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Relationship between evapotranspiration and precipitation pulses in a semiarid rangeland estimated by moisture flux towers and MODIS vegetation indices

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Abstract

We used moisture Bowen ratio flux tower data and the enhanced vegetation index (EVI) from the moderate resolution imaging spectrometer (MODIS) on the Terra satellite to measure and scale evapotranspiration (ET) over sparsely vegetated grassland and shrubland sites in a semiarid watershed in southeastern Arizona from 2000 to 2004. The grassland tower site had higher mean annual ET (336 mm yr^{-1}) than the shrubland tower site (266 mm yr^{-1}) ($P < 0.001$). ET measured at the individual tower sites was strongly correlated with EVI ($r = 0.80$–0.94). ET was moderately correlated with precipitation (P), and only weakly correlated with net radiation or air temperature. The strong correlation between ET and EVI, as opposed to the moderate correlation with rainfall, suggests that transpiration (T) is the dominant process controlling ET at these sites. ET could be adequately predicted from EVI and P across seasons and tower sites ($r^2 = 0.74$) by a single multiple regression equation. The regression equation relating ET to EVI and P was used to scale ET over 25 km^2 areas of grassland and shrubland around each tower site. Over the study, ratios of T to ET ranged from 0.75 to 1.0. Winter rains stimulated spring ET, and a large rain event in fall, 2000, stimulated ET above T through the following year, indicating that winter rain stored in the soil profile can be an important component of the plants' water budget during the warm season in this ecosystem. We conclude that remotely sensed vegetation indices

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can be used to scale ground measurements of ET over larger landscape units in semiarid ranglelands, and that the vegetation communities in this landscape effectively harvest the available precipitation over a period of years, even though precipitation patterns are variably seasonally and interannually.

Keywords: Remote sensing; Semiarid environments; Riparian; Shrubland; Grassland; Ecohydrology

1. Introduction

1.1. Ecohydrology of water-limited ecosystems

Precipitation (P) typically arrives with wide spatial and temporal variability in arid and semiarid ecosystems. Interactions between plant cover type and topoedaphic features of the landscape produce complex ecological and hydrological patterns of response to P (Huxman et al., 2004). Understanding these complex relationships is important in understanding how natural dryland ecosystems are structured, and in predicting the effects of land use and climate change on the ecohydrology of water-limited biomes (Huxman et al., 2005; Newman et al., 2006; Wu and Archer, 2005).

Huxman et al. (2004) showed that under water-limited conditions, 14 different plant communities converged on a common, high rainfall use efficiency (RUE) of about $1\,\mathrm{g\,m^{-2}}$ annual net primary productivity (ANPP) per $2.2\,\mathrm{mm\,yr^{-1}}$ rainfall. This finding supports the conclusion that water is used efficiently by vegetation in dryland ecosystems. On the other hand, a compilation of literature values by Huxman et al. (2005) showed that the ratio of transpiration (T) to evapotranspiration (ET) varied from 0.07 for a sparse creosote stand to 0.85 for a mesquite community in the Sonoran Desert ($P = 250$–$280\,\mathrm{mm\,yr^{-1}}$), suggesting that water use efficiency might be variable, depending on plant species composition over the landscape. These two sets of observations could be reconciled if it could be shown that individual plant species or plant associations may vary in T/ET and RUE at the plot scale, but that at the landscape scale, mixed stands of plants maximize these parameters regardless of rainfall regime and physiological features of the plant communities (Huxman et al., 2004). Testing this hypothesis will require scaling plant-level and plot-level measurements over wider landscape units. This study developed a remote sensing method to scale ET measured at moisture flux towers to larger landscape areas in a semiarid rangeland.

1.2. Remote sensing methods for scaling ET

Two types of methods have been developed to estimate ET by remotely sensed data. Energy balance methods (reviewed in Diak et al., 2004) use remotely sensed data to solve the surface energy balance equation:

$$\lambda \mathrm{ET} = R_n - H - G, \tag{1}$$

where λET is the latent heat of evaporation of water, R_n is net radiation (incoming minus outgoing long- and short-wave radiation), H is the sensible heat flux from the surface to the atmosphere, and G is the soil heat flux. These methods require remotely-sensed land surface temperatures (from thermal IR bands), as well as data from visible and NIR bands, and varying amounts of meteorological and canopy data from ground observations, to estimate R_n, H and G; λET is then calculated as a residual. These methods do not require independent ground estimates of ET for calibration, although ground estimates of ET are useful in validating the methods. Most of these methods rely on an instantaneous measurement of land surface temperature at the time of a satellite overpass, hence they provide a snapshot of ET, although results can be scaled to longer time periods by assuming that ET/R_n is constant over a given time period.

A second type of method is possible when ground measurements of ET or ANPP are available. Remotely sensed vegetation indices (VIs), obtained as a time series over a growing season, and micrometeorological data can be used to project plot level measurements of ET (Hunsaker et al., 2003, 2005; Nagler et al., 2005b) or ANPP (Holm et al., 2003; Wylie et al., 2003) over larger landscape units, using empirical relationships developed for specific ecosystems. Although the results cannot necessarily be extrapolated to different ecosystems, they can provide an accurate method for temporal and spatial scaling of ET within a biome type. In an agricultural setting, Hunsaker et al. (2003) showed that a time-series of normalized difference vegetation index (NDVI) values combined with micrometerological estimates of ET_0 predicted actual ET of stressed and unstressed cotton crops within 9% of values derived from lysimeter studies over a crop cycle. Similar results were reported for wheat (Hunsaker et al., 2005). In a natural setting, Szilagyi (2000, 2002) regressed annual rates of ET, measured over different forested catchments areas in Georgia over multiple years by water balance methods, against time-averaged NDVI values from AVHRR satellite sensors. He obtained an r^2 of 0.88 between ET and NDVI over catchments and years, sufficient to scale ET over larger landscape units within the error term of the ground ET estimates. Nagler et al. (2005a, b) showed that ET measured by eddy covariance and Bowen ratio flux towers in three western US riparian zones could be scaled across river systems and plant types ($r^2 = 0.74$) with 16-day, time series MODIS enhanced vegetation index (EVI) data from the Terra satellite and meteorological station air temperature data. We extended that approach to a semiarid rangeland in the present research.

1.3. Objectives of the study

The study was conducted in the Upper San Pedro River Basin (USPRB) of Arizona, US, a region encompassing the Walnut Gulch Experimental Watershed (Goodrich et al., 2000). We examined seasonal and interannual interactions between vegetation cover, ET and P at two long-term ET monitoring sites to provide an overview of the factors controlling the annual water balance in shrubland and grassland sites at the plot and landscape scales in the USPRB. The objectives of the study were: (1) to develop a relationship between MODIS VIs, and micrometeorological and ET data from flux towers that could be used to scale ET over grassland and shrubland plant associations; and (2) to use that relationship to understand the variable response of ET to P at multiple temporal and spatial scales in the USPRB.

2. Materials and methods

2.1. Description of upland sites

The two flux tower sites for this study are located on the USPRB in southeastern Arizona (Emmerich, 2003). The climate is semiarid with cool winters and warm summers. This region has a bimodal precipitation pattern, with 60% of the annual precipitation in this watershed arriving in the July–September summer monsoon season, and with the remainder arriving as gentler, longer duration frontal winter systems (Scott et al., 2000). Mean annual precipitation is 356 mm and mean annual temperature is 17 °C. A grass site was selected in mid-1996 on an area identified as Kendall (109 56′ 28″W 31 44′ 10″N; elevation: 1526 m). Vegetation at the site is predominantly sideoats grama (*Bouteloua curtipendula*), black grama (*Bouteloua eriopoda*), hairy grama (*Bouteloua hirsuta*), and lehmann lovegrass (*Eragrostis lehmanniana*), with a few shrubs of fairy duster (*Calliandra eriophylla*), and burroweed (*Haplopappus tenuisectus*). The soils at the site are a complex of Stronghold (coarse-loamy, mixed, thermic Ustollic Calciorthids), Elgin (fine, mixed, thermic, Ustollic Paleargids), and McAllister (fine-loamy, mixed, thermic, Ustollic Haplargids) soils, with Stronghold the dominant soil. The eluvial parent material for these soils contains some limestone rock fragments. Slopes range from 4% to 9%.

A present day brush community site was selected in mid-1996 on an area known as Lucky Hills (110 3′ 5″W 31 44′ 37″N; elevation: 1372 m). The dominant shrubs at this site are whitethorn acacia (*Acacia constricta*), tarbush (*Flourensia Cernua*), creosotebush (*Larrea tridentata*), and desert zinnia (*Zinnia pumila*). The only grass species remaining at the site, which historically was a black grama (*Bouteloua eriopoda*) community, is bush muhly (*Muhlenbergia porteri*). The soil at this site is Luckyhills series (coarse-loamy, mixed, thermic Ustochreptic Calciorthids) with 3–8% slopes. The alluvial parent material for this soil contains many rock fragments of limestone. This site was reportedly converted to shrubland through overgrazing.

2.2. ET estimation and measurement of micrometeorological variables

ET was estimated using a Bowen ratio energy balance system (BREB) (Model 023/CO_2 Campbell Scientific Inc., Logan, UT, USA) (Emmerich, 2003; Hogue et al., 2005). The BREB system measures air temperature and moisture content at two heights above the canopy at 2 s intervals and computes the gradient of temperature and moisture content between the sensor sets at 20 min intervals. The data are used to calculate the Bowen ratio, which is the ratio between the difference of air temperature and moisture content at the two sensor stations:

$$\beta = \gamma[T_1 - T_u]/[e_1 - e_u] = H/\lambda \mathrm{ET}, \tag{2}$$

where T_1 and T_u are upper and lower temperatures and e_1 and e_u are lower and upper moisture contents, and γ is the psychometric constant (ratio of the specific heat of the air to the latent heat of water vapor). The BRED has additional instruments that measure R_n (with a net radiometer) and G (with soil heat flux plates), allowing λET to be calculated by combining Eqs. (1) and (2):

$$\lambda \mathrm{ET} = (R_n - G)/(\beta + 1). \tag{3}$$

The BRED method is considered to be an indirect method for estimating ET, because the gradients of heat and moisture above the canopy cannot be used to directly calculate heat and moisture flux rates, because the transport coefficients for each entity are not known (Rana and Katerji, 2000). However, if they are assumed to be the same (because the same eddies of air in the turbulent boundary layer above the canopy carry both entities), ET can be indirectly calculated by the Bowen ratio and the surface energy balance equation.

The BRED systems were placed in locations with a fetch of >200 m in all directions. The theory and procedures used to calculate the fluxes has been presented in detail (Emmerich, 2003; Rana and Katerji, 2000). Kendall gradients were measured at 1 and 2.5 m, and Lucky Hills at 1.5 and 3.0 m above the soil surface. Vegetation canopy height at Kendall ranged from 0.4 to 0.7 m during the growing season and at Lucky Hills an almost constant 1 m height. Atmospheric moisture concentrations were measured with an infrared gas analyzer (LI-6262, LI-COR Inc., Lincoln, NE, USA). Meteorological data were obtained from a net radiation sensor model Q*7 (REBS, Seattle, WA, USA), soil heat flux from five plates (model HFT3 REBS), average of soil temperature from thermocouples above each heat flux plate, wind speed and direction from model 03001 R.M. Young Wind Sentry Set (R.M. Young Company, Traverse City, MI, USA), and RH and air temperature from model HMP35C temperature and RH probe (Vaisala Inc., Woburn, MA, USA). Net radiometers were calibrated yearly over a grass canopy. Water vapor, and energy fluxes were calculated from the 20 min average data.

Flux tower data sets were not complete for all years. The Kendall set covered the period from Julian Day 49, 2000, through Julian Day 353, 2004, but with a gap from Julian Day 178, 2001 to Julian Day 17, 2002. The Lucky Hills set covered the period from Julian Day 1, 2000, to Julian Day 353, 2004.

2.3. *Sources of error in flux tower estimates of ET*

Flux measurements are subject to several sources of error and uncertainty (Rana and Katerji, 2000). Natural vegetation often is less than homogeneous both vertically and horizontally, so the flux measurements may not be representative of the vegetation of interest. The Bowen ratio method has reduced accuracy when the gradients of temperature or moisture are small. Comparisons between fixed and portable Bowen ratio sensor sets showed a spread in values of about 20% even under uniform measurement conditions in cropped fields in Kansas (Nie et al., 1992). Site specific errors for Bowen ratio towers in riparian mesquite woodlands in Arizona were also about 20%, while instrument limitations led to the loss of about 50% of the data (Unland et al., 1998). As an indirect method, the Bowen ratio results cannot be internally checked for accuracy. In the present study, an error term of 20–30% in ET estimates can be assumed (Emmerich, 2003).

2.4. *Collection of MODIS data*

The relationship between flux tower ET and MODIS VIs was analyzed with five years (2000–2004) of MODIS VI, 16-day, time series data at 250 m resolution. The MODIS VI products ingest level 2G (gridded) daily surface reflectances (MOD09 series), corrected for molecular scattering, ozone absorption, and aerosols (Huete et al., 2002). The 16-day VI product uses a quality assurance (QA) filtering scheme to provide improved spatial and temporal consistency in VI values on an operational basis. The NDVI, Eq. (1), and EVI, Eq. (2), are generated as

$$\mathrm{NDVI} = (\rho_{\mathrm{NIR}} - \rho_{\mathrm{Red}})/(\rho_{\mathrm{NIR}} + \rho_{\mathrm{Red}}), \quad (4)$$

$$\mathrm{EVI} = 2.6(\rho_{\mathrm{NIR}} - \rho_{\mathrm{Red}})/(\rho_{\mathrm{NIR}} + 6\rho_{\mathrm{Red}} + 7.5\rho_{\mathrm{Blue}} + 1.0), \quad (5)$$

where ρ is the surface reflectance in the wavelength band. In EVI, the blue and red band coefficients are to minimize aerosol variations, and EVI also has a canopy background correction term of 1.0 (Huete et al., 2002).

MODIS pixels encompassing each tower site were used to establish a relationship between flux tower ET and MODIS VIs. Then the relationship was used to scale ET over larger areas for the period 2000–2004. The larger areas were 5 km × 5 km squares centered on each tower site, for which 400 MODIS pixels per site were extracted. Inspection of aerial photographs showed that the large area Kendall site was approximately 80–90% grassland similar to the tower site, and 10–20% shrubland (W. Emmerich, unpublished). On the other hand, the large area Lucky Hills site was nearly all shrubland typical of the tower site. Both large area sites were dissected by occasional ephemeral drainage channels (washes) that were more thickly vegetated than the flats.

2.5. *Other data sources and statistical methods*

Precipitation was measured by rain gauges at the Kendall and Lucky Hills tower sites. Precipitation over the large area sites combined tower P data with data from other rain gauges arrayed over the study area. LAI was measured at dawn with a Licor LAI-2000 Plant Leaf Area Index Analyzer (Licor Co., Lincoln, Nebraska) using procedures described in their manual and in Nagler et al. (2004). LAI and percent cover were measured along eight (100 m length) transects around each tower site. LAI was recorded at regular intervals along the transects, and many of the readings were at points that were unvegetated. Hence, the values do not reflect the LAI of individual plant types but of the site in general. Percent cover was determined by measuring the cover of bare soil and vegetation along each transect line.

Statistical tests were based on methods in Snedecor and Cochran (1989) and Sokal and Rohlf (1995). The relationships between ET and meteorological variables and VIs were tested by correlation and multiple linear regression analyses. Standard regression coefficients were calculated for rainfall and EVI by converting all variables into standardized units in which the mean value of each variable is 0 and the standard deviation of each variable is 1.0. The standard regression coefficients calculated by this method range from 0 to 1.0 and are a measure of the proportion of the variability in the dependent variable that can be explained by each independent variable in the equation of best fit. Note that for expressing the closeness of the relationship between ET and independent variables we report correlation coefficients (r), while for regression equations we report coefficients of determination (r^2) as they indicate the fraction of the variability in the dependent variable that can be explained by the independent variables.

Time-series data such as we used in this study are subject to autocorrelation, in which the error term is not independent over time; this can exaggerate the accuracy of the analysis (Meek et al., 1999). We tested for autocorrelation by plotting the residuals (measured minus predicted values) against observation number, and by computing the first-order autocorrelation coefficient and the Durbin–Watson D-statistic (Montgomery and Peck, 1982; Meek et al., 1999). We further evaluated the robustness of our final predictive model for ET by cross validation, in which the data are split into sets, with one set used to derive the regression equation and the second set used to test its validity (Montgomery and Peck, 1982). In one cross validation test, the Lucky Hills ET data were predicted from a regression equation developed from the Kendall data. In a second test, the combined ET for the two towers were divided into two equal time periods (2000 to June, 2002, and July, 2002 to 2004), and period 2 ET values were predicted from a regression equation developed from period 1 data. For each cross validation we calculated the Bias and the standard error of prediction (SEP):

$$\text{Bias} = \sum_{t=1}^{n} (y_{\text{measured}} - y_{\text{predicted}})/n \tag{6}$$

and

$$\text{SEP} = \left[(n^{-1}) - 1 \sum_{t=1}^{n} (y_{\text{measured}} - y_{\text{predicted}} - \text{Bias})(t)^2 \right]^{1/2}, \tag{7}$$

where n is the number of observations (84 for each data set); and t is the observation number. Note that SEP is similar to the standard error of the estimate (SEE) based on the variance around the mean except that it includes the Bias term as an additional source of error (Montgomery and Peck, 1982; Meek et al., 1999).

3. Results

3.1. LAI and vegetation cover at the sites

Both sites were sparsely vegetated. In July, 2004, LAI by Licor 2000 was 0.25 (SEM = 0.03, $n = 84$ measurements) at the Kendall grassland site and 0.41 (SEM = 0.05, $n = 47$ measurements) at the Lucky Hills shrubland site. Percent cover determined along 100 m transects ($n = 8$) at the Kendall site was: 52.1% grass; 39.6% bare soil, rocks and litter; 5.4% mixed shrubs; and 3.0% shrubby mesquites. Percent cover at the Lucky Hills site along 100 m transects ($n = 8$) was: 37.1% bare soil; rocks, and litter; 17.1% whitethorn acacia; 15.7% desert zinnia; 14.3% creosotebush; 12.1% tarbush; and 3.6% other plants.

3.2. Relationship between ET, MODIS VIs and meteorological data

Fig. 1 shows the time series data and mean values of ET, P, EVI, and NDVI at the grassland and shrubland sites. ET followed an irregular pattern at the sites, with ET maxima roughly corresponding to precipitation events. Mean annual ET at the Kendall site was 0.92 mm d^{-1}, higher than the value of 0.73 mm d^{-1} at the Lucky Hills site ($P<0.001$ by paired t-test). Annual totals were 336 and 266 mm, respectively. The ratio ET/P was 1.07 at the Kendall site and 0.83 at the Lucky Hills site (significantly different at $P<0.001$). Both NDVI and EVI were also significantly higher at the Kendall site than the Lucky Hills site ($P<0.001$).

A screening of meteorological variables correlated net radiation, maximum daily air temperature and precipitation with ET at each site (Table 1). Data were divided into summer (April–October) and winter (November–March) periods. ET was strongly

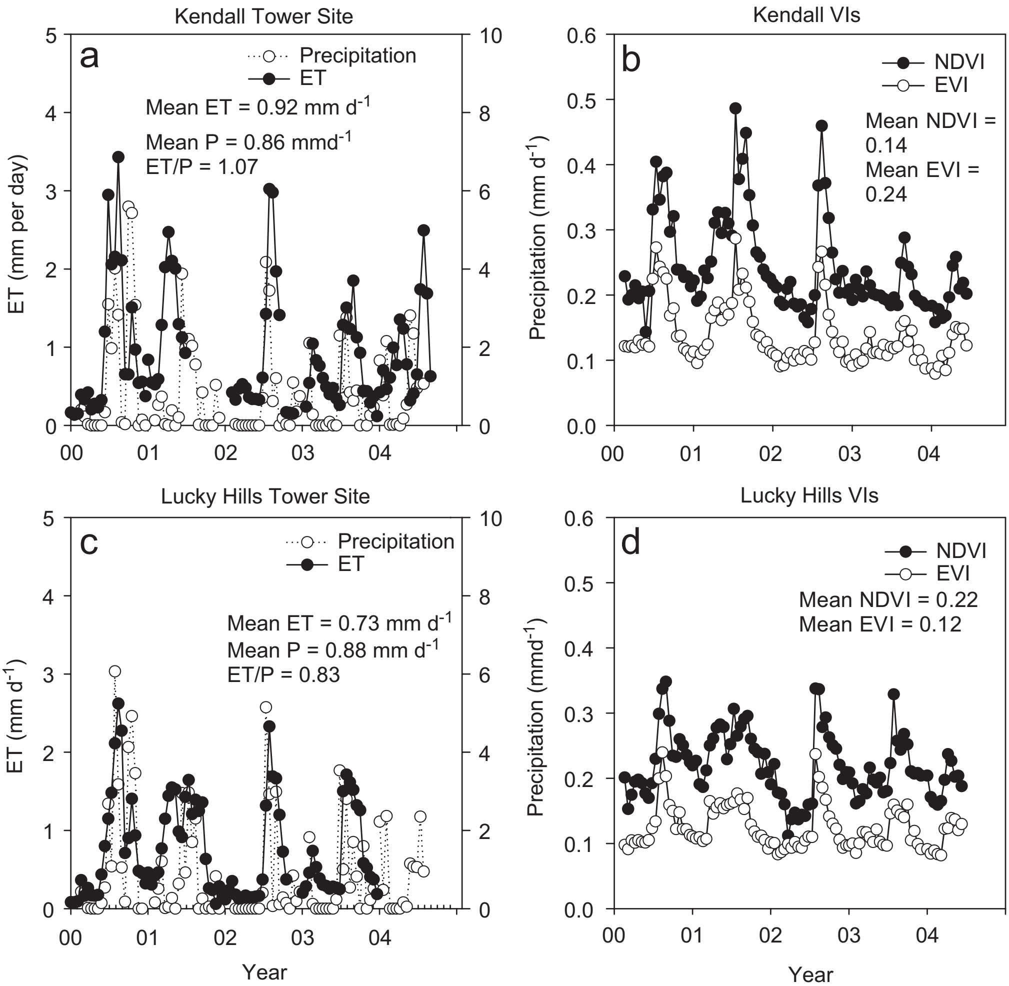

Fig. 1. Time course of ET and VIs at Kendall (a,b) and Lucky Hills (c,d) tower sites in the Upper San Pedro River Basin.

correlated with EVI, and less strongly with NDVI across sites and seasons. The correlation with P was moderate in summer and not significant ($P>0.05$) in winter at both sites. Correlation coefficients between ET and air temperature and radiation were low in both seasons.

3.3. Equation to predict ET

A multiple linear regression equation was developed to predict ET across sites and seasons, for the purpose of scaling ET over larger areas. ET was predicted with $r^2 = 0.74$ by a multiple linear regression equation that included both EVI and P (Fig. 2). Other meteorological variables did not increase predictive power at $P<0.05$. For individual sites

Table 1
Mean and standard error of evapotranspiration (ET, $mm\,d^{-1}$) at two upland sites in the San Pedro, Arizona, watershed, and correlation coefficients and multiple regression equations of best fit of ET vs. MODIS vegetation indices and meteorological data

	Kendall–Grassland		Lucky Hills–Shrubland	
Parameter	Summer	Winter	Summer	Winter
Mean ET	1.22 (0.13)	0.64 (0.08)	1.08 (0.10)	0.39 (0.05)
Correlation coefficients				
EVI	0.817***	0.715***	0.865***	0.800***
NDVI	0.801***	0.705***	0.775***	0.593***
P ($mm\,d^{-1}$)	0.664***	0.076ns	0.721***	0.282ns
Air temp (°C)	0.102ns	0.358*	0.210ns	0.398*
Radiation ($W\,m^{-2}$)	−0.236ns	0.311*	−0.234ns	0.165ns
Equation of best fit	ET = 13.6(EVI) + 0.093(P)−1.0 $r^2 = 0.69$***		ET = 15.1(EVI) + 0.053(P)−1.2 $r^2 = 0.81$***	
Std. Coef				
EVI	0.74		0.82	
P	0.16		0.12	

Data were collected from 2000 to 2004 and divided into winter (November–April) and summer (May–October) periods for correlation analyses. Data were composites at 16-day intervals corresponding to MODIS data reporting intervals. Asterisks indicate level of significance (0.05*, 0.01**, 0.001***, and ns = not significant at $P > 0.05$). The equation of best fit includes independent variables that were significant at $P < 0.05$ in the multiple regression analyses. Std. coefficients of the regression equations are the fraction of the variance in the dependent variable accounted for by the variance in each independent variable in the equation.

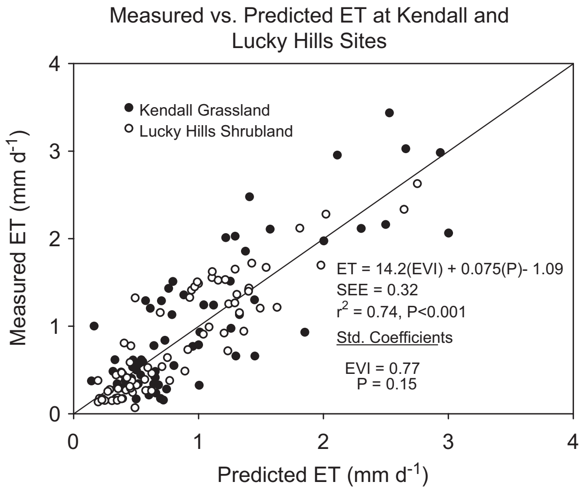

Fig. 2. Equation of best fit for predicting measured ET from EVI and P at Kendall and Lucky Hills tower sites in the Upper San Pedro River Basin.

(Table 1) and combined data (Fig. 2), standard coefficients for EVI were much higher than standard coefficients for P, and the sum of the standard coefficients of EVI and P for combined sites was 0.92, indicating that a high proportion of the variability in ET was explained by the regression equation across seasons and plant types. The SEE of the ET estimate was 0.32 mm d^{-1} (33% of the mean value of ET across sites and years).

The coefficient of autocorrelation was 0.38, indicating a low to moderate degree of autocorrelation. The Durban–Watson *D*-statistic was 1.21. A *D*-statistic of 2.0 indicates no autocorrelation, while values <1 require adjustment of the model (Montgomery and Peck, 1982). A plot of residuals across time (not shown) showed that residual values were lowest during the cool months, as expected, because ET values were also low at that time of year.

Cross validation plots are in Fig. 3. A regression equation developed from Kendall data produced a good fit with low Bias when applied to Lucky Hills data, and an equation developed from period 1 gave a good fit with low Bias when applied to period 2 data. Hence, the pooling of data across sites and years to predict ET is justified.

3.4. ET scaled over large areas

The equation for predicting ET from EVI was used to extrapolate ET over larger areas of the watershed for 2000–2004 (Fig. 4). As with the individual tower sites, the wide-area ET values (and EVI values from which they were derived) were weakly but significantly correlated with *P* ($r = 0.34$, $P = 0.001$ for Kendall, $r = 0.31$, $P = 0.004$ for Lucky Hills) and air temperature ($r = 0.28$, P = 0.007 for Kendall, $r = 0.29$, $P = 0.06$ for Lucky Hills). Unlike the case for individual tower sites, ET scaled from MODIS EVI values was higher at the Lucky Hills large area site (0.81 mm d^{-1}) than at the Kendall large area site (0.67 mm d^{-1}) ($P<0.001$).

The main peaks of ET were in the July–September period, corresponding to the summer monsoon season. However, secondary peaks sometimes occurred in winter or spring following large winter rain events (shown with arrows in Fig. 4a,b). The most prominent peaks occurred in winter and spring of 2001, following the unusually large winter rains of 2000.

3.5. Seasonal variations in ET at the tower- and wide-area sites

Averaged over all years of the study, the seasonal patterns of ET were the same at Kendall and Lucky Hills sites, and for tower sites (Fig. 5) as well as wide area sites (Fig. 6). In all cases, ET exceeded *P* from April to June, whereas *P* exceeded or was equal to ET during the other periods of the year. Over all years, ET/*P* was 0.75 at the Kendall wide-area site and 1.00 at the Lucky Hills wide-area site ($P<0.05$). However, the ratio of ET to *P* showed considerable year to year variation (Fig. 7). ET was lower than *P* in 2000. On the other hand, following the large rains of 2000, ET/*P* exceeded 1.0 in 2001 and 2002 at both sites then decreased to values of ca. 1.0 by 2004.

4. Discussion

4.1. Relationship between VIs, meteorological variables, and ET at the tower sites

Actual ET is determined by a complicated interaction of plant, soil, and meteorological variables, as expressed in the Penman–Monteith equation (Monteith and Unsworth, 1990). In many ecosystems, however, ET is constrained by a subset of the variables that can be used to predict ET from canopy and meteorological data. Over large areas of uniform

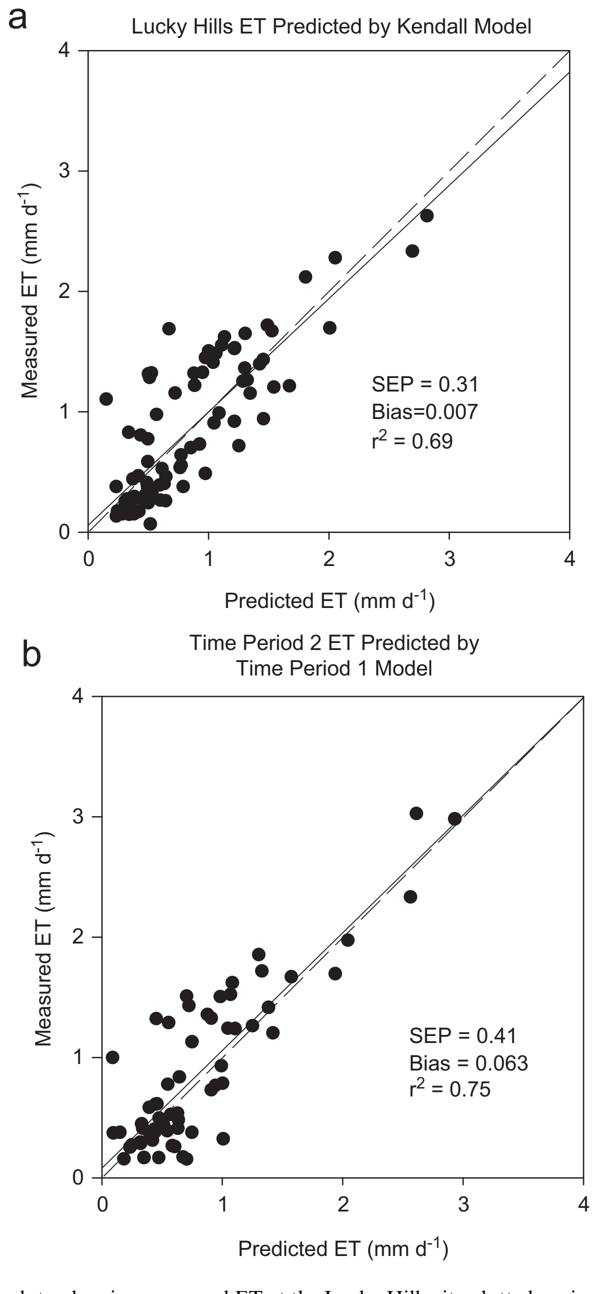

Fig. 3. Cross validation plots, showing measured ET at the Lucky Hills site plotted against predicted ET based on a regression equation developed from Kendall data (a); and measured ET for the second half of the study (period 2) plotted against predicted ET based on a regression equation developed from period 1 data (b). The solid lines in each plot show regression lines of best fit while the dashed lines are 1:1 lines.

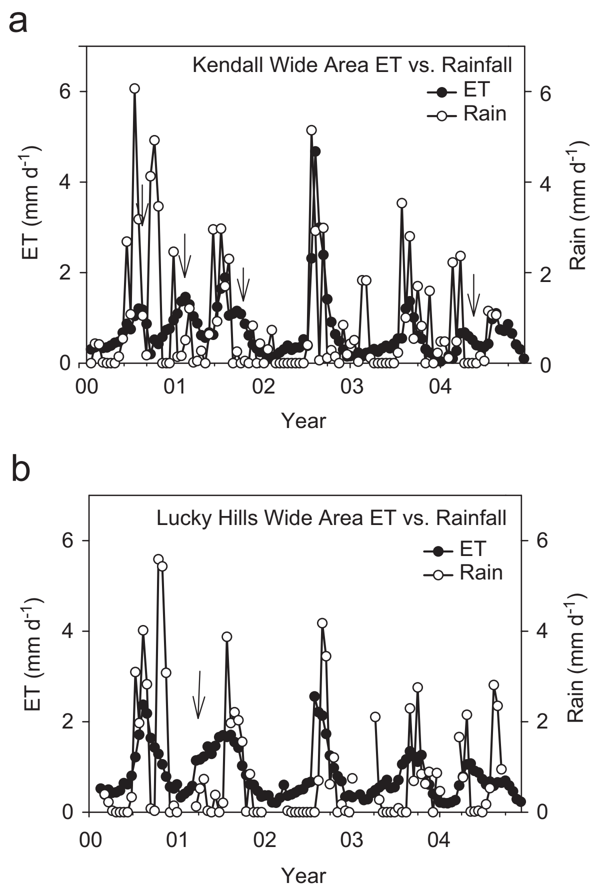

Fig. 4. Time course of projected ET and *P* at Kendall (a) and Lucky Hills (b) wide area sites. Arrows show extended periods when ET exceeded *P*.

vegetation and moist soil, for example, actual ET may approach R_n, which defines the "available energy" to drive ET (Diak et al., 2004; Monteith and Unsworth, 1990). On the other hand, in sparse landscapes such as semi-arid grasslands and shrublands, actual ET is a function of the available soil moisture (determined by *P*) and the amount and type of vegetation on the land surface; actual ET will be substantially lower than R_n except for a few days after a rainfall when the surface soil is wet and plants are transpiring freely.

In this study, ET was strongly correlated with EVI (a measure of foliage density) in both summer and winter. ET was moderately correlated with rainfall in summer at both the grassland and shrubland sites. ET was more weakly correlated with winter air temperatures. The weak correlation of ET with R_n across seasons shows that the plants were not radiation-limited most of the time. Hence, ET was mainly determined by the amount of green or functioning vegetation on the landscape at a given time.

Over time, *P* must ultimately set the upper limit for actual ET in a water-limited ecosystem. However, ET and *P* do not necessarily co-vary over short time intervals.

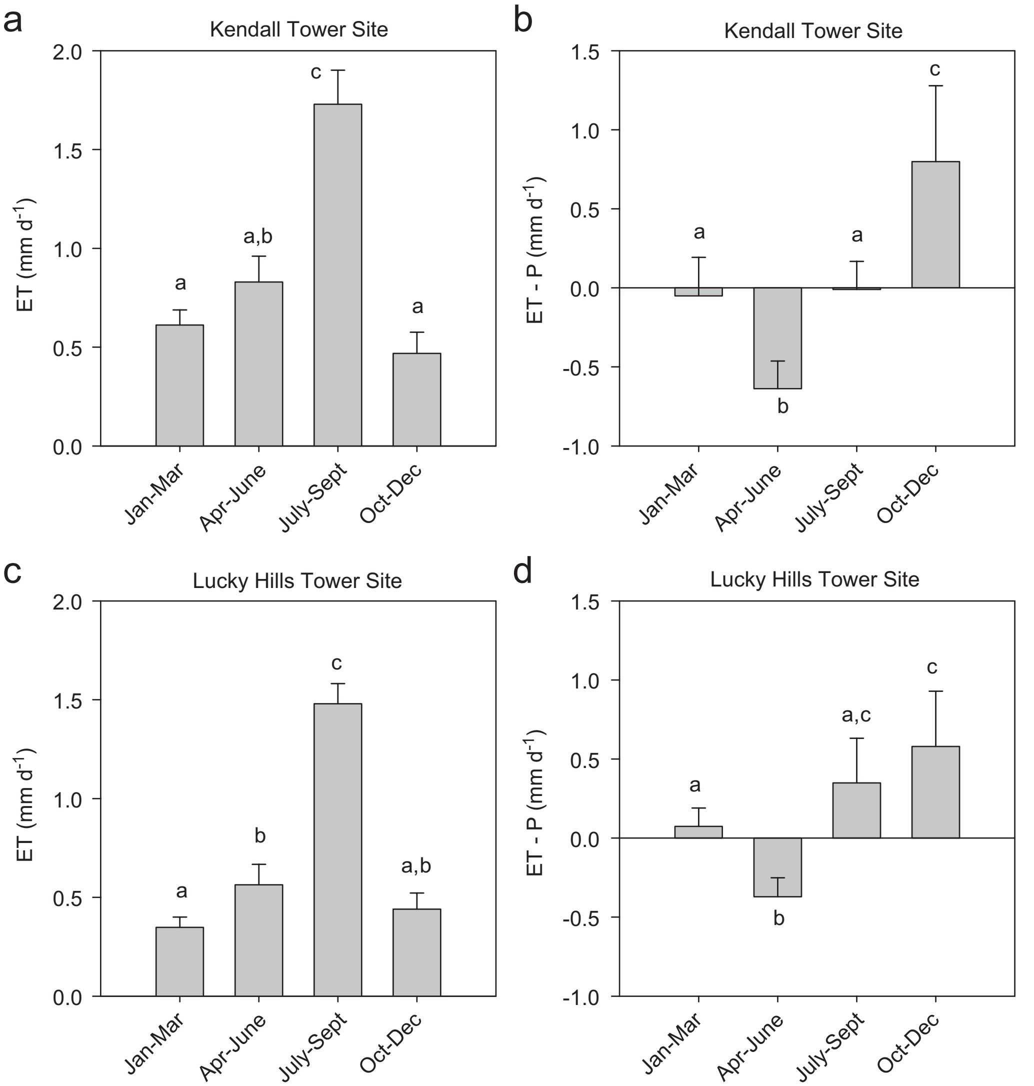

Fig. 5. Seasonal measured ET and *P*–ET for Kendall (a,b) and Lucky Hills (c,d) tower sites in the Upper San Pedro River Basin. Values were averaged over the period 2000–2004. Bars with different letters are significantly different at $P<0.05$ by Tukey's means separation test.

The statistical analyses in Table 1 provides an indirect means to differentiate between E and T in the control of ET. If E is the dominant term in ET, a strong correlation is expected between rainfall events and ET, because E will be most rapid immediately after rain events when the surface soil is moist (e.g., Small and Kurc, 2003; Yepez et al., 2005). On the other hand, a strong correlation of ET with EVI is expected if T is the dominant component of ET, as water loss will depend on the amount of foliage present on the surface, which is not exactly coincident with individual rainfall events. In the multiple

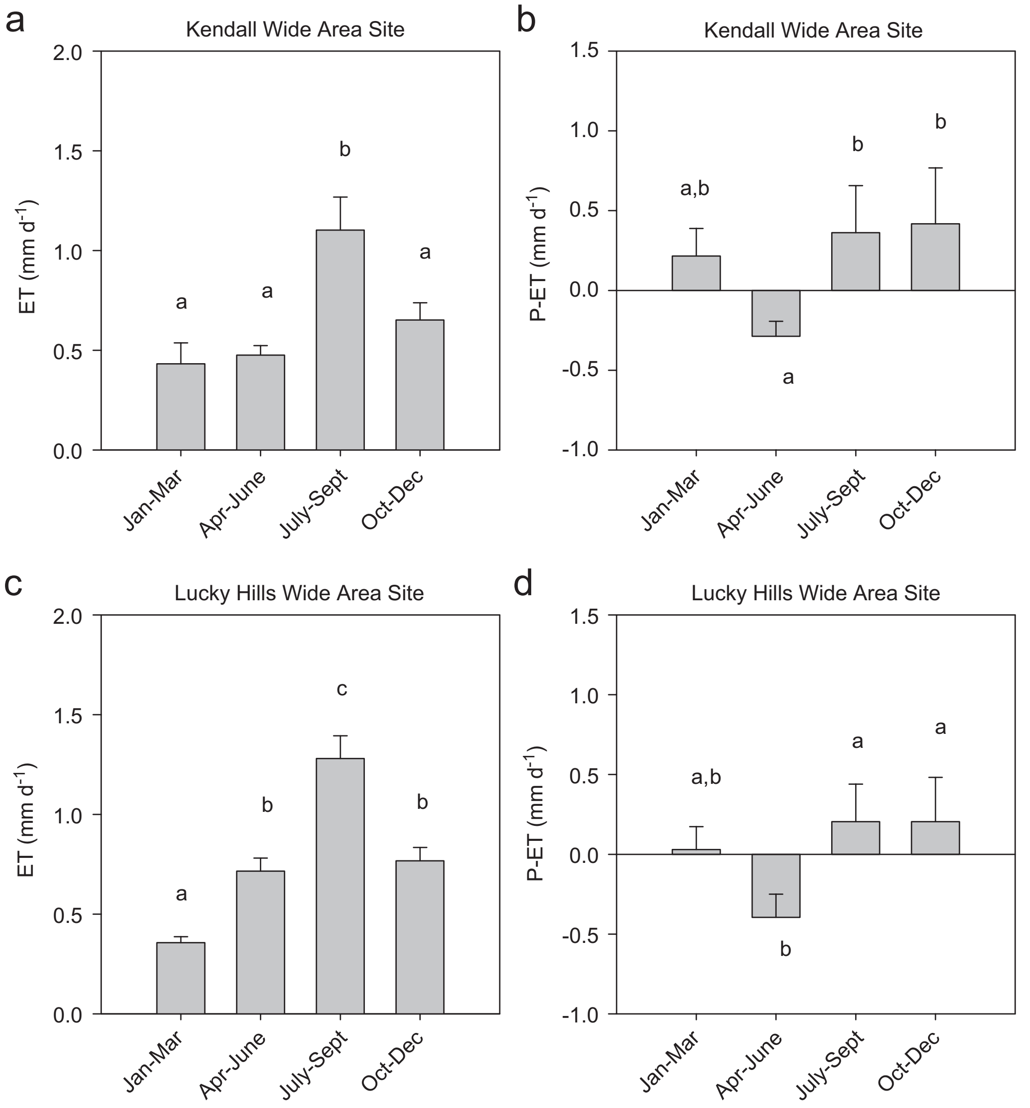

Fig. 6. Seasonal project ET and P–ET for Kendall (a,b) and Lucky Hills (c,d) wide-area sites in the Upper San Pedro River Basin. Values were averaged over the period 2000–2004. Bars with different letters are significantly different at $P<0.05$ by Tukey's means separation test.

regression analyses, the standard coefficients for ET on EVI were 0.74 and 0.82 for Kendall and Lucky Hill sites, respectively, whereas the standard coefficients for ET on P were only 0.16 and 0.12. Based on these values, T/ET ratios are 0.82 for the Kendall grassland site and 0.87 for the Lucky Hills shrub site, suggesting a high efficiency of water capture by vegetation in this ecosystem.

These results support studies in other semi-arid ecosystem that partitioned ET into E and T based on stable isotope methods. As examples, Ferretti et al. (2003) used isotope

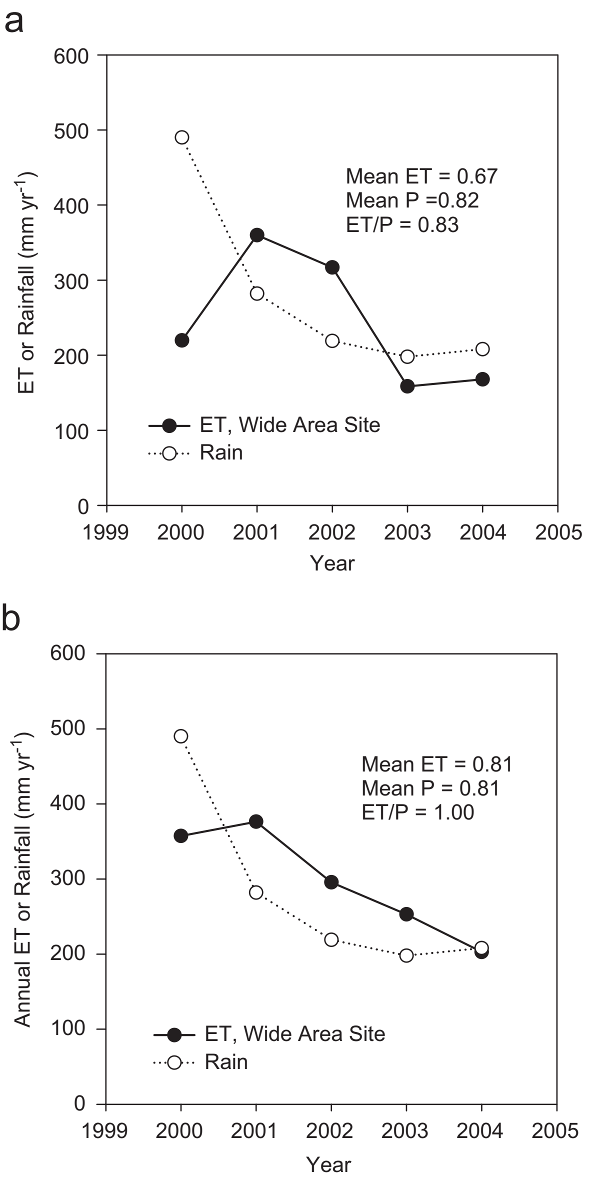

Fig. 7. Annual values for ET and *P* at wide area sites centered on the Kendall grassland tower site (a) and the Lucky Hills shrubland tower site (b) in the Upper San Pedro River Basin.

signatures of water to show that approximately 90% of ET was due to T in a semiarid grassland in Colorado, while Yepez et al. (2003) reported that 85% of ET was due to T in a semiarid savanna woodland in Arizona. Yepez et al. (2005) showed that E increased rapidly in the first few days after an experimental irrigation of a semiarid grassland plot, but that the soil surface dried after 7 days. Scott et al. (2006) partitioned ET into E (30%)

and T (70%) for 2003 at the Lucky Hills site, using eddy covariance and sap flow measurements on shrubs.

4.2. Comparison of grassland and shrubland sites

Overgrazing of livestock on semiarid ranges has led to the widespread conversion of grasslands to shrublands throughout the subtropics, with possible consequences for regional water balances (Huxman et al., 2004). Numerous studies (reviewed in Huxman et al., 2004, 2005) have compared grasslands and shrublands with respect to ET, ET/P, T/ET and RUE.

A simple model suggests that ET/P and T/ET decreases as grasslands convert to shrublands, as more bare soil is exposed than in shrublands (Holm et al., 2003; Huxman et al., 2005). The patchy distribution of vegetation in shrublands can increase erosion in the exposed areas, leading to further land degradation and runoff (Ludwig et al., 2005). This model was partially supported at the plot level in our study, as the Lucky Hills shrub site had significantly lower ET, EVI and ET/P than the Kendall grassland site. However, the ratios of T/ET did not appear to be different. At the wide area sites, Lucky Hills ET (estimated by EVI) was higher than at the Kendall site, and ET/P was 1.00 at the Lucky Hills site but only 0.75 at the Kendall site.

A single tower site cannot be expected to give representative data for a large landscape unit. Hence, it is possible that numerous tower sites scattered over the landscape would give different results than the single tower sites in this study. However, it is also possible that the larger landscape units have additional landscape features that ameliorate the ecohydrological differences between shrublands and grasslands, and create a tendency for RUE to converge across different water-limited ecosystems (Huxman et al., 2004). Flux towers typically measure moisture exchange over fetches of approximately 50 m, and the towers must be set in level areas of uniform vegetation type to produce reliable data (Rana and Katerji, 2000). Ludwig et al. (2005) showed that the steepness of slopes, soil types, and the intensity and duration of rainfall events can alter patterns of runoff, and they discuss why methods to study ecohydrological processes at the landscape scale are needed. By contrast to the tower sites, our wide areas sites encompassed areas with varying slopes as well as numerous ephemeral washes that drain the watershed. The washes are thickly vegetated, and it is likely that at the wide area sites, water that runs off the uplands was recaptured by vegetation in the washes, leading to high RUE at this level of measurement. As a general conclusion, however, grassland and shrubland sites did not differ greatly in water use efficiency in this study.

4.3. Seasonal and interannual lags in ET Versus P

Most of the monsoon rainfall in the southwestern US arrives in short-duration, low-volume pulse events. Loik et al. (2004) emphasized the importance of small, frequent precipitation events that only penetrate the top few cm of the soil in controlling water availability for plants in these climates. Small and Kurc (2003), working in shrubland and grassland habitats with annual precipitation of under 200 mm in central New Mexico, US, also concluded that ET is closely tied to surface soil moisture conditions, and found that bursts of ET following rainfall are typically of short duration (a few days). Kurc and Small

(2004) concluded that all but the largest rain events only moisten the top 10 cm of soil, and that ET should be closely coupled to *P*.

However, other studies have shown that water in arid and semiarid zone soils can be partitioned into two or more soil layers extending 5 m or deeper into the soil profile, with shallow layers supporting grasses and annual herbaceous plants, and deeper layers supporting shrubs and trees (e.g., Dodd et al, 1998; Lee and Lauenroth, 1994; Miller et al., 2001; Sala et al., 1981). In these savanna systems, plants can use water that accumulates over seasons or even years. *Bouteloua* spp., which dominated the Kendall site, normally derive most of their soil moisture from the top 15 cm of soil (Sala et al., 1981), but as that layer dries their roots penetrate deeper, and they can extract water from as deep as 60–90 cm in the soil profile (Dodd et al., 1998; Lee and Lauenroth, 1994). Ferretti et al. (2003) showed that unusually large spring rains in a semiarid grassland in Colorado moistened the soil to 0.5 m and that his moisture was transpired by vegetation in the early summer.

Our study showed that the majority of annual ET occurred during the summer monsoons. However, based on Figs. 5 and 6, the spring green-up period was supported in part by precipitation arriving in fall and winter (October–February). Following the unusually large fall rains of 2000 (due to a hurricane passing over the Gulf of California), both shrub and grassland sites showed a secondary peak of ET in winter and spring, and ET exceeded *P* in the two years following these rains. Scott et al. (2000), working at the same Lucky Hills and Kendall sites, found that fall and winter rain events of 200 mm recharged up to 100 mm of moisture into the soil profile to a depth of 2 m, while rains of 150–200 mm could recharge smaller volumes of water into the top 0.5 m of soil. Over a 16 year period from 1990 to 2005 at the Kendall site, 6 years had October–March precipitation greater than 150 mm, and 3 years (1993, 1995 and 2000) exceeded 200 mm (R. Scott, unpublished data). The mean October–March precipitation over that period was 105 mm, and the coefficient of variation was 74%. Hence, the winter rains may represent a significant supplemental source of water for plants in about a third of years in this ecosystem, but the monsoons represent the largest and most reliable source of water in all years.

Human-induced climate change is likely to affect the strength of El Nino cycles, through an increase in sea surface temperatures, but the magnitude and direction of the changes are currently not understood (Merryfield, 2006). Nevertheless, any change in the frequency or strength of El Nino events will impact the winter rain regime and hence the ecohydrology of the San Pedro watershed.

5. Conclusions

In support of Huxman et al. (2004), which showed a tendency for water-limited ecosystems to converge on a common, high value for water use efficiency, the native flora in this rangeland has apparently adapted to capture most of the annual *P* to support T. Most of the annual ET at grassland and shrubland sites was driven by summer monsoon rains, but winter precipitation also contributed to ET, and based on the statistical analyses, T was the dominant process contributing to ET at both sites. While the shrubland site had lower ET than the grassland site at the plot scale, the situation was reversed at the landscape scale, emphasizing the potential importance of scale in determining ecohydrological processes (Huxman et al., 2004; Ludwig et al., 2005).

Although woody plant encroachment is considered a form of land degradation, the ratio of ET/P was 1.00 over the wide-area Lucky Hills shrub site, supporting the concept that resilient landscapes retain the capacity for high water use efficiency even though plant functional-forms might change (Holm et al., 2002). On the other hand, severe land degradation could be expected to have more profound effects on the water balance.

Regarding the utility of remote sensing for scaling ET, the MODIS sensors on the Terra satellite offer a relatively simple method for scaling foliage density and related biophysical parameters such as ET and ANPP over mixed semiarid landscapes. Statistical analyses of measured ET rates versus time-series VI values and micrometeorological data not only provide a means to scale ET, but they can also reveal the relative importance of E, T and meteorological variables in driving ET and foliage density over large landscape areas. However, errors on the order of 20–30% in absolute values of ET estimates can be expected, due to limitations of the scaling method as well as errors inherent in the flux tower measurements (Rana and Katerji, 2000; Wilson et al., 2002).

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