditions that occurred following the fire (figure 4). Other factors that resulted in the presence of some unreliable or missing values within the *ET* dataset included precipitation events, power supply interruptions, instrument malfunction, and various electrical problems.

Figure 4

Monthly precipitation totals during 2005 through 2008 at the study area are shown along with the long-term average at San Angelo, Texas. The 2007 data were obtained from the National Weather Service Forecast Office at San Angelo.

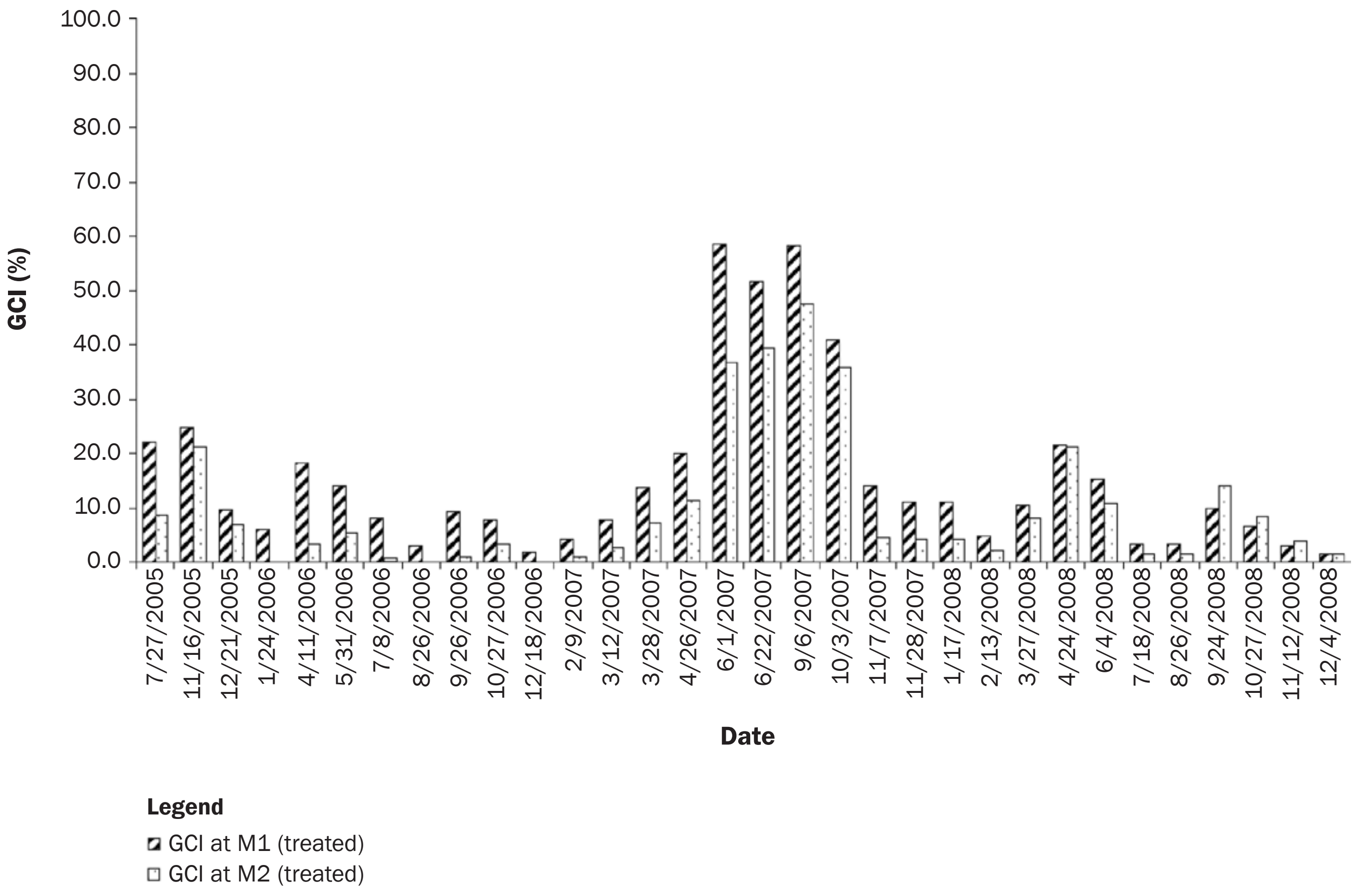


In June 2007, the EC sensors and data loggers were shipped to Campbell Scientific Inc for recalibration, resulting in a three-month interruption of *ET* data collection. The sensors and data loggers were calibrated under identical laboratory conditions by Campbell Scientific Inc, and the calibration data provided by Campbell Scientific Inc indicated that there were no statistically significant differences between instruments. When the sensors and dataloggers were ready for reinstallation in September 2007, the calibrated sensors were exchanged between the two sites. The differences in *ET* recorded between the two sites continued to be similar to what had been recorded prior to shipping the instruments for calibration. This verified that the observed differences in treated and untreated sites were a representation of observed field conditions and not a function of instrumentation.

In this study, the data from periods of weak turbulent mixing (friction velocity less than 0.35 m s^{-1} [1.14 ft sec^{-1}] [Su et al. 2008]) were discarded. Next, an effective approach to identify questionable *ET* data was a comparative analysis in which the concurrently collected EC data and rainfall data from the treated and untreated sites were plotted and compared by visual inspection. Rainfall events helped identify the problem sources (from instrument malfunction or weather). If over any time interval (1) the paired data had large discrepancies, (2) either site had missing data, or (3) either site had out-of-range data, the calculated ET data for that time interval at both sites were rejected, since this was a paired site study. If the questionable data were from a single 30-minute interval record, and the data immediately preceding and following were good, the questionable data were interpolated from the before and after data points.

Cumulative Evapotranspiration at Different Time Scales. To demonstrate the difference in *ET* between the two sites over various time scales, the estimated 30-minute interval *ET* data were converted into daily, weekly, and monthly time scales. The cumulative *ET* values were calculated using data obtained during an optimum period of *ET* activity from 9 a.m. to 6 p.m. Central Standard Time (when net radiation > 0 W m^{-2}), rather than a complete 24-hour period

Figure 5
Grass Cover Index (GCI) during 2005 through 2008.



of record. Cleverly et al. (2002) set criteria to determine whether to estimate daily ET with missing data. Similarly, the daily, weekly, or monthly *ET* would not be computed if the missing data exceeded 50% of the corresponding time period. It is important to note that the daily, weekly, and monthly *ET* values presented in this study are for comparison purposes only, and the data do not represent the actual measured daily, weekly, and monthly *ET* values, because questionable data were rejected, and missing records occurred.

Statistical Analyses on Evapotranspiration Data. The nonparametric matched-pair statistical test (Helsel and Hirsch 2002) was performed using the PROC UNIVARIATE program within Statistical Analysis Systems (SAS Institute, Inc, Cary, North Carolina, USA) to determine whether the *ET* data at the untreated site were statistically significantly (α = 0.05) different from those at the treated site. A nonparametric method was employed because the distribution of the *ET* values used in this study was unknown.

Results and Discussion

Precipitation and Grass Cover Index during Study Period. Precipitation records obtained from onsite rain gages and supplemented by the NWS gages were compared to the long-term average annual precipitation of 566 mm (22.3 in) for the San Angelo area (figure 4). This comparison revealed that the study period included a nearly normal rainfall year in 2005 (566 mm [22.3 in]), two dry years in 2006 (267 mm [10.5 in]) and 2008 (386 mm [15.2 in]), and a wet year in 2007 (814 mm [32.0 in]).

Figure 5 illustrates the distribution of the *GCIs* computed by equation 6 during the study period. Overall, the Grass Cover Indexs (*GCIs*) at the treated site were greater than at the untreated site. The greater *GCIs* recorded at the treated site are due to the lack of competition for water and sunlight from active shallow lateral roots of mesquite trees and associated canopy cover (Ansley et al. 2004). The *GCI* at the untreated site in January 2006 was zero because of the fire event during that month. However, the new grasses started to grow back in the spring. In addition to the fire, 2006 was very dry, leading to the *GCIs* at both sites to be much lower than in 2007, in which moisture supply was abundant. Similar to 2006, low *GCI* values were observed in 2008 for both sites due to below average rainfall.

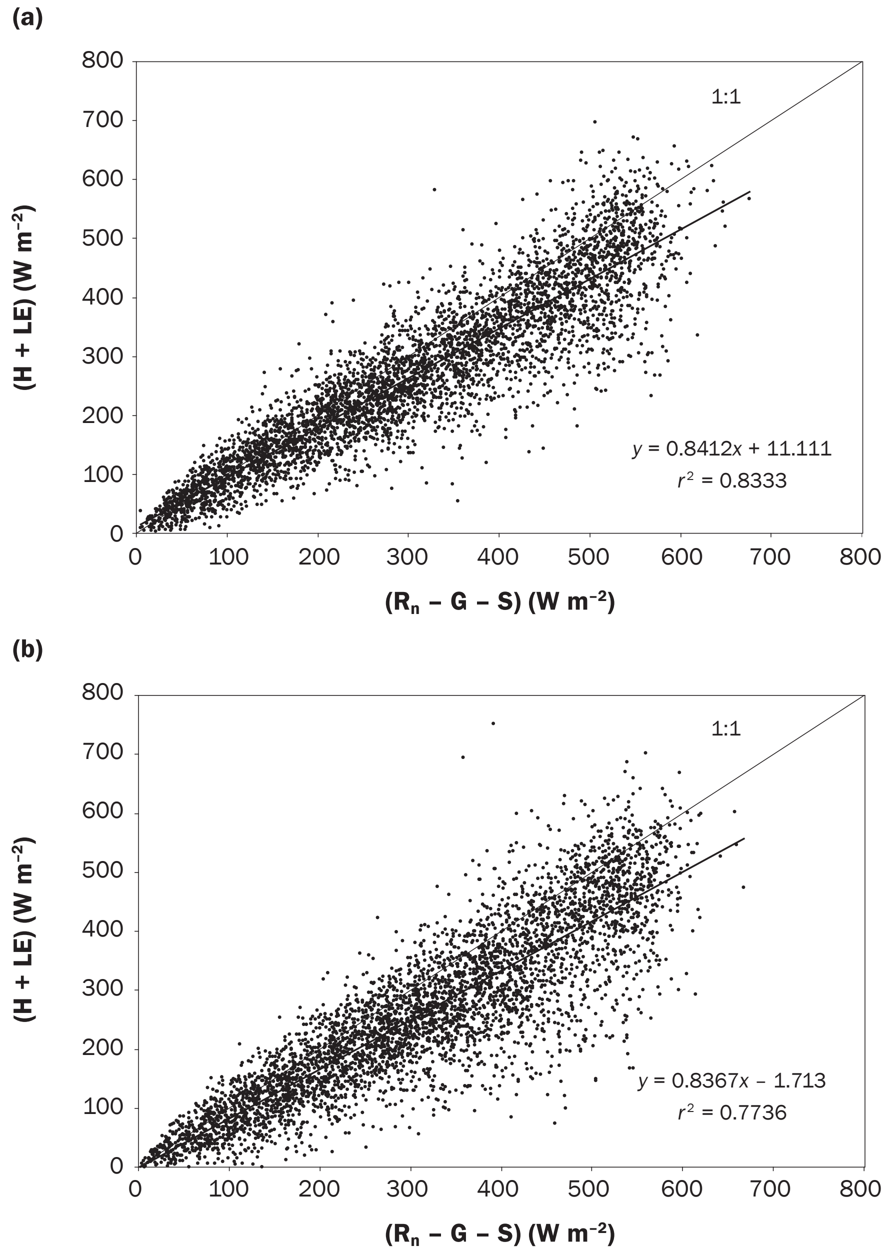
Energy Balance Closure Evaluation. The straight-line regressions between $H + LE$ and $R_n - G - S$ at the treated and untreated sites during daytime (9 a.m. to 6 p.m.) when the *ET* data were considered in this study, from March through December 2008, are displayed in figures 6a and 6b. The intercept and slope between $H + LE$ and $R_n - G - S$ were 0.84 and 11.1 W m^{-2} and 0.84 and 1.71 W m^{-2} for the treated and untreated sites, respectively. The r^2 was 0.83 for the treated site and 0.77 for the untreated site. The average daytime closure rate was 0.90 for the treated site and 0.83 for the untreated site. Even though energy balance closure information was not collected prior to March 2008, the newly obtained energy balance closure data indicate that the *ET* measured by EC at the treated and untreated sites are acceptable, and thus, the measured fluxes from the two sites can be used to perform comparisons.

Evapotranspiration Comparison at Daily Scale. The paired *ET* data accumulated at a daily scale from the two sites during the observation period, along with the corresponding daily rainfall, are illustrated in figures 7a, 7b, 7c, and 7d for each year. Any breaks along the graph lines represent missing data for that specific period (e.g., day). The operation of the EC system at both sites started on April 7, 2005, when the winter grasses at both sites were still alive and the mesquite trees at the untreated site had started to leaf out, resulting in the fairly high *ET* rates recorded during this time (figure 7a). The first autumn freeze occurred on November 16, 2005. As a result, the *ET* rate fell rapidly because the mesquite trees started to lose leaves due to freezing temperatures and go dormant during the winter. Also, the *GCI* values decreased from 20% in mid-November to less than 10% in late December at both sites. Similar results were reported by Scott et al. (2000). In 2006, the last spring freeze was recorded on March 24, and the first autumn freeze was on November 16, which resulted in significant variations in *ET* rates (figure 7b). In 2007, March 4 was the last spring freeze, and November 22 was the first fall freeze (figure 7c). December 2007 data were missing due to an equipment problem at the treated site. The last spring freeze in 2008 was March 8 (figure 7d).

Based on the measured daily *ET* during the four-year study period, *ET* values at both sites were low but similar during the first three months of each year. However, during the start of the growing season (April), the *ET* at the treated site exceeded the untreated site for a brief period. This is attributable to a lack of mesquite tree leaf emergence at both sites and higher surface grass cover at the treated site (indicted by higher *GCI* at this site as compared to the untreated site) during this period. The month of May was a transition time, in which the *ET* at the untreated site gradually surpassed the treated site as mesquite trees became very active in water use. The higher values of *ET* at the untreated site,

Figure 6

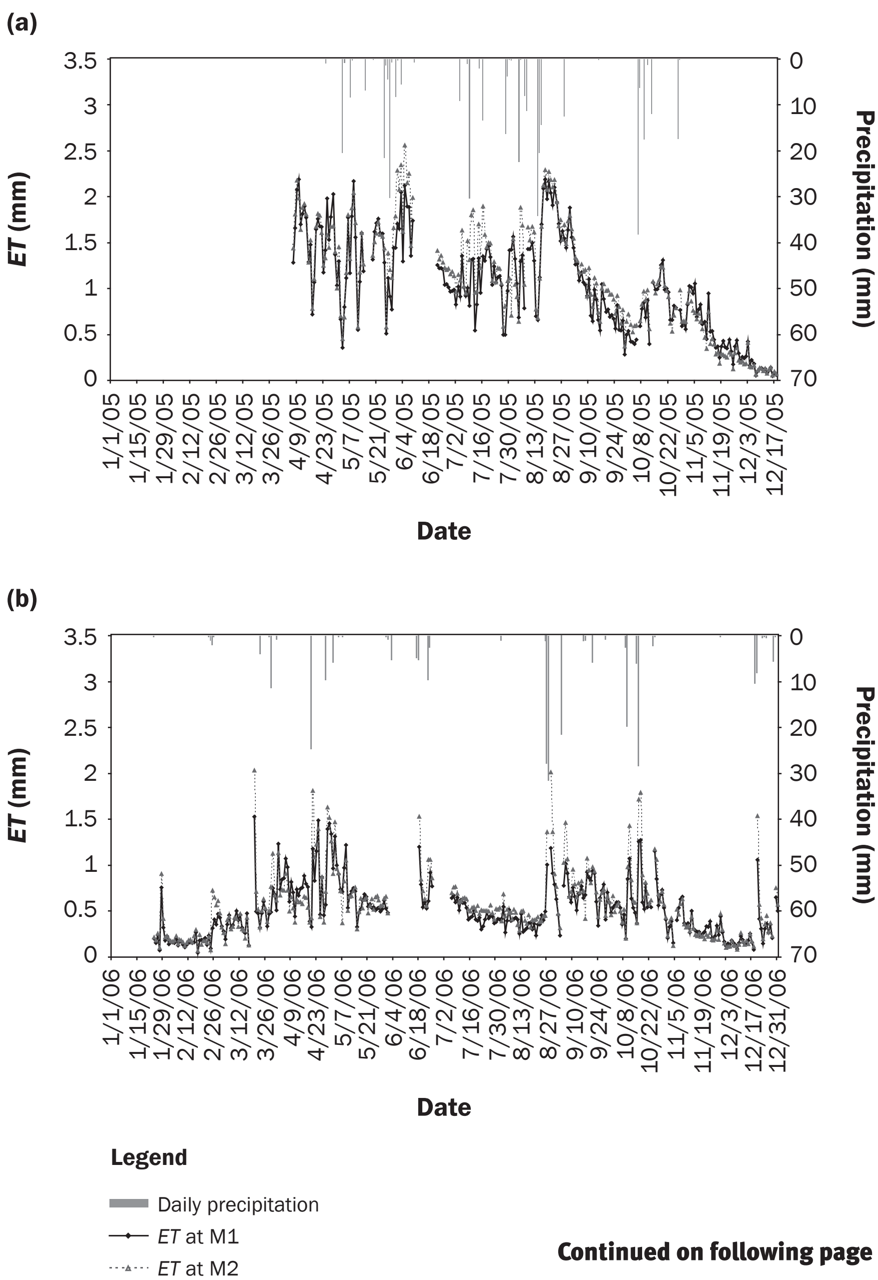
(a) Surface energy balance closure at the treated site (M1) for the period of March through December 2008. (b) Surface energy balance closure at the untreated site (M2) for the period of March through December 2008.



with living mesquite trees, as compared to that of treated site with dead trees, increased during the June to September time period. According to Ansley et al. (1997), the annual growth cycle of mesquite trees starts with a six-week period of leaf emergence and twig elongation from April and May, followed by a period of radial stem growth. Thus, by June, mesquite tree leaves were fully mature, resulting in a high transpiration rate. During July to August 2006 when severe drought occurred in the study area, vegetative growth of the mesquite subsided with the onset of summer drought (Mooney et al. 1977). Thus, it was observed that *ET* values from both sites were unusually low (below 0.5 mm [0.02 in]). However, due to more water consumption by mesquite trees, *ET* at the untreated site still consistently exceeded that of the treated site. After the growing season

Figure 7

(a) Evapotranspiration (*ET*) accumulated at a daily scale at the treated (M1) and untreated (M2) sites and the precipitation in 2005. (b) Evapotranspiration accumulated at a daily scale at the M1 and M2 sites and precipitation in 2006. (c) Evapotranspiration accumulated at a daily scale at the treated M1 and untreated M2 sites and precipitation in 2007. (d) Evapotranspiration accumulated at a daily scale at the treated M1 and untreated M2 sites and precipitation in 2008.



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was over, once again the *ET* values dropped and became similar at both sites. In addition, it was observed that the *ET* values increased following significant rainfall events, and the differences in *ET* between the untreated and treated sites increased in most cases.

During September 2007, the EC systems were switched between the sites. As shown in figures 7c and 7d, *ET* at the untreated site exceeded the treated site most of the time during September and early October 2007, and the overall tendency of *ET* values went down as the end of the growing season approached. The comparison pattern in *ET* for the first half of 2008 was similar to the previous years.

Evapotranspiration Comparison at Weekly Scale. Figure 8 displays the paired *ET* accumulated at a weekly scale at both sites during the study period. Before June 2005, the *ET* values were similar at the two sites. As the mesquite trees became the dominant vegetation at the untreated site during the period of June to mid-October 2005, the measured *ET* values at the untreated site exceeded the treated site in most weeks. In November, the *ET* at the treated site was slightly higher than the untreated site. By this time, the mesquite growing season was over and trees went into dormancy. The only source of transpiration was from the grasses, which were more abundant at the treated site ($GCIM_1$ = 25%; $GCIM_2$ = 21%) (figure 5). During December, *ET* at the treated site was either slightly higher or the same as compared with the untreated site; where *GCI* at the treated site was 10%, it was only 7% at the untreated site. From January to March 2006, *ET* rates at both sites were very similar. However, *ET* at the untreated site was lower than the treated site in April and became higher than the treated site in May. From June through October 2006, the weekly *ET* at the untreated site was consistently higher than that of the treated site. In November 2006, *ET* at the treated site was slightly higher. During the first two weeks of December 2006, *ET* of the two sites was about the same. However, *ET* became slightly higher at the untreated site during the last two weeks of December 2006. It is believed that the unusually high rainfall (about 20 mm [0.79 in]) prior to and during the last two weeks caused a high bare soil evaporation at the untreated site. This was because the major portion of surface vegetation, which was destroyed by the fire, recovered at a much lower rate under severe drought during the growing season.

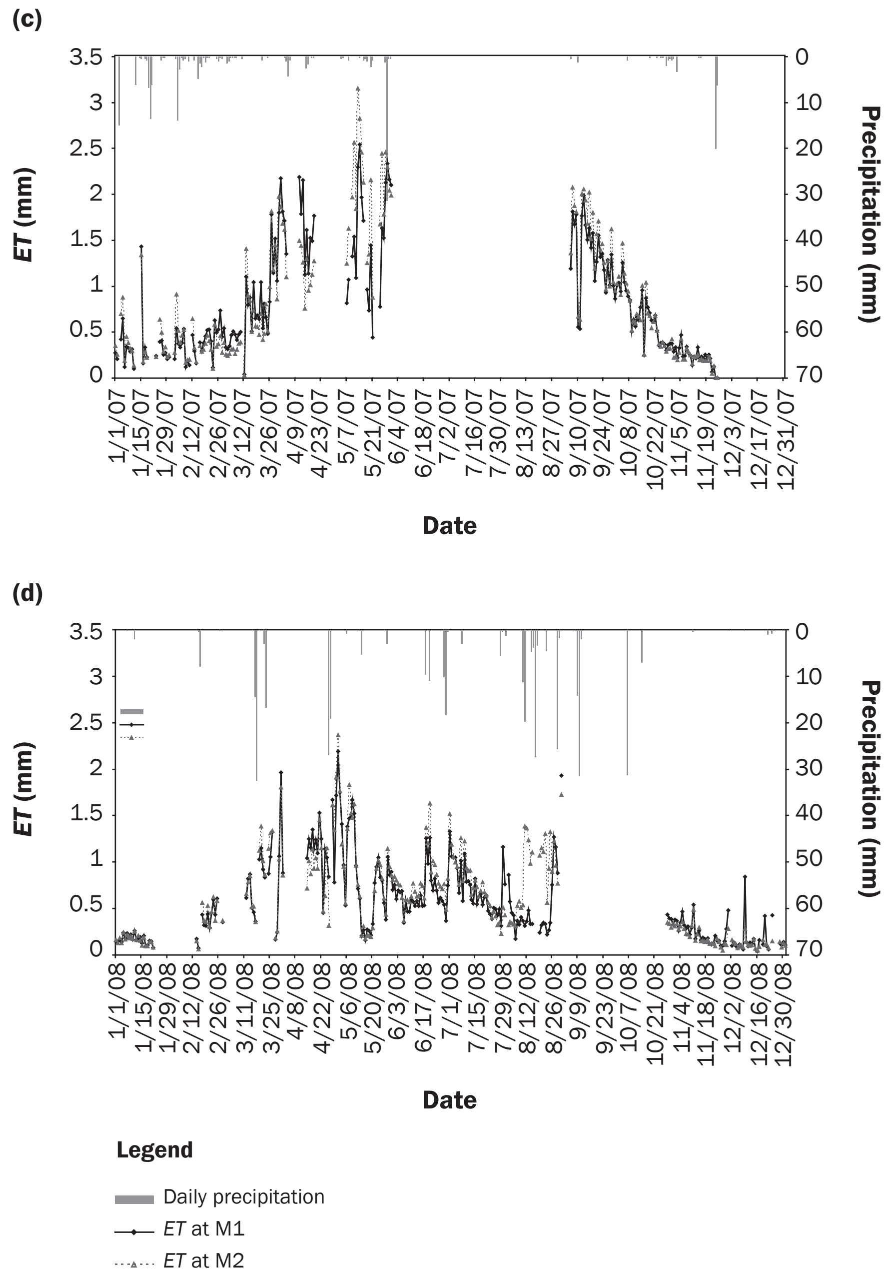
In January and February 2007, the *ET* at the untreated site either slightly exceeded or equaled the treated site. In March and April, *ET* at the treated site surpassed the untreated site because the surface grass cover, as indicated by *GCI* values, was higher at the treated site than at the untreated site (the average *GCI* was 14% at the treated site, as compared to 7% at the untreated site). In May when the mesquite trees became more active in transpiration, *ET* at the untreated site surpassed that of the treated site again. After the exchange of EC systems between the treated and untreated sites in September 2007, similar to past years, ET rates at the untreated site were greater than at the treated site at the end of the season and became similar during the mesquite dormant season.

Evapotranspiration Comparison at Monthly Scale. Figure 9 illustrates the variation of accumulated differences in ET ($\Delta ET = ET_{M2} - ET_{M1}$) at a monthly scale during the study period. The differences exhibited large variations over the seasons. During the mesquite dormant season, the differences in ET were small in magnitude (either positive or negative, and most were less than 2 mm [0.08 in] per month). During the mesquite growing season, the differences were of a larger positive magnitude (all were greater than 2 mm [0.08 in] per month, and the largest difference reached more than 10 mm [0.39 in] per month in August 2008).

Evapotranspiration Comparison at Yearly Scale. Figures 10a to 10d show the annual cumulative ET for both sites. From early April through the end of May 2005, a negligible difference in ET was obtained for both sites (ΔET = 1 mm [0.04 in]) (figure 10a). From June through October of 2005, field observations and measured data indicated that mesquite trees became the main source of ET at the untreated site as compared to the treated. Correspondingly, the accumulated ΔET reached its maximum (19 mm [0.75 in]) by November 1. By the end of 2005, the net accumulated ΔET was 16 mm (0.63 in). A higher ET was measured at the treated site during November to December because of more surface grass growth at the treated site (GCI_{M1} = 24.8% in November and 9.7% in December as compared to GCI_{M2} = 21.3% and 6.9%). The effect of the fire that occurred in January 2006 was apparent in that from January 1, 2006, to the end of May, the accumulated ΔET was only about 2 mm (0.08 in) (figure 10b). Beginning in June, the differences consistently became greater until early November of 2006, when the ΔET reached its maximum (13.3 mm [0.52 in]). This increase in ΔET is the result of regrowth of mesquite and grass at the untreated site during the growing season following the fire.

The accumulated ΔET was about 7.5 mm (0.30 in) in mid-October (figure 10c). This was lower than expected mainly because of the lack of measurements from June to early September while the equipment was being recalibrated. The ET at the untreated site exceeded the ET at the treated site by about 7 mm (0.28 in) by the end of December 2008 (figure 10d).

Figure 7
Continued.



Seasonal Change in Evapotranspiration Differences. To reflect the differences in ET during different growing stages, the individual months were grouped into five periods: dormancy period (January to March), pregrowing period (April), growing period (May to October), peak-growing period (June to September), and dormancy period (November to December). Table 1 summarizes the total ET for each site, total precipitation, and the overall differences in ET between the two sites over the five periods. The total difference in ET between untreated and treated sites for the entire growing season of 2005 was 19.4 mm (0.76 in). Thus, ET at the untreated site was about 10% higher than at the treated site. The percentage difference increased slightly to 12% during May to October 2006. The total precipitation in the same period was 402 mm

Figure 8
Evapotranspiration (*ET*) accumulated at a weekly scale at the treated (M1) and untreated (M2) sites and precipitation during 2005 to 2008.

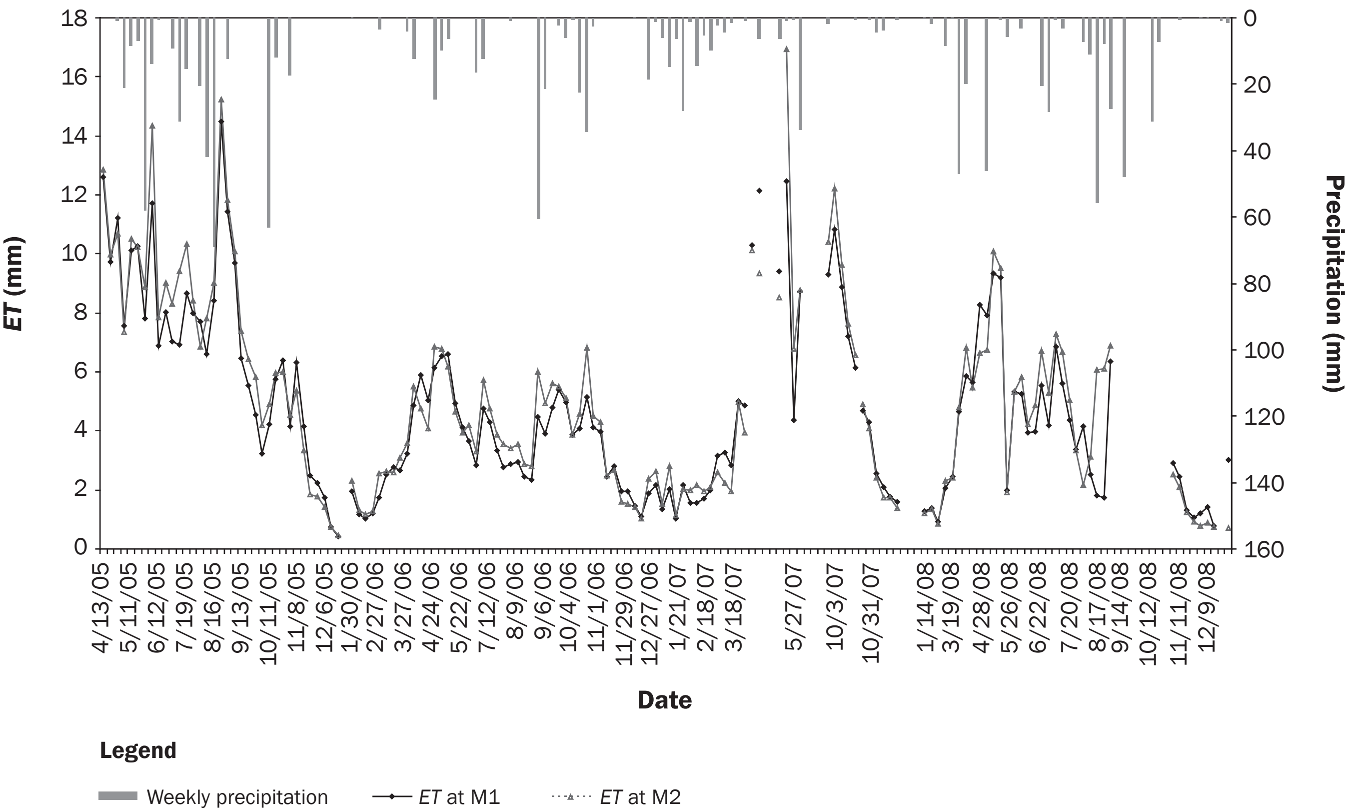


Figure 9
Difference in evapotranspiration ($ET_{M2} - ET_{M1}$) accumulated at a monthly scale during 2005 to 2008.

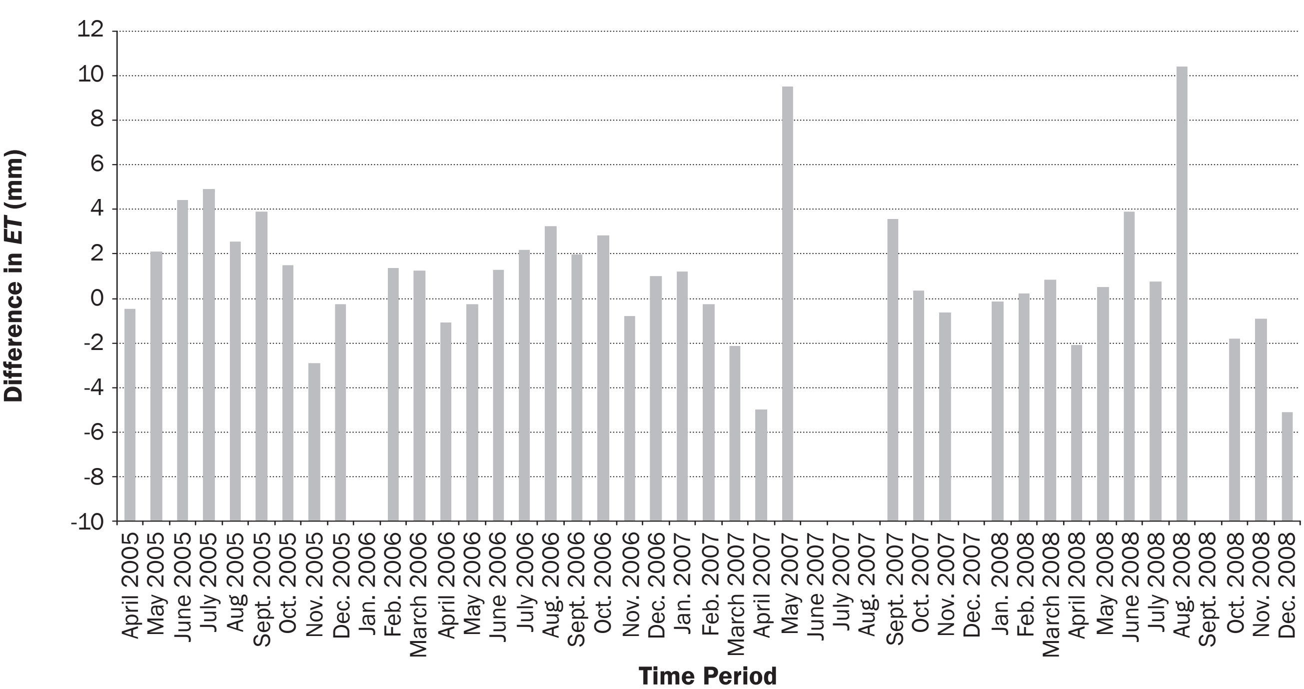
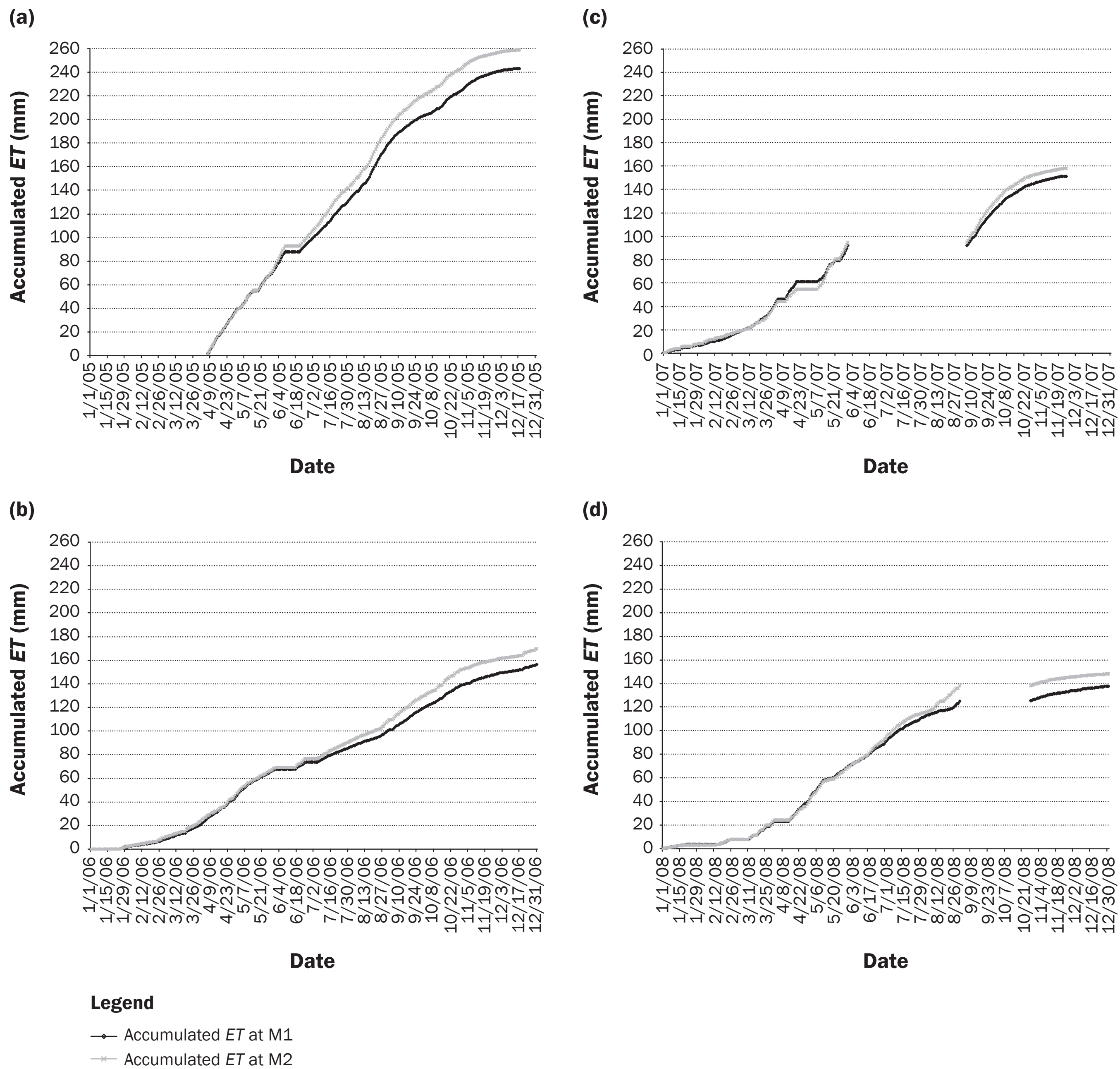


Figure 10

(a) Accumulated evapotranspiration (*ET*) in 2005. (b) Accumulated *ET* in 2006. (c) Accumulated *ET* in 2007. (d) Accumulated *ET* in 2008.



(15.8 in) in 2005 and 187 mm (7.36 in) in 2006. Measurements obtained during the peak mesquite growing season revealed that the *ET* at the untreated site was about 12% higher in 2005, 17% higher in 2006, and 25% higher in 2008 as compared to what was measured at the treated site. Recorded precipitation during the peak mesquite growing season was 299 mm (11.8 in) in 2005, 121 mm (4.76 in) in 2006, and 163 mm (6.42 in) in 2008. This indicates that during dry periods when surface grass growth is limited (e.g., dormant) the mesquite trees seem to become the dominant agent of water uptake from the soil profile.

In 2007, although data during the critical periods of the growing season were missing, the total difference in *ET* during the months of May, September, and October was 13 mm (0.51 in), indicating *ET* at the untreated site was 16% higher than at the treated site with precipitation of 49 mm (1.93 in) during this short period.

During the peak growing season of 2008, the largest observed difference in *ET* between sites was recorded. The difference in *ET* during this period was approximately 13.6 mm (0.54 in), which represents a difference in *ET* of 25%.

Based on 952 daily measurements obtained throughout the four-year study, the experimental data indicated that the mesquite-dominated untreated site had a net consumption of over 46 mm (1.8 in)

Table 1

Summary of measured *ET* and rainfall over various time periods for treated and untreated sites. Time periods were divided into five groups based on the growing periods: dormancy period (January to March), pregrowing period (April), growing period (May to October), peak-growing period (June to September), and dormant period (November to December).

Year	Time period	Total rainfall over the time period (mm)	Total ET over the period (mm) Treated	Untreated	*ET* difference ($ET_{M2} - ET_{M1}$) (mm)	Number of measured days and (potential days)
2005	Pregrowing	0.90	38.0	37.6	–0.40*	24 (30)
	Growing	402	186	206	19.4	164 (184)
	Peak-growing	206	131	146	15.7	109 (122)
	Dormant	0	19.0	15.8	–3.20*	48 (61)
	Total of 2005	403	243	259	15.8	236 (275)
2006	Dormancy†	19.3	18.5	21.1	2.60	57 (90)
	Pregrowing	35.1	24.7	23.6	–1.10*	30 (30)
	Growing	187	93.8	105	11.3	155 (184)
	Peak-growing	121	52.7	61.4	8.70	94 (122)
	Dormancy	25.9	17.3	17.5	0.20	58 (61)
	Total of 2006	267	154	167	13.0	300 (365)
2007	Dormancy	89.4	39.3	38.1	–1.20*	76 (90)
	Pregrowing	11.2	21.8	16.9	–4.90	13 (30)
	Growing‡	48.5	84.5	97.9	13.4	76 (184)
	Dormancy‡	30.7	5.7	5.0	–0.70*	23 (61)
	Total of 2007	180	151	158	6.60	188 (365)
2008	Dormancy‡	69.1	17.8	18.5	0.70	38 (90)
	Pregrowing	46.0	19.6	17.5	–2.10*	17 (30)
	Growing	172	83.0	97.2	14.2	118 (184)
	Peak-growing	163	55.8	69.4	13.6	87 (122)
	Dormancy	3.66	11.3	9.02	–2.28*	55 (61)
	Total of 2008	291	132	142	10.5	228 (365)

* *ET* at treated site is greater than the untreated site.

† January is not included due to the fire incident.

‡ Months missing due to insufficient data.

more water than the treated site. The results above were obtained from actual days of valid observations and do not represent the total potential water consumed during the entire study period. In an effort to obtain an estimate of the total potential difference, the actual recorded difference between sites was extrapolated to the total potential number of days within the study period of April 2005 through December 2008 (1,370 days). Extrapolation of the data to include every day of the four-year study period indicated that the mesquite-dominated untreated site yielded a net usage of about 71 mm (2.8 in) more water than the treated site. Truncation of the data set to include only measurements obtained during the months within the mesquite growing season indicated that water consumption at the untreated site was 58 mm (2.3 in) higher than at the treated site and is the sum of 513 daily measurements. The extrapolation of the data set to include every potential day within the growing season (732) resulted in an estimated potential of 90 mm (3.5 in) of water use by the untreated site as compared to the treated site, assuming measurements of *ET* were obtained each day of the 184-day growing season during each of the four years. When quantifying how much groundwater was being used by sacaton grassland and mesquite trees, Scott et al. (2000) confirmed that grasses relied primarily on the near surface water from recent precipitation, while the mesquite trees could obtain water from deeper in the soil profile. During the dry period when the surface lacks moisture, most of the surface grasses, therefore, become inactive, and the live mesquite trees become the dominant consumers of water.

Nonparametric Matched-pair Test. The monthly nonparametric matched-pair test results, including *p*-values, means of differences, and conclusions based on the *p*-values and means, are summarized in table 2. From June through September, during the peak mesquite growing season, *ET* at the untreated site was consistently statistically significantly greater (at $\alpha = 0.05$) than at the treated site, with the exception of July 2008. On the other hand, *ET* at the treated site always was statistically significantly greater than at the untreated site in November when the surface grasses at the treated site were more abundant than at the untreated site and mesquite trees were dormant. For the remaining months, no consistent trends were detected.

Summary and Conclusions

A study was conducted on two adjacent sites within the North Concho River watershed, located in West Central Texas. The goal of this study was to investigate changes in the total water budget with implementation of brush control. Field *ET* values were measured with the eddy covariance technique from two 80 ha (200 ac) mesquite-dominated sites. On the treated site, mesquite trees were killed with herbicide, while no herbicide application occurred at the untreated site. The study period included a year with nearly normal precipitation (2005), two years with much lower than average precipitation (2006 and 2008), and a year with abundant precipitation (2007).

The *ET* comparative analyses at various time scales throughout the years showed that differences in *ET* between the untreated and treated sites were negligible during the dormancy season of the mesquite trees. The results also showed that the *ET* values at the untreated site exceeded the *ET* values at the treated site typically during the period from May to October. As mesquite trees became more active in transpiration, the maximum cumulative ΔET ($ETM_2 - ETM_1$) was typically measured by the end of October or early November. Quantitatively, for the paired data available, the *ET* at the untreated site was about 10% higher than the treated site for the entire growing season of 2005, with precipitation of 402 mm (15.8 in). The percentage increased to 12% in 2006, with lower precipitation of 187 mm (7.36 in). During the peak mesquite-growing period in 2005, the *ET* at the untreated site was about 12% higher than the treated site, with precipitation of 299 mm (11.8 in). During this same time period in 2006, *ET* at the untreated site was about 17% higher than at the treated site with precipitation of only 121 mm (4.76 in). The results also showed that based on partial growing season observations, *ET* at the untreated site was 16% higher than at the treated site during 2007. The highest recorded percent difference in *ET* between sites was 25% and occurred in 2008 during the peak growing season in which the measured *ET* was 14 mm (0.55 in) more at the untreated site. The nonparametric matched-pair test results indicated that the *ET* at the untreated site was statistically significantly greater than the treated site from June through September at a 95% confidence level.

Table 2
Results of nonparametric matched-pair test (α = 0.05).

Time period	Mean of difference (per day)	*p*-value	Conclusion
April 2005	−0.01888	0.97793	ns
May 2005	0.07837	0.00744	+
June 2005	0.24578	0.00001	+
July 2005	0.15853	0.00002	+
August 2005	0.08521	0.00554	+
September 2005	0.12937	0	+
October 2005	0.05386	0.00878	+
November 2005	−0.09768	0	–
December 2005	−0.01397	0.26453	ns
January 2006	0.04453	0.01563	+
February 2006	0.04832	0.00054	+
March 2006	0.04225	0.5054	ns
April 2006	−0.03639	0.05012	ns
May 2006	−0.00898	0.65962	ns
June 2006	0.14419	0.00781	+
July 2006	0.0846	0	+
August 2006	0.10836	0.00006	+
September 2006	0.06853	0.0007	+
October 2006	0.09396	0.00084	+
November 2006	−0.02779	0.00226	–
December 2006	0.03485	0.08145	ns
January 2007	0.05742	0.00297	+
February 2007	−0.01123	0.48708	ns
March 2007	−0.07127	0.01213	–
April 2007	−0.38439	0.00024	–
May 2007	0.4748	0.00003	+
September 2007	0.14331	0	+
October 2007	0.0109	0.55222	ns
November 2007	−0.0277	0.0001	–
January 2008	−0.00692	0.03859	–
February 2008	0.01944	0.2334	ns
March 2008	0.04935	0.08865	ns
April 2008	−0.12279	0.03052	–
May 2008	0.01711	0.3866	ns
June 2008	0.12832	0	+
July 2008	0.0257	0.056	ns
August 2008	0.3470	0.0019	+
October 2008	−0.0553	0.2500	ns
November 2008	−0.0388	0	–
December 2008	−0.1707	0.2880	ns

Notes: + = $ET_{untreated}$ is statistically significantly greater than $ET_{treated}$. – = $ET_{treated}$ is statistically significantly greater than $ET_{untreated}$. ns = *ET* between the two sites is not statistically significantly different.

Based on a total of 952 daily measurements obtained during the fouryear study period, the mesquite-dominated untreated site had consumed over 46 mm (1.8 in) more water than the treated site. Extrapolation of the data to include every potential day that *ET* could have been recorded during the study period (1,370 days) indicated that the untreated site had a potential net consumption of about 71 mm (2.8 in) more water over the four-year period than the treated site. Truncation of the data set to include only the 513 daily values recorded during the mesquite growing season for each year indicated that the untreated site had consumed approximately 58 mm (2.3 in) more water than the treated site. Extrapolation of the growing season dataset to include every day of the 184-day growing season (732 days) over the four-year period indicated that the total potential water consumption at the untreated site would exceed that of the treated site by about 90 mm (3.5 in).

Although efforts to collect *ET* data during the pretreatment period failed, and the results presented here were obtained after imposition of the treatment, the seasonal *ET* variations demonstrate that the reduced *ET* at the treated site was caused by killing of living mesquite trees rather than systematic differences in *ET* between the two sites. The consistency of the field observations with measured values by the EC technique indicates the dependability and accuracy of this method. It is also believed that the accumulated *ET* values for each site and the overall *ET* differences between the two sites could be actually larger than the values presented in this paper. This is because questionable data were not taken into account in the statistical analyses. The results from this study are consistent with the fact that mesquite trees can take advantage of their shallow lateral roots to compete for surface moisture with grasses, and of their deep roots to take up water from lower in the soil profile and shallow groundwater when the surface becomes very dry during drought and typical Texas summers. The consistency of field observations with *ET* values measured by the EC system indicates the dependability and accuracy of this system. Ultimately, this study suggests that a brush control approach has great potential for increasing water yield in the Concho River Watershed, which could support the further development and sustainability of San Angelo and its surrounding communities.

Acknowledgements

We acknowledge and thank the Texas State Soil and Water Conservation Board and its Water Supply and Enhancement Program for funding this research. Mention of trade names or commercial products does not constitute endorsement or recommendation for use.

References

Ansley, R.J. 2005. How much of a water thief is mesquite? The Cattleman 92(1):20-32.

Ansley, R.J., J.A. Huddle, and B.A. Kramp. 1997. Mesquite ecology. *In* Proceedings of Brush Sculptors Symposium, ed. Rollins, D.N. Ueckert, and C.G. Brown, 21-25. Uvalde, August 21-22 and Abilene, Sept. 17-18, 1997, TAEX Misc. Pub. San Angelo: TAES.

Ansley, R.J., P.W. Jacoby, and G.J. Cuomo. 1990. Water relations of honey mesquite following severing of lateral roots: Influence of location and amount of subsurface water. Journal of Range Management 43(5):436-442.

Ansley, R.J., W.E. Penchak, W.R. Teague, B.A. Kramp, D.L. Jones, and P.W. Jacoby III. 2004. Long-term grass yields following chemical control of honey mesquite. Journal of Range Management 57:49-57.

Ansley, R.J., X.B. Wu, and B.A. Kramp. 2001. Observation: Long-term increase in mesquite canopy cover in a North Texas savanna. Journal of Range Management 54(2):171-176.

Bidlake, W.R. 2000. Evapotranspiration from a bulrush-dominated wetland in the Klamath Basin, Oregon. Journal of the American Water Resources Association 36(6):1309-1320.

Cleverly, J.R., C.N. Dahm, J.R. Thibault, D.J. Gilroy, and J.E. Coonrod. 2002. Seasonal estimates of actual evapotranspiration from Tamarix ramosissima stands using three-dimensional eddy covariance. Journal of Arid Environments 52:181-197.

Griffin, R.C., and B.A. McCarl. 1989. Brushland management for increased water yield in Texas. Water Resources Bulletin 25(1):175-186.

Helsel, D.R., and R.M. Hirsch. 2002. Statistical methods in water resources: Techniques of water resources investigations. *In* Hydrologic Analyses and Interpretation, Chapter A3. US Geological Survey. http://pubs.usgs.gov/twri/twri4a3/.

Hinnert, A.R. 1983. Water yield improvement potential by vegetation management on western rangelands. Water Resources Bulletin 19(3):375-381.

Jones, H.G. 1983. Plant and microclimate: A quantitative approach to environmental plant physiology. Cambridge University Press, Cambridge.

Kaimal, J.C., and J.J. Finnigan. 1994. Atmospheric Boundary Layer Flows: Their Structure and Measurement. New York, NY: Oxford University Press.

Laxson, J.D., W.H. Schacht, and M.K. Owens. 1997. Above-ground biomass yields at different densities of honey mesquite. Journal of Range Management 50(5):550-554.

Lee, X., J. Finnigan, and K.T. Paw U. 2004. Coordinate systems and flux bias error. *In* Handbook of Micrometeorology, ed. Lee, X., W. Massman, and B. Law, 33-66. Dordrecht: Kluwer Academic Publishers.

Mooney, H.A., B.B. Simpson, and O.T. Solbrig. 1977. Phenology, morphology, physiology. *In* Mesquite—Its Biology in Two Desert Ecosystems, US/IBP Synth Series No. 4, ed. B.B. Simpson, 26-41. Stroudsburg, PA: Dowden, Hutchinson and Ross, Inc.

NWS (National Weather Service). 2008. National Weather Service Forecast Office San Angelo, TX. http://www.srh.noaa.gov/sjt/html/climate/climo.html.

Schotanus, P., F.T.M. Nieuwstadt, and H.A.R. DeBruin. 1983. Temperature measurement with a sonic anemometer and its application to heat and moisture fluctuations. Boundary-Layer Meteorology 26:81-93.

Scott, R.L., W.J. Shuttleworth, D.C. Goodrich, and T. Maddock. 2000. The water use of two dominant vegetation communities in a semiarid riparian ecosystem. Agricultural and Forest Meteorology 105:241-256.

Smith, R. 2000. Brush control project will improve rangeland, Concho River stream flow. Southwest Farm Press. http://southwestfarmpress.com/mag/farming_brush_control_project/index.html.

Su, H.B., H.P. Schmid, C.S.B. Grimmond, C.S. Vogel, and P.S. Curtis. 2008. An assessment of observed vertical flux divergence in long-term eddy-covariance measurements over two Midwestern forest ecosystems. Agricultural and Forest Meteorology 148(2):186-205.

Texas Water Development Board. 2006. 2007 State Water Plan. http://www.twdb.state.tx.us/wrpi/swp/swp.htm.

Tiedemann, A.R., and J.O. Klemmedson. 2004. Responses of desert grassland vegetation to mesquite removal and regrowth. Journal of Range Management 57:455-465.

Thurow, T.L., A.P. Thurow, and M.D. Garriga. 2000. Policy prospects for brush control to increase off-site water yield. Journal of Range Management 53:23-32.

Twine, T.E., W.P. Kustas, J.M. Norman, D.R. Cook, P.R. Houser, T.P. Mayers, J.H. Prueger, P.J. Starks, and M.L. Wesely. 2000. Correcting eddy-covariance flux underestimates over a grassland. Agricultural and Forest Meteorology 103:279-300.

van Dijk, A., W. Kohsiek, and H.A.R. DeBruin. 2003. Oxygen sensitivity of krypton and Lyman-alpha hygrometers. Journal of Atmospheric and Oceanic Technology 20:143-151.

Walker, J.W., F.B. Dugas, F. Baird, S. Bednarz, R. Muttiah, and R. Hicks. 1998. Site selection for publicly funded brush control to enhance water yield. *In* Proceedings of Water for Texas Conference, Austin, Texas, Texas A&M University, College Station, Texas, December 1998.

Warren, A., J. Holechek, and M. Cardenas. 1996. Honey mesquite influences on Chihuahuan desert vegetation. Journal of Range Management 49:46-52.

Webb, E.K., G.I. Pearman, and R. Leuning, 1980. Correction of flux measurements for density effects due to heat and water vapor transfer. Quarterly Journal of The Royal Meteorological Society 106:85-100.

Wilcox, B.P., W.A. Dugas, M.K. Owens, D.N. Ueckert, and C.R. Hart. 2005. Shrub control and water yield on Texas rangelands: Current state of knowledge. Texas Agricultural Experiment Station Research Report 05-1. College Station.

Wu, X.B., E.J. Redeker, and T.L. Thurow. 2001. Vegetation and water yield dynamics in an Edwards Plateau watershed. Journal of Range Management 54:98-105.

doi:10.2489/jswc.65.4.83A

READERS' FORUM

Commentary on "Effect of brush control on evapotranspiration in the North Concho River watershed using the eddy covariance technique" by Saleh et al. (2009)

Bradford P. Wilcox, John W. Walker, and James L. Heilman

In a paper "Effect of brush control on evapotranspiration in the North Concho River watershed using the eddy covariance technique," published in the September/October 2009 issue of the *Journal of Soil and Water Conservation*, Saleh et al. argue that clearing mesquite has "great potential" for increasing water yield in the North Concho River watershed near San Angelo, Texas. The clear implication is that shrub removal is a viable strategy for increasing water supply to the city of San Angelo. The authors make this argument mainly on the basis of the small differences in evapotranspiration rates they measured between pastures with mesquite and those without mesquite.

We do not dispute the fact that the timing and amount of evapotranspiration may be affected by differences in tree cover and density, but we do not agree that these modest differences will translate to meaningful changes in water supply. There is already overwhelming evidence that brush management in the North Concho watershed will not lead to increases in water flow in the North Concho. A brush control project was begun in the North Concho watershed 10 years ago, and even though this period included one of the wettest years on record (2007), there has been no evidence of increased flow. In other words, brush control has been tried and has not worked in terms of increasing streamflows to the North Concho.

The North Concho project has been one of the most comprehensive and coordinated brush-control efforts in Texas. Between 2000 and 2005, about 1200 km^2 (463 mi^2) of the 3100 km^2 (1,196 mi^2) watershed was cleared of either mesquite or juniper in the hope of increasing flows in the North Concho River. In fact, as highlighted by Saleh et al., water planners were projecting that flows in the North Concho would increase three- to fivefold as a result of this $14 million program. However, as of 2010, there has been no perceptible increase in flow in the North Concho and even a suggestion of further decline since the brush control program was implemented (figure 1).

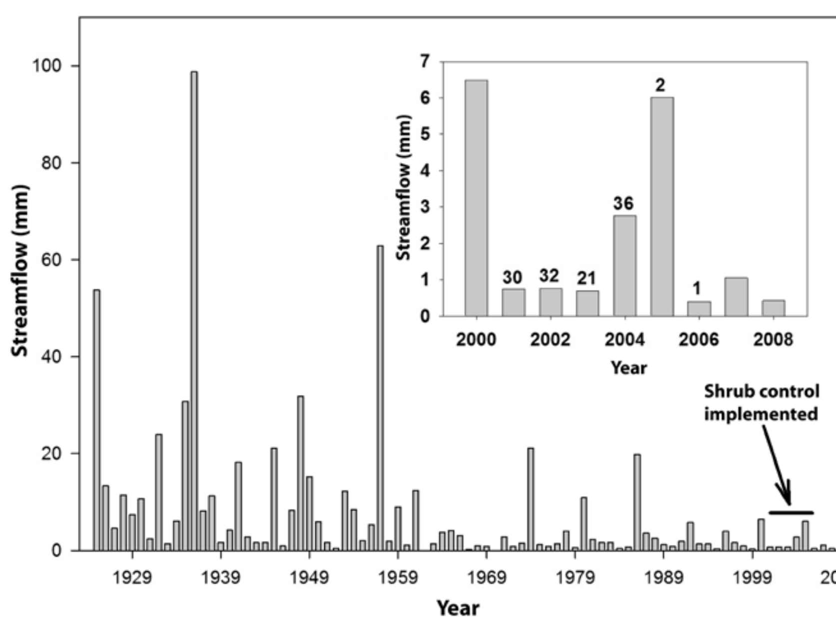
What is clear from figure 1, however, is that streamflows in the North Concho are much lower now than they were before 1960. Wilcox et al. (2008) attribute these declines to improvements in the condition of the rangelands, as the numbers of grazing animals were dramatically reduced. Improved range condition has lead to smaller flood events for a given amount of rainfall.

Given that background information, what Saleh and coauthors should have been asking is, Why are the results of our evapotranspiration study at variance with those of the North Concho River clearing program? Our response to this question would be that evapotranspiration is effectively decoupled from streamflow in this semiarid environment.

The underlying but unstated assumption of Saleh et al. is that differences in evapotranspiration between sites with and without mesquite will translate directly to differences in groundwater recharge, which in turn will translate to differences in streamflow. However, this is not the case, as demonstrated by a detailed analysis of streamflow on the North Concho (Wilcox et al. 2008). This analysis highlights the fact that groundwater sources provide only about 10% of the North Concho's flow. The remainder comes from surface runoff during flood events (Wilcox et al. 2008). The clear implication is that evapotranspiration is effectively decoupled from

Figure 1

Historical streamflow (mm) for the North Concho measured at US Geological Survey Gage 0813400 near Carlsbad, Texas. The inset graph highlights the last decade, and the numbers on top of the bars are the approximate areas of shrubland (1000s of hectares) treated in a given year.



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streamflow. In other words, since streamflow is primarily a surface phenomenon, vegetation-management strategies that reduce evapotranspiration cannot have any significant effect.

Further, streamflow in the North Concho accounts for only 0% to 2% of the rainfall (during the period of this study, streamflow accounted for only 0.1% to 1.5% of annual rainfall). If one assumes that the North Concho is the major outlet for groundwater and surface water flows, then evapotranspiration must be on the order of 99%—unless one is prepared to argue that groundwater recharge in this semiarid upland region is significant. In fact, groundwater recharge of more than a few millimeters a year is extremely unlikely on these upland sites (Scanlon et al. 2005). Local evidence arguing against a groundwater connection includes the following:

- Except for the alluvial aquifer adjacent to the river, there is no obvious, heavily used groundwater source (groundwater pumping is very limited in the basin).
- The groundwater table is 30 m (98 ft) deep or more in most locations.
- The Angelo soils on the site have well-developed calcic horizons, which cannot form where significant leaching is occurring.

Brush control on mesquite rangelands is a vitally important land management practice. If done properly, it can lead to better wildlife habitat, increased grazing potential, improved biodiversity, and even watershed protection. However, there is no compelling evidence at this time that it is a viable strategy for increasing water supply. In the case of the North Concho watershed, there is strong evidence that it does not increase water supply. To continue arguing otherwise confuses the public and ultimately undermines the credibility of the watershed conservation community.

REFERENCES

Scanlon, B.R., R.C. Reedy, D.A. Stonestrom, D.E. Prudic, and K.F. Dennehy. 2005. Impact of land use and land cover change on groundwater recharge and quality in the southwestern US. Global Change Biology 11:1577-1593.

Saleh, A., H. Wu, C.S. Brown, F.M. Teagarden, S.M. McWilliams, L.M. Hauck, and J.S. Millican. 2009. Effect of brush control on evapotranspiration in the North Concho River watershed using the eddy covariance technique. Journal of Soil and Water Conservation 64(5):336-349.

Wilcox, B.P., Y. Huang, and J.W. Walker. 2008. Long-term trends in streamflow from semiarid rangelands: uncovering drivers of change. Global Change Biology 14(7):1676-1689.

doi:10.2489/jswc.65.4.85A

READERS' FORUM

Response to commentary on "Effect of brush control on evapotranspiration in the North Concho River watershed using the eddy covariance technique" by Wilcox et al. (2010)

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Notwithstanding the differing professional opinion of our colleagues, the authors of this article stand by our concluding statement that brush control offers great potential for increasing water yield in the Concho River Watershed. The commenting authors are not disputing our basic finding that decreases in tree cover and density decrease evapotranspiration; rather, they dispute our statement that these seemingly modest differences will translate to meaningful changes in water supply in this watershed. Hence, we find ourselves defending not the methods and findings of our research, but rather our assertion regarding the implications of our findings.

Beginning with the support for our position, it is for the most part still amply presented in the brush control planning, assessment, and feasibility study (UCRA 1999). Therein is provided the historical grassland vegetative setting of the watershed prior to the 1880s, the infestation by evasive shrubs and brush largely culminating by the late 1950s, and ample anecdotal evidence from numerous "old time" residents of perennial streamflow and permanent spring conditions ceasing in the North Concho River and its tributaries during the 1950s. Despite no notable pumping of the groundwater resources, evidence from water well measurements in the watershed is also provided of generally declining groundwater levels of an average of over 6 m (20 ft) at most locations based on measurements made by the Texas Water Development Board in the early 1940s and then again in the early 1960s (UCRA 1999). The anecdotal evidence of the "old time" residents and hard data of declined groundwater levels are either ignored or dismissed by our colleagues without mention.

Further, our colleagues wonder why the increased evapotranspiration results of our study are at variance with what has occurred with the present brush clearing program. Their statement is that the difference in evapotranspiration we measured has not parlayed into increased streamflow from the recent brush control efforts in the watershed. They conjecture that the reason is the decoupling of evapotranspiration from streamflow in this environment.

We counter that the drawdown of groundwater levels through decades of dense brush infestation is not broadly reversed within a matter of a couple of years in a watershed with a nonkarst geology, such as this one, especially since those years are coincident with yet another multiyear drought in the region. Given the coincident drought conditions with the brush clearing in an already semiarid region, we suggest that the lack of response in the streamflow record only proves that a positive response has not occurred yet, and it does not mean that increased streamflow will not occur. (Note: We do not dispute our colleagues' statement that the year 2007 was a very high rainfall year, but that year occurred in the midst of a number of prior years that were predominately and substantially below average in rainfall.)

In their commentary they highlight the statement from Wilcox et al. (2008) "that groundwater sources provide only about 10% of the North Concho's flow." They then conclude, "The clear implication is that evapotranspiration is effectively decoupled from streamflow" Wilcox et al. (2010). We will present flow duration curves developed from the data they used as a means of checking the reasonableness of their data analysis.

Their assertion that groundwater comprises only 10% of the river's flow comes from their analysis of the gaged streamflow record on the North Concho for the period from 1926 to 2005 and application of an automated baseflow separation method to the daily measured flows. Nowhere in their article do they establish that the automated baseflow filter results used for their analysis were tested as to their validity for the North Concho River. Arnold and Allen (1999) in presenting the automated technique used in Wilcox et al. (2008) provide data indicating that the technique gives a "reasonable" estimate of baseflow as compared to measured baseflow. Their results, however, for the sole example of a river with a comparably low amount of baseflow to total flow as the North Concho showed an error of 70%. This discrepancy of itself only casts doubt, a need for cautious application, and does not prove erroneous results from their application to the North Concho.

We performed a simple analysis to test the finding from Wilcox et al. (2008) that there was only about a 10% decline in baseflow over the period of record (1926 to 2005) as determined from their flow separation. Flow duration curves are at times used to gain insight into the hydrologic conditions of a river. We developed flow duration curves using the same US Geological Survey published data they used and developed separate curves for each of the two 24-year periods they used in some of their analyses (1926 to 1949 and 1974 to 1997). They report that these two periods were comparable in terms of average rainfall. Overall they found that streamflow for the later period was less than a third of that for the earlier period, but they attribute very little of that difference to decline in baseflow. Our flow duration curve results are provided in figure 1. (Note: The graphed lines show a "stair-step" pattern, which is an artifact that the streamflow data are only reported to the nearest tenth of a cfs.) If the baseflow had only decreased about 10% over the entire period of 1926 to 2005, the anticipation would be that the two flow duration curves should be quite similar in appearance at the low flows or high exceedances. Visual inspection of the graph should cause the reader to pause at our colleagues' statement that baseflow only reduced 10% over the period of

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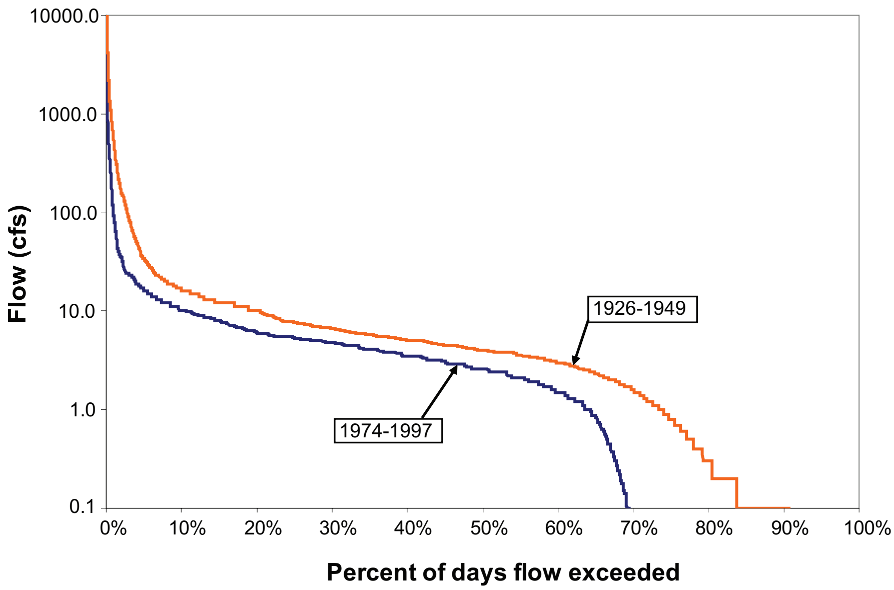
Figure 1

Flow duration curve for two selected periods of comparable rainfall, North Concho River, US Geological Survey Gage 0813400 near Carlsbad, Texas (vertical axis on log scale).



record. In particular, one can see that during the 1926 to 1949 period days of no flow (<0.1 cfs) occurred less than 10% of the time, whereas during the 1974 to 1997 period no-flow conditions had increased to over 25% of the time. Further, the early period has visibly greater flows than the later period not only for stormwater flows, as both parties agree to, but also under all other conditions. For example, for the data between the 30% and 60% exceedances, which purposefully avoids the extremely high and low flows that would give very high percent differences, the later period flows are about 35% less than the early period's. Though not conclusive, this simple analysis using flow duration curves provides contrary results that bring into question the validity of the stormflow and baseflow data derived using the baseflow filter, and thus brings into question their entire analysis, which was based on unvalidated flow separation data.

We conclude by stating that our colleagues' criticism is based on data analysis, assumptions, and presentation that contain concerns regarding validity.

We feel their arguments against the disputed benefit of brush control ignore abundant anecdotal information and historical groundwater level data contrary to their arguments. Further, we established concerns with their analyses that form the basis of their conclusions and criticisms. Our convictions remain as stated in our paper.

REFERENCES

Arnold, J.G. and P.M. Allen. 1999. Automated methods for estimating baseflow and ground water recharge from streamflow records. Journal of the American Water Resources Association. 35:411-424.

UCRA (Upper Colorado River Authority). 1999. North Concho River Watershed Brush Contol Planning, Assessment & Feasibility Study. Final Report Amended 1999.

Wilcox, B.P., Y. Huang, and J.W. Walker. 2008. Long-term trends in streamflow from semiarid rangelands: uncovering drivers of change. Global Change Biology 14(7):1676-1689.

Wilcox, B.P., J.W. Walker, and J.L. Heilman. 2010. Commentary on "Effect of brush control on evapotranspiration in the North Concho River watershed using the eddy covariance technique" by Saleh et al. (2009). Journal of Soil and Water Conservation 65(4):83A-84A.