Journal of Arid Environments 117 (2015) 84–95

Contents lists available at ScienceDirect

Journal of Arid Environments

journal homepage: www.elsevier.com/locate/jaridenv

Wide-area ratios of evapotranspiration to precipitation in monsoon-dependent semiarid vegetation communities

Edward P. Glenn [a,*], Russell L. Scott [b], Uyen Nguyen [a], Pamela L. Nagler [c]

[a] The University of Arizona, Department of Soil, Water and Environmental Science, 1177 E. 4th Street, P.O. Box 210038, Tucson, AZ 85721-0038, USA
[b] Southwest Watershed Research Center, USDA-Agricultural Research Service, 2000 E. Allen Road, Tucson, AZ 85719, USA
[c] US Geological Survey, Southwest Biological Science Center, Sonoran Desert Research Station, 1110 E. South Campus Drive, Room 123, Tucson, AZ 85721, USA

ARTICLE INFO

Article history:
Received 30 June 2014
Received in revised form
12 November 2014
Accepted 10 February 2015
Available online 2 March 2015

Keywords:
Remote sensing
Eddy covariance flux
MODIS
MODIS ET product
Enhanced vegetation index
Rangeland ecology
Shrub encroachment
Invasive grasses

ABSTRACT

Evapotranspiration (ET) and the ratio of ET to precipitation (PPT) are important factors in the water budget of semiarid rangelands and are in part determined by the dominant plant communities. Our goal was to see if landscape changes such as tree or shrub encroachment and replacement of native grasses by invasive grasses impacted ET and ET/PPT and therefore watershed hydrology in this biome. We determined ET and ET/PPT for shrublands, grasslands and mesquite savannas in southern Arizona at five moisture flux towers and determined the environmental factors controlling ET in each plant community. We then scaled ET over areas of 4–36 km^2, representing homogeneous patches of each plant community, using the Enhanced Vegetation Index (EVI) from MODIS sensors on the Terra satellite. Over wide areas, estimated ET/PPT projected from MODIS EVI ranged from 0.71 for a sparsely-vegetated shrub site to 1.00 for grasslands and mesquite savannas. The results did not support hypotheses that encroachment of mesquites into grasslands or that replacement of native grasses with introduced *Eragrostis lehmanniana* (lehmann lovegrass) have increased rangeland ET.

1. Introduction

In arid and semiarid (dryland) ecosystems the ratio of evapotranspiration (ET) to precipitation (PPT) is important because water not discharged in ET can produce runoff, erosion and groundwater recharge, with implications for erosion, aquifer properties and regional stream flows (Milly, 1994). Rather large shifts in ET/PPT and other ecohydrological variables have been attributed to changes in dryland vegetation communities (Moore and Hielman, 2012; Heilman et al., 2014). Zhang et al. (2001) presented a conceptual model based on a review of the literature, in which ET/PPT was higher in woodland and shrubland ecosystems compared to grasslands across the PPT spectrum, with the disparity increasing as PPT increased going from arid to semiarid to humid climate conditions. In theory, deeper-rooted woody plants can harvest more of the soil moisture arriving as PPT than the shallower-rooted grasses, resulting in higher ET/PPT ratios and less runoff and infiltration. Similar models (Dugas et al., 1998; Baldocchi et al., 2004; Farley et al., 2005) have been used to justify the removal of woody vegetation from upland regions to increase surface and subsurface runoff to enhance local stream flows (Tennesen, 2008) and as a caution against artificially increasing forest cover to capture carbon, as that might lead to reduced stream flows in critical ecosystems (Farley et al., 2005).

However, Huxman et al. (2005) pointed out that the Zhang et al. (2001) model as applied to semiarid regions was mainly supported by data from sites with predominantly winter precipitation. They argued that in monsoon-driven rangelands where most of PPT arrives as small rainfall events in summer, the relationship between ET and PPT is more complex. For semiarid systems driven by summer precipitation they postulated that the ratio of transpiration (T) to ET (T/ET) can be higher in woody compared to grass-dominated systems, but that the ET/PPT ratio can remain the same (near 1.0) as water not lost to T is discharged as evaporation due to the shallow penetration of summer PPT into the soil and high atmospheric water demand due to high air temperatures (T_{air}) (see also Kurc and Small, 2004, 2007).

Determining ET/PPT is challenging because both ET and PPT are subject to measurement errors that can be greater than the

* Corresponding author.
E-mail addresses: eglenn@ag.arizona.edu (E.P. Glenn), russ.scott@ars.usda.gov (R.L. Scott), uyenn@email.arizona.edu (U. Nguyen), pnagler@usgs.gov (P.L. Nagler).

http://dx.doi.org/10.1016/j.jaridenv.2015.02.010
0140-1963/

difference between ET and PPT in many semiarid ecosystems. Non-intrusive ground measurements of ET from eddy covariance flux towers, are subject to errors and uncertainties on the order of 10–30% (Allen et al., 2011), and measurements of PPT are prone to uncertainty if too few gages are deployed to capture the inherent spatial variability of infrequent rains over wide areas (Goodrich et al., 2008; Yathereendradas et al., 2008). Furthermore, tower results are only applicable to the footprint source area of the local measurements, while PPT, ET and plant stand density vary widely over most arid and semiarid landscapes. PPT and ET can also differ greatly from year to year, so patterns observed over short measurement intervals might not reflect long term trends.

This study compared ET and ET/PPT for semiarid, monsoon-dependent grasslands, mesquite savannas and shrublands in the southwestern U.S. by combining long-term moisture flux tower results with satellite imagery from the Moderate Resolution Imaging Spectrometer (MODIS) sensors on the NASA Terra satellite. The study was conducted in two well-characterized study areas: the Walnut Gulch Experimental Watershed (WGEW) (Moran et al., 2008) near Tombstone, AZ, and the Santa Rita Experimental Rangeland (SRER) (Sayre, 2003) near Tucson, AZ. Both areas are a patchwork of vegetation communities. Eddy covariance and Bowen ratio moisture flux towers have characterized ET in different plant communities in these rangelands (e.g., Emmerich, 2003; Scott et al., 2010) providing data on which remote sensing can be applied to scale ET over whole plant communities rather than just over the footprint area of the flux towers (Bunting et al., 2014). The rich sources of ground data available for validation offered an opportunity to scale ground measurements of ET over wide areas with remote sensing to test hypotheses about response of ET/PPT to land cover changes.

Three prominent trends have been identified in these rangelands. First, *Prosopis velutina* (velvet mesquite) trees have encroached into the grassland in the SRER and the higher elevation regions that surround WGEW (for WGEW see Kepner et al., 2000, 2002; King et al., 2008; for SRER see McClaran, 2003) with the potential for increasing ET through their early green-up and deep root systems, thereby possibly decreasing recharge and runoff as noted in other grasslands undergoing woody plant encroachment (Tennesen, 2008; Farley et al., 2005).

The second trend is the spread of introduced *Eragrostis lehmanniana* (Lehmann's lovegrass) at the expense of native C4 grasses in both WGEW (Hamerlynck et al., 2012) and SRER (McClaran, 2003). This conversion could also increase upland ET due to the possible earlier green-up and deeper root system of *E. lehmanniana* compared to native grasses (Frasier and Cox, 1994) and production of 2–4 times more biomass per unit area compared to native grasses (Anable et al., 1992). Third, historic overgrazing in the lower-rainfall portions of both WGEW and SRER has resulted in the conversion of some native grasslands to sparse shrublands dominated by *Larrea tridentata* (creosote) (Emmerich, 2003; Cavanaugh et al., 2011), with a possible reduction in ET and an increase in runoff and erosion (Tromble, 1988; Ritchie et al., 2005; Turnbull et al., 2010; Brazier et al., 2014).

These three expectations of shifts in ET and ET/PPT due to land cover changes have not been systematically tested at the landscape scale of measurement. Our goal was to develop remote sensing algorithms for ET to explore wide-scale patterns of ET/PPT across ecosystem types, including those subject to vegetation changes. We first determined the environmental factors controlling ET in each plant community type, then developed remote sensing algorithms to scale ET and ET/PT over wide areas and multiple years within WGEW and SRER with meteorological data and satellite imagery.

Vegetation conversions are taking place throughout the world's semiarid ecosystems and are tipping the water balance towards more runoff and erosion in some systems (when replacement vegetation uses less water than the original vegetation) (Farley et al., 2005; Tennesen, 2008), or towards less aquifer recharge and lower stream flows (when the replacement vegetation uses more water than the original vegetation) (Tromble, 1988; Ravi et al., 2010). The present study offers a remote sensing approach to the problem of estimating wide-area ET and ET/PPT in sparsely vegetated ecosystems.

2. Materials and methods

2.1. Overview of research

A number of Ameriflux eddy covariance flux towers have been installed in grasslands, mesquite savannas and shrublands in WGEW and SRER. These provide estimates of ET over footprint areas of several thousand square meters at each tower site. Our objectives were, first, to determine the environmental factors that are most closely correlated with seasonal and inter-annual values of flux tower ET in each plant community; then, second, to develop remote sensing ET algorithms based on a vegetation index (VI) approach that could be applied to grasslands, shrublands and mesquite savannas in our study area to compare their water use characteristics and in particular their ET/PPT ratios.

PPT and therefore ET are episodic in these rangelands. Therefore, a frequent-return satellite was needed to acquire VI data. Vegetation communities tend to be homogeneous over areas of 1 km^2 or greater (King et al., 2008; Scott, 2010). Therefore, high-resolution imagery was not necessary. We chose to use the Moderate Resolution Imaging Spectrometer (MODIS) sensors on the Terra satellite for image acquisition (Huete et al., 2011). It has a near-daily return time and supplies 16-day, 250 m resolution, composite images for the best cloud-free days in each period. We used the Enhanced Vegetation Index (EVI) as the VI in this study. It was better correlated with ET than the Normalized Difference Vegetation Index (NDVI) in previous ET studies in the southwestern U.S. (Nagler et al., 2005, 2007).

2.2. Study sites

The location and general characteristics of each study site in WGEW and SRER are in Table 1. WGEW, established by the USDA in 1953, is located in southeastern Arizona and occupies 14,900 ha surrounding the town of Tombstone (Nichols and Renard, 2007). Elevations range from 1190 to 2150 m and annual precipitation is approximately 312 mm (1956–2005), with 60% arriving in the summer monsoon (July–September) and most of the rest as winter storm fronts. There is evidence that much of the area was formerly grassland, but possibly due to heavy grazing over the past 150 years, mid-slope and ridge areas have converted to shrublands and about one-third of the area remains as grassland (Biedenbender et al., 2004; King et al., 2008). *P. velutina* trees have encroached into some of the remaining grassland areas (Kepner et al., 2000, 2002) although the timing of this conversion is not agreed upon (King et al., 2008). SRER is a 21,500 ha area of protected rangeland about 70 km south of Tucson, AZ, ranging in elevation from 900 m to 1300 m, with mean precipitation of about 345 mm yr^{-1}, increasing from 250 mm yr^{-1} to 500 mm yr^{-1} along the elevation gradient within the rangeland (Sayre, 2003; McClaran, 2003). Established in 1903, SRER has a long history of experimental manipulations to enhance grazing potential for cattle, including introduction and subsequent spread of *E. lehmanniana*, clearing of encroaching *P. velutina*, and control of fire regimes in selected areas of the rangeland. The middle to upper elevations of the SRER are

Table 1
Location and characteristics of sites used in this study. All sites were equipped with an eddy covariance moisture flux tower except SRER Mesquite-2, for which only MODIS satellite data was available.

Site name	Lat/Lon	Tower ET Data period	Elevation (m)	Vegetation type
SRER Mesquite Savanna	Santa Rita Experimental Rangeland, 31.821 N, 110.866 W	DOY 1, 2004 – DOY 365, 2012	1116	Mesquite savanna, ca. 35% *P. velutina*, 22% grasses, 43% bare soil, litter
WGEW Kendall Grassland	Walnut Gulch Experimental Watershed, 31.736 N, 109.941 W	DOY 128, 2004 – DOY 365, 2012	1531	Formerly dominated by native C4 grasses, converted in 2007 *Eragrostis lehmanniana* grass, 15–70% cover, 30–85% soil + litter
WGEW Lucky Hills Shrubland	Walnut Gulch Experimental Watershed, 31.743 N, 110.052 W	DOY 128, 2004 – DOY 365, 2004; DOY 180, 2007 – DOY 365, 2012.	1370	Ca. 50% canopy cover with*Larrea tridentata*, *Parthenium incanum; Acacia constricta*; other shrubs and forbs, 50% bare soil, litter.
SRER Creosote	Santa Rita Experimental Rangeland, 31.908 N, 110. 839 W	DOY 200–285, 2008	1000	24% vegetation cover; 14% *Larrea tridentata*, 10% grasses, forbs, others; 76% bare soil, litter
SRER Grassland	Santa Rita Experimental Rangeland, 31.789 N, 110.827 W	DOY 51, 2008 – DOY 365, 2012	1291	Ca. 70% grasses, mostly *E. lehmanniana*, 10% *P. velutina*, 20% bare soil, litter
SRER Mesquite-2	Santa Rita Experimental Rangelands, 31.802 N, 110.820 W		1278	45% *Prosopis velutina*, 65% grasses, 20% bare soil, litter

primarily semi-desert grasslands, most now thoroughly encroached by mesquite trees to form savannas with *E. lehmanniana* as the dominant grass, but with areas of *Larrea tridentata* – dominated sparse shrublands in the lower elevation portions of the range.

Four tower sites were used to determine the environmental controls on ET and to develop and validate a predictive ET algorithm based on MODIS EVI. Two tower sites were in WGEW and two were in SRER (Table 1). The WGEW Kendall Grassland Ameriflux site has operated from 2004 to the present (Scott, 2010; Scott et al., 2010). We used data for the years 2004–2012. From 1974–2005 the vegetation at the Kendall site consisted predominantly of the native C4 grasses *Bouteloua curtipendula* (sideoats grama), *Bouteloua eriopoda* (black grama) and *Bouteloua hirsuta* (hairy grama), along with the introduced C4 grass, *E. lehmanniana*, and with a few shrubs of *Calliandra eriophylla* (fairy duster) and *Haplopappus tenuisectus* (burroweed) (Emmerich, 2003). The native grasses died back in 2006 due to a severe drought from 2003 – spring 2006 (Moran et al., 2009a; Hamerlynck et al., 2012; Polyakov et al., 2010). They were succeeded in 2006 by a flush of broadleaf forbs, including annuals (primarily *Allonia incarnata*, *Chamaesyce hyssopifolia*, *Kallstromeia grandiflora*, and *Mimulus* spp.) and perennial species (*Bahia absinthifolia* and *Evolvulus arizonicus*) during the monsoon season, and then by *E. lehmanniana* from 2007 to the present. Total vegetation cover measured during the monsoon season in 2005 was 47% (King et al., 2008).

A second tower site in WGEW was the Ameriflux Lucky Hills Shrubland site, about 10 km from the Kendall tower, in shrubland habitat. Elevation is 1375 m and annual precipitation is about 322 mm. Data were available for day of year (DOY) 128, 2004 to DOY 365, 2004 and DOY 180, 2007 to DOY 365, 2012. The site was thought to have originally been dominated by *B. eriopoda* but converted to dominance by Chihuahuan desert shrubs due to historic overgrazing (Emmerich, 2003). Based on a 2004 survey (cited in Scott et al., 2006), total vegetation cover was 51% consisting *L. tridentata*, *Parthenium incanum* (mariola), *Acacia constricta* (whitethorn acacia) and other shrubs in less abundance. The site has a very sparse understory of herbs and grasses. Estimates of total vegetation cover have ranged from 51% in 2004 to 27% in 2008.

Data from two primary tower sites in SRER were used in the present study. The Ameriflux SRER Mesquite Savanna site (Scott, 2010) is at an elevation of 1116 m. Cover consisted of 35% *P. velutina*, 22% grasses, subshrubs and succulents, and 43% soil or litter. *E. lehmanniana* is the dominant vegetation between trees (Scott et al., 2009). Data from 2004–2012 was used in the study. Data for 2008–2012 from the SRER Grassland site was also used for model calibration and validation (R. Scott unpublished data). The site is in a former mesquite savanna area that had been fenced and cleared of mesquite to encourage development of grasses. The dominant grass species is *E. lehmanniana*. Elevation is 1296 m. Based on archival imagery in Google Earth, the site was nearly devoid of tree cover in 1992, but tree cover had increased to about 10% by 2011. An uncleared control site (SRER Mesquite-2) 2.5 km from the SRER Grassland site was selected for comparison with the grassland site in the present study. There was no tower at this site (MODIS data only). Tree cover in 2011 was about 40% based on imagery in Google Earth. A further validation site was the SRER Creosote site, using tower data collected during the monsoon season in 2008 (Cavanaugh et al., 2011). This site has 24% total vegetation cover, 14% of which was *L. tridentata* in 2008. Elevation is 1000 m and mean annual precipitation is about 345 mm (Cavanaugh et al., 2011).

2.3. Environmental and ET measurements at flux towers

Details of the instrumentation and data processing procedures at the SRER Mesquite Savana, WGEW Kendall Grassland and WGEW Lucky Hills flux tower sites are in Scott (2010) and are described briefly here. Equipment and procedures were the same at the SRER Grassland site, 2008–2012 (Scott, unpublished). Above-canopy net radiation (R_n) was measured above the canopy using a 4-component radiometer (CNR1, Kipp & Zonen, Delft, The Netherlands) at the SRER Mesquite Savanna, SRER Grassland and WGEW Kendall Grassland sites and a 2- component net radiometer (CNR2, Kipp & Zonen) at the shrubland site. Also at these sites, photosynthetically active radiation (PAR; LI-190, LI-COR, Lincoln, NE) sensors measured upwelling and downwelling fluxes. Ground heat flux was measured with soil heat flux plates ($n = 5$–8 per site, REBS Inc., Seattle, WA) installed 0.05 m below ground level under both inter-canopy and under-canopy positions. Precipitation (PPT) was quantified at the sites by using tipping-bucket rain gages (TE525, Campbell Scientific, Inc.) at SRER Mesquite Savanna and Grassland sites and Belfort weighing-recording gages at the WGEW Kendall Grassland and Lucky Hills Shrubland sites. At all the sites there was an additional precipitation gage at or near the site (<0.5 km), and these were used as a check on the accuracy of the primary precipitation gage. The difference between the primary and check gage annual totals averaged less than 5 mm (Scott, 2010). Precipitation data for the SRER Creosote site was from the NE SRER gage located about 600 m from the tower site (http://ag.arizona.edu/SRER/precip/precip.xls).

ET was measured with the eddy covariance systems that consisted of three-dimensional, sonic anemometers (CSAT-3; Campbell Scientific) and open-path infrared gas analyzers (LI-7500, LI-COR) mounted 5 m above the height of the vegetation to measure the three components of the wind velocity vector, sonic temperature and concentrations of water vapor and carbon dioxide. Data were sampled at 10 Hz. Covariances were calculated by first filtering spikes and then using a 30-min block average. The fetch at all of the sites is representative of the cover immediately surrounding the towers over several kilometers.

A comparison of flux tower ET results with site water balance measurements was conducted for WGEW Kendall Grassland, WGEW Lucky Hills Shrubland and SRER Mesquite Savanna sites using 13 years of site data (Scott, 2010). Each site was equipped with a tipping bucket rain gage to measure precipitation and soil moisture sensors to measure changes in soil moisture following rain events. In addition, each site was located in a local catchment area for which runoff was measured through a series of flumes and weirs. Hence, an on-going site water balance could be constructed to estimate ET for comparison with eddy covariance data in daily time steps. The two independent methods agreed within 3% over all years, and varied by 10%–17% for any given year, hence the flux tower estimate was in good agreement with the site water balance, especially when aggregated across years.

Commonly, 30 min latent and sensible heat fluxes measured at eddy covariance flux towers do not add up to the $R_n - G$ terms in the energy balance equation, and they are corrected for "energy closure" by the method of Twine et al. (2000). However, Scott et al. (2010) found that introducing this correction led to worse agreement between flux tower and water balance methods in nine of the 13 years of measurement; furthermore, increasing the ET term to force closure led to ET greater than PPT in many of the years. Hence, in this study we did not force energy closure in calculating ET. ET calculated without forcing energy closure was lower than ET with forced closure by 11.9% for the SR Grass tower; 7.2% for the SRER Mesquite Savanna tower; 9.5% for the WGEW Lucky Hills Shrubland tower; and 6.7% for the WGEW Kendall Grassland tower.

2.4. MODIS imagery

MODIS EVI data were obtained from the Oak Ridge National Laboratory DAAC site (ORNL DAAC, 2014) in the form of MOD13Q1 16-day composite images. The ORNL MODIS subset tool displays the approximate pixel footprint area (6.25 ha) on a high-resolution Google Earth image. We obtained data for single pixels encompassing WGEW Kendall Grassland and SRER Mesquite Savanna tower sites for 2004–2012, for WGEW Lucky Hills Shrubland site for 2004 and 2007–2012 and for the SRER Grassland site from 2008 to 2012. Wide-area pixel arrays were also obtained for each study site for 2004–2012. The areas were selected based on apparent homogeneity of habitat type around each tower site by inspection of Google Earth imagery. For the SRER Grassland site, a 4 km^2 area encompassing most of the fenced, mesquite-cleared area was selected. The SRER Mesquite-2 and SRER Creosote sites were also 4 km^2. For the WGEW Kendall Grassland and SRER Mesquite Savanna sites, 36 km^2 areas (6 km $\times$ 6 km) of apparently homogeneous habitat type centered on each tower site were collected. The WGEW Lucky Hills Shrubland wide-area site was also 36 km^2 but was offset to the north of the tower site to avoid encompassing developed areas near Tombstone: the center of this polygon was at 31.7929 Latitude, −110.0589 Longitude.

MODIS science products also include 1 km resolution ET estimates, based on an algorithm developed by Mu et al. (2011). This algorithm uses MODIS land cover classification, MODIS leaf area index, EVI and daily meteorological data from NASA's Global Modeling and Assimilation Office as input data and calculates ET at 8-day, monthly or annual intervals. We obtained single pixels of the 8-day MOD16A2 product from the ORNL DAAC website for the SRER Mesquite and Grassland and the WGEW Lucky Hills Shrubland and Kendall Grassland tower site locations.

2.5. Determining the best predictors of ET at tower sites

We conducted correlation analyses between ET measured at the four primary flux tower sites with EVI as a measure of green plant density and environmental variables measured in monthly time steps. Environmental variables included PPT, vapor pressure deficit (VPD), T_{air}, net radiation (R_n) and two estimates of reference crop ET (ET_o), using either the Penman-Monteith FAO-56 formula for a hypothetical short grass reference crop ($ET_{o\text{-}PM}$) (Allen et al., 1998) or the Blaney–Criddle formula ($ET_{o\text{-}BC}$) (Brouwer and Heibloem, 1986), which is simply based on mean monthly T_{air} and latitude to estimate monthly daylight hours.

EVI and environmental variables were then combined in multiple linear regression analyses to determine the best predictive equation for ET at the four primary tower sites. Statistical analyses were carried out using procedures described in Montgomery et al. (2012) with SigmaPlot Version 12.5 (Systat Software, Inc., San Jose, CA). All predictive variables were used in a best-subsets regression analysis, then the subset of variables that had the highest adjusted r^2 and the lowest Mallows coefficient (C_p) was accepted as the most parsimonious set to use as predictors (Montgomery et al., 2012). ET data across sites were then combined to determine if a common relationship could be determined across sites using the minimum possible explanatory variables. The standardized coefficient (β coefficient) for each explanatory variable was calculated to assess its individual contribution to the equation of best fit (Montgomery et al., 2012). Multicollinearity among predictive variables was tested by calculating Variable Inflation Factors (VIF) for each variable (Montgomery et al., 2012).

2.6. Developing a common ET algorithm across plant communities

In addition to developing separate regression equations for ET in each plant community, we attempted to develop a generalized algorithm that could be applied across plant community types. This is important because plant communities are patchy within WGEW and SRER and wide area scenes often contain mixed plant communities. We used a VI approach to scaling ET from potential or reference crop ET (ET_o) (Bausch and Neale, 1987). The FAO-56 formula for determining crop ET (Allen et al., 1998) is:

$$ET = K_c ET_o \tag{1}$$

where ET_o is calculated from meteorological data. K_c is normally an empirical coefficient relating crop ET at a particular growth stage to the potential ET. A VI can replace K_c, providing information about the actual status of the vegetation at the time of measurement (Bausch and Neale, 1987). Vegetation index algorithms for ET take the form:

$$ET = f(\mathrm{VI}) * ET_o \tag{2}$$

where the function f(VI) replaces K_c in Equation (1). ET is not necessarily a linear function of a VI, because VIs, as well as leaf area index (LAI), have a non-linear relationship with light absorption by a canopy and with physiological processes that depend on light absorption (Choudhury, 1987). Although developed originally for crops (Bausch and Neale, 1987), VI methods have been successfully applied to a wide variety of natural ecosystems (Glenn et al., 2011) including semi-arid grasslands and shrublands (Nagler et al., 2007;

Bunting et al., 2014) and even sparse desert shrub communities (Breshlof et al., 2013). Algorithms of the type in Equation (2) have been successfully applied to mixed plant communities and even mixtures of agricultural and natural ecosystems but they need to be calibrated and validated for each new application (Glenn et al., 2011). The final ET equation was determined by regressing tower ET against EVI(ET_o) using curve-fitting procedures in SigmaPlot software. It took the form:

$$ET = a\left(1 + e^{-(ET_o{*}EVI - b)/c}\right) \quad (3)$$

where a,b and c are coefficients determined by regression, and the term $(1 + e^{-(ETo{*}EVI\ -\ b)/c})$ is a logistic (sigmoidal) equation describing the behavior of ET with respect to ET_o*EVI, consisting of an initial lag period, a period of exponential increase, and a final period of slower rise then leveling off (Nagler et al., 2005).

The algorithm was calibrated and validated by splitting data from WGEW Kendall Grassland, WGEW Lucky Hills Shrubland, SRER Grassland and SRER Mesquite Savanna sites into two subsets each. The first subset, representing the first half of the time series at each site, was used for determining the regression coefficients in Equation (3). The second subset, representing the last half of the time series at each site, was used for testing the goodness of fit between ET calculated by the ET algorithm and tower ET measured over the second half of the measurement period. The combined data set was used to determine the root-mean-square error (RMSE), bias and r^2 of the ET algorithm. Differences between slopes of modeled versus measured ET were tested for significance with the t-test method (Cohen et al., 2003). Determining if slopes were different from 1.0 was tested by constructing 95% confidence intervals around regression lines. Results were compared to ET estimates obtained as MOD16A2 ET estimates.

3. Results

3.1. General patterns of ET and environmental variables at calibration flux tower sites

EVI (Fig. 1A) and tower ET (Fig. 1B) at Kendall Grassland and SRER Mesquite sites followed regular annual cycles, with main peaks during the summer monsoon rains (Fig. 1C), and with annual peak heights approximately matched to the magnitude of the rains. At both sites, smaller peaks of EVI and ET were also evident in spring of some years (e.g., 2005, 2010), apparently tied to cool season (November–March) rains. The Kendall Grassland site had 15–20% lower EVI, PPT and ET than the SRER Mesquite site ($P < 0.05$). Similar time series results observed at the WG Lucky Hills Shrubland and SR Grass tower sites (not shown).

3.2. Correlation between ET and environmental variables

Monthly ET at grassland, shrubland and mesquite savanna sites had very similar responses to environmental variables as determined by correlation analyses (Table 2). The strongest correlation for all four main tower sites was between ET and EVI, which by itself explained over 70% of the variability in monthly ET ($r = 0.853$–0.880 among sites). Next in importance was PPT ($r = 0.684$–0.784), followed by air temperature, $ET_{o\text{-}BC}$ and $ET_{o\text{-}PM}$ for meteorological variables. VPD was not significantly correlated with ET at the SRER Mesquite and WGEW Kendall Grassland sites, and was a positive factor at the SRER Grassland and WGEW Lucky Hills Shrubland sites. EVI, in turn, was significantly correlated with PPT at all tower sites, with r values of 0.589 for SRER Mesquite Savanna, 0.643 for WGEW Kendall Grassland, 0.509 for SRER Grassland, and 0.555 for WGEW Lucky Hills Shrubland (all significant at $P < 0.001$).

3.3. Multiple regression analyses

Multiple regression analyses were conducted for the mesquite savanna, shrubland and one grass (WGEW Kendall Grassland) sites. For all three, the set of variables that produced the highest adjusted r^2 and the lowest C_p were EVI, PPT, T_{air}, VPD and R_n. However, the last three variables had VIF >4.0, indicating that these variables exhibited collinearity. Final equations that contained only EVI, PPT and T_{air} had low VIFs and high adjusted r^2 values (Table 3). Standardized coefficients (β coefficients) indicate the relative importance of each variable in explaining the variance in the dependent variable, and were similar for all three sites, with EVI explaining 59–62%, PPT 28–36% and T_{air} 10–27% of the explained variance in ET (Table 3). A combined regression equation across tower sites had an r^2 of 0.82.

The relationships between ET and PPT or EVI were linear (Fig. 2A and B). The relationship between ET and T_{air} was more complicated (Fig. 2C). One group of points showed a linear increase in ET with T_{air}, as expected when the plants are not water-limited, as during the summer monsoon season. A second group showed little response of ET to T_{air}, as expected when plants are water-limited as during the early summer pre-monsoon period, when T_{air} is high but soil moisture levels are low. A third group was intermediate between the two extremes.

3.4. Generalized algorithm for estimating ET from EVI

We also developed a generalized algorithm based on the simple crop coefficient approach in Equation (2), using $ET_{o\text{-}BC}$ and EVI as the predictors of monthly ET for the first half of the time series data at each flux tower site with multiple years of data (SRER Mesquite Savanna, SRER Grassland, WGEW Kendall Grassland and WGEW Lucky Hills). The response of ET to EVI($ET_{o\text{-}BC}$) was best fit with a logistic (sigmoidal) curve (Fig. 3A), with $r^2 = 0.82$ (SEM = 0.302). The logistic function was:

$$ET = 4.03\Big/\left(1 + e^{-(ET_{o\text{-}}BC\ (EVI) - 1.44)/0.458)}\right) \quad (4)$$

The constant 4.03 sets an upper limit for mean monthly ET in mm d^{-1}, which is then diminished according to the divisor in Equation (4), which tends towards 1.0 when $ET_{o\text{-}BC}$(EVI) becomes large compared to the constant 1.44. Since the response of Tower ET to EVI was linear (Fig. 2A), the sigmoidal shape of the ET to EVI($ET_{o\text{-}BC}$) curve suggests that this is due to the non-linear response of ET to T_{air} (Fig. 2C) since $ET_{o\text{-}BC}$ is based mainly on T_{air} with a correction for differences in hours of daylight per month. In fact, an alternative analysis using T_{air} instead of $ET_{o\text{-}BC}$ also produced a sigmoidal curve with $r^2 = 0.82$ (data not shown).

When Equation (4) was applied to EVI and $ET_{o\text{-}BC}$ for the second half of each time series, MODIS ET predicted Tower ET with $r^2 = 0.72$ and slope not significantly different from 1.0 or the calibration regression line ($P > 0.05$). Environmental conditions were similar for first and second halves of the time series, with mean T_{air} of 18.6 °C and 18.0 °C, and PPT of 289 mm yr^{-1} and 316 mm yr^{-1}, respectively. Combined data sets also produced a scatter plot whose slope was not significantly different from 1.0 ($P < 0.05$) (Fig. 3B). The algorithm in Fig. 3A predicted ET of the combined set with $r^2 = 0.75$, RMSE = 0.362 mm d^{-1} and bias = 0.076 mm d^{-1} (Fig. 3B). MODIS ET estimates were also compared to literature values for Tower ET for the SRER Creosote site measured during the 2008 summer monsoon season (Cavanaugh et al., 2011). Using Equation (3), MODIS ET and Tower ET estimates agreed within 13% of each

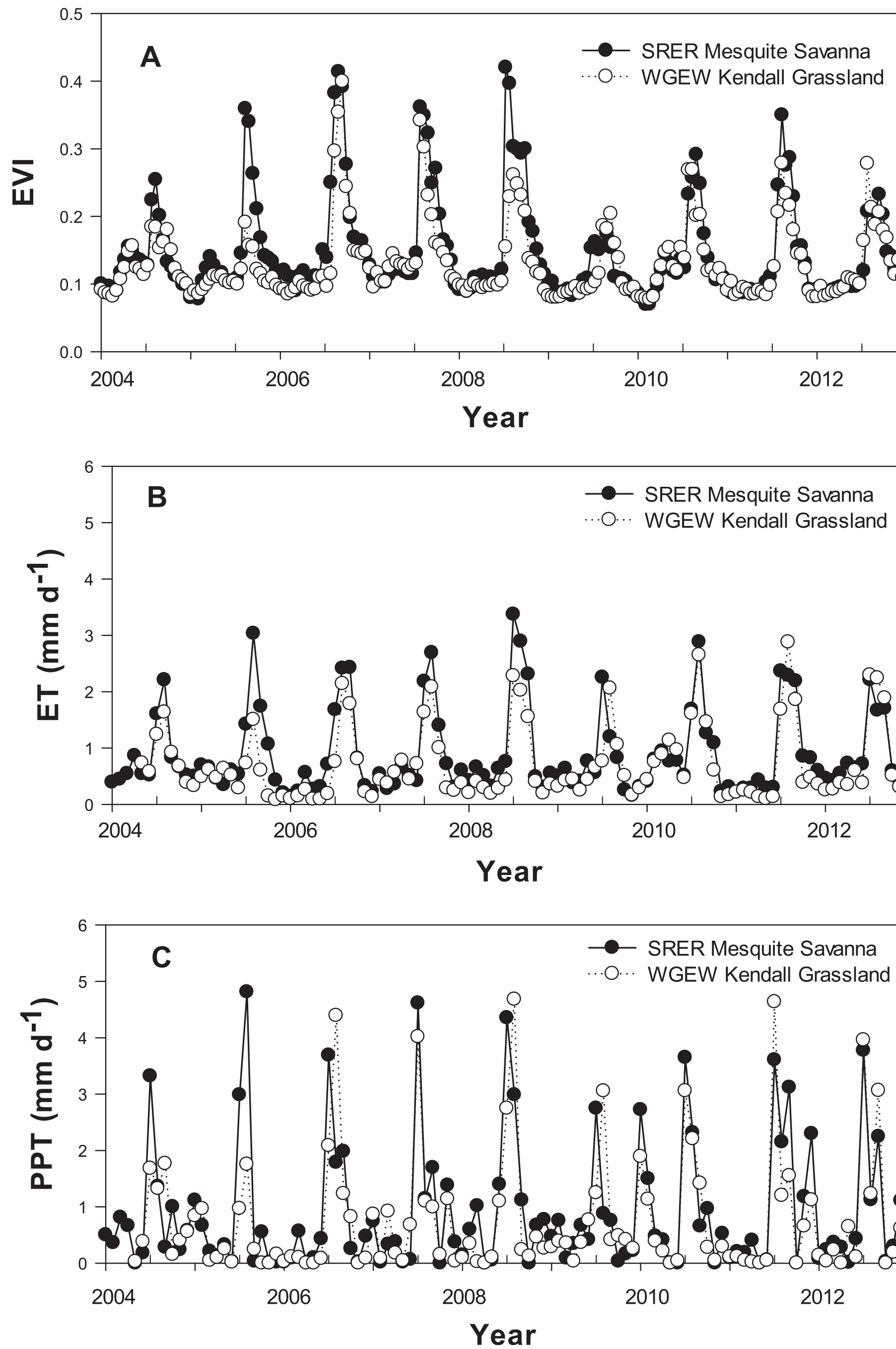

Fig. 1. 16-day means of EVI (A), tower ET (B) and precipitation (C) at SRER Mesquite (closed circles) and Kendall Grassland (open circles) tower sites, 2004–2012.

other. Tower ET and MODIS ET are compared for all sites in Table 4. The mean value of MODIS ET across sites and years was 6.5% lower than Tower ET, indicating a small amount of apparent bias in the MODIS ET estimate. Differences between MODIS ET and Tower ET ranged from +5.3% to −14.5% for individual sites.

By contrast to ET estimated by Equation (3), ET from MOD16A2 under-predicted Tower ET by 54.7% across sites (Table 4). The mean r^2 between Tower ET and MOD16A2 ET was 0.66 and ranged from 0.60 to 0.73 among tower sites, lower than the r^2 for Equation (4). The MODIS land classification program also failed to differentiate among plant community types in this study, classifying all as open shrublands.

3.5. Wide-area estimates of ET/P based on MODIS ET estimates

We concluded that ET of grasslands, shrublands and mesquite savannas converged in their response to environmental variables and that the MODIS ET algorithm in Equation (3) was sufficiently accurate to project tower ET values across larger landscape areas within the region. This algorithm was preferred over the separate regression equations in Table 3 because it did not contain PPT as an explanatory variable for ET, which could lead to possible spurious autocorrelation in predicting ET/PPT. Also, over wide areas it is difficult to distinguish between different plant communities without detailed vegetation maps, which would be needed if

Table 2
Correlation coefficient between monthly means of environmental variable and ET measured at Four flux tower sites in southern Arizona, 2004–2012. Asterisks denote significance at >0.05 (n.s.), <0.05 (*), <0.01 (**) or <0.001 (***).

Variable:	SRER Mesquite ET	WGEW Kendall Grassland ET	SRER Grassland ET	WGEW Lucky Hills Shrubland ET
EVI	0.880***	0.853***	0.866***	0.871***
Precipitation	0.749***	0.784***	0.725***	0.684***
Air Temperature	0.564***	0.522***	0.549***	0.709***
ET_o Blaney–Criddle	0.532***	0.499***	0.521***	0.725***
ET_o FAO-56	0.314***	0.307**	0.341**	0.504***
Vapor Pressure Deficit	0.164n.s.	0.173n.s.	0.521***	0.442***
Radiation	0.172n.s.	0.250*	0.184n.s.	0.420***

different algorithms were required for each plant community. Seasonal patterns of PPT and MODIS ET at wide-area grassland, mesquite savanna and shrubland sites are in Fig. 4. All sites had the same basic seasonal patterns of ET, with minor peaks in spring and early summer corresponding to spring green-up and major peaks in the monsoon season. However, PPT and projected ET were notably higher in the mesquite savanna (Fig. 4A and B) and grassland (Fig. 4C and D) sites than in the shrubland (Fig. 4E and F) sites.

Wide-area ET, PPT and ET/PPT mean values across years are in Table 5. ET was lower ($P < 0.05$) at the two shrub sites compared to the SRER Mesquite Savanna and Grassland sites, while WGEW Kendall Grassland was intermediate. However, PPT was also lower at those sites, and there were no significant differences in ET/PPT for five of the six sites ($P > 0.05$), with values of 0.88–1.00. The SRER Creosote site, with ET/PPT of 0.71 was significantly different from the SRER Mesquite Savanna, SRER Grassland and SRER Mesquite-2 sites ($P < 0.05$) but overlapped with WGEW Kendall Grassland and WGEW Lucky Hills Shrubland sites ($P > 0.05$). A regression of ET on PPT showed a linear relationship existed, but the slope of the line (0.87) was significantly lower ($P < 0.05$) than 1.0 (Fig. 5), indicating that as PPT increases, the proportion discharged as ET decreases as well.

Table 3
Multiple linear regression analyses of tower ET predicted by monthly environmental variables at SRER Mesquite Savanna, WGEW Kendall Grassland and WGEW Lucky Hills Shrubland sites, 2004–2012.

Site/Variable	Coefficient	Std. error	β coefficient	t	P	VIF
1. SRER Mesquite						
Constant	−1.12	0.096	–	−11.6	<0.001	–
EVI	10.4	0.73	0.625	14.2	<0.001	1.79
PPT	0.236	0.026	0.361	9.13	<0.001	1.54
T_{air}	0.0109	0.0042	0.095	2.58	0.011	1.35
Adj. $r^2 = 0.89$						
2. Kendall Grassland						
Constant	−0.600	0.101	–	−5.93	<0.001	–
EVI	7.46	0.80	0.588	9.38	<0.001	2.00
PPT	0.204	0.035	0.334	5.75	<0.001	1.71
T_{air}	0.0103	0.005	0.099	1.93	0.057	1.36
Adj. $r^2 = 0.80$						
3. Lucky Hills						
Constant	−0.708	0.089	–	−7.95	<0.001	–
EVI	8.57	0.96	0.543	8.97	<0.001	2.17
PPT	0.162	0.027	0.321	5.94	<0.001	1.35
T_{air}	0.0109	0.0052	0.266	3.27	0.039	1.85
Adj. $r^2 = 0.85$						
4. Combined						
Constant	−0.813	0.063	–	−12.8	<0.001	–
EVI	8.50	0.528	0.603	16.1	<0.001	2.17
PPT	0.173	0.021	0.283	8.38	<0.001	1.76
T_{air}	0.0152	0.003	0.147	4.83	<0.001	1.42
Adj. $r^2 = 0.82$						

We also compared EVI, MODIS ET, PPT and ET/PPT values for the WGEW Kendall Grassland site for the years 2000–2005, when native C4 grasses dominated the site, and 2007–2012, when *E. lehmanniana* was dominant, to see if the vegetation change resulted in a change in foliage density. Wide-area EVI values were used to calculate MODIS ET. No significant differences were found in any of the variables between the two periods (Table 6).

4. Discussion

Grasslands, shrublands and mesquite savannas in this semiarid biome responded similarly to environmental factors. The main determinant of ET was green plant cover, as measured in this study

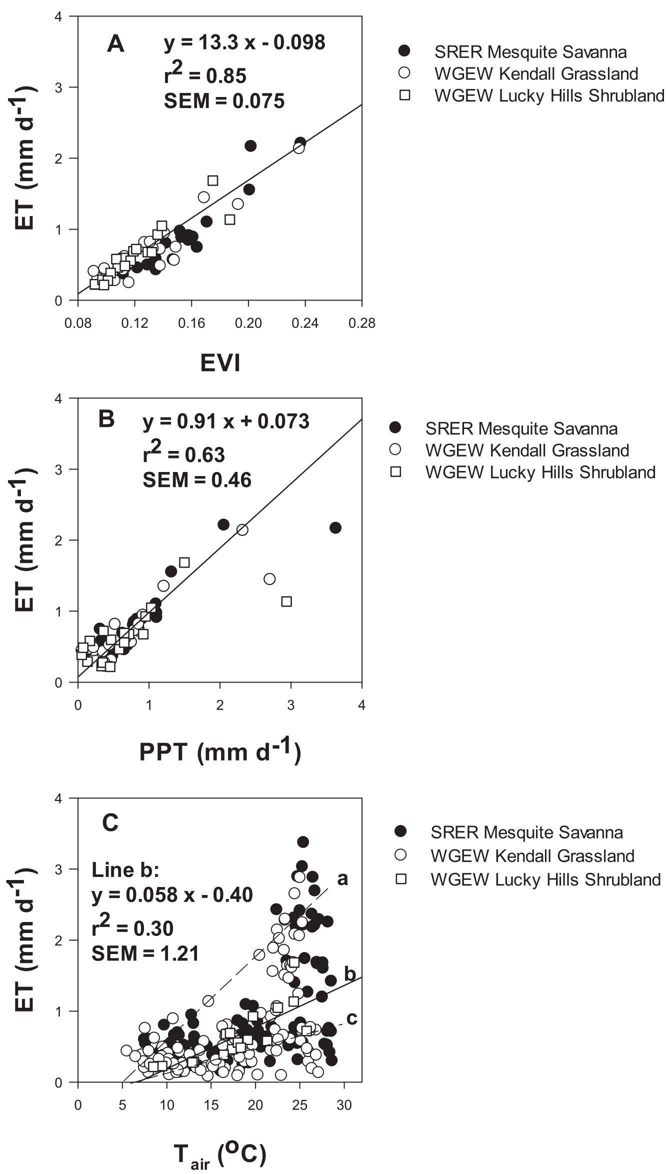

Fig. 2. Tower ET regressed against EVI (A), PPT (B) and T_{air} (C) at SRER Mesquite Savanna (closed circles), WGEW Kendall Grassland (open circles) and WGEW Lucky Hills Shrubland (open squares) sites, 2004–2012. Data points are mean monthly values over years and mean annual values for each year. Plots A and B were fit with linear regression lines. Points for T_{air} appeared to fall into three clusters, one showing maximum response of ET to T_{air} (dashed line a), one showing a minimal response (dashed line c) and one showing an intermediate response (overall regression line b).

by MODIS EVI, suggesting that plant transpiration rather than direct evaporation was the main determinant of ET. In studies in WGEW that measured transpiration separately from ET, values of T/ET have ranged from 0.58 to 0.79 depending on plant community and duration of the measurement period (Scott et al., 2006; Moran et al., 2009b). Ratios of 0.40–0.70 have been reported for other semi-arid rangelands, with sparse creosote shrublands at the low end (Dugas et al., 1996; Kemp et al., 1997) and mesquite savannas at the high end (Dugas et al., 1996).

EVI, in turn, was correlated with PPT, with the major period of leaf development occurring during the summer monsoon season.

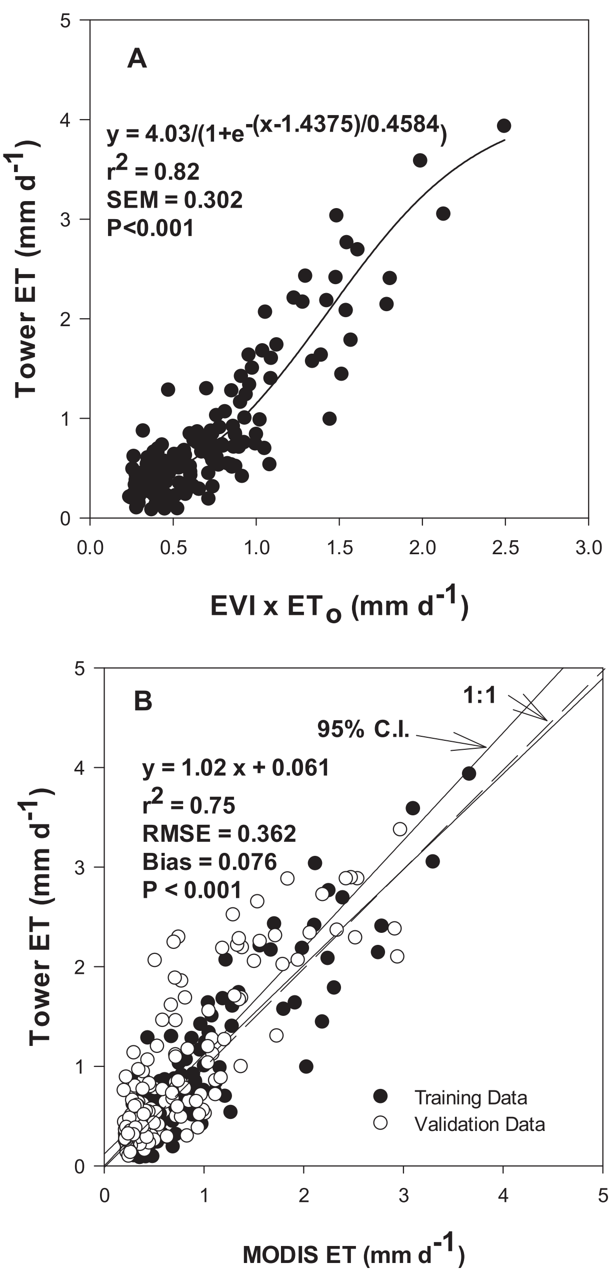

Fig. 3. (A) Sigmoidal relationship between tower ET and the product of EVI and Blaney–Criddle reference crop ET based on mean monthly values over the first half of each measurement period at four flux towers sites in southern Arizona. (B) MODIS ET predicted from the equation in (A) using calibration data (closed circles) and validation data (open circles). The validation set was the second half of each measurement period. The plot shows 95% confidence intervals for the regression line (solid lines) and the 1:1 line (dashed line).

Table 4
Comparison of eddy covariance Tower ET with MODIS ET calculated from MODIS EVI and $ET_{o\text{-}BC}$ (this study) and ET from the MODIS MOD16A2 product at tower sites in SRER and WGEW rangelands. Values are means and standard error across years for each site, and means and standard errors in parentheses for all years across sites. The SRER Creosote site had only one season of data so standard error was not calculated. Mean % difference across sites was calculated from absolute differences of individual sites.

Site	Tower ET ($mm\ yr^{-1}$)	MODIS ET this study	Bias (%)	MOD16A2 ET	Bias (%)
SRER Creosote DOY 200–285, 2008	147	155	+7.5	–	–
WGEW Lucky Hills Shrubland 2004, 2007–2012	241 (14)	206 (16)	−14.5	128 (11)	−46.9
SRER Grassland 2008–2012	400 (32)	379 (30)	−5.3	138 (18)	−65.5
SRER Mesquite 2004–2012	325 (21)	299 (24)	−8.0	129 (8)	−60.3
WG Kendall Grassland 2004–2012	256 (16)	257 (18)	+0.004	157 (13)	−38.7
Mean	275 (47)	257 (43)	−6.5	138 (7)	−54.7

However, all ecosystems also had a period of pre-monsoon greenup in March to May, supported by soil moisture from fall and winter rains (Hamerlynck et al., 2012; Barron-Gifford et al., 2012). The similar responses of different plant communities to environmental constraints is consistent with the convergence hypothesis for response to stress factors (Field, 1991), and allowed the development of a common algorithm to predict wide-area ET across ecosystems with MODIS EVI and the temperature-driven $ET_{o\text{-}BC}$.

At daily or sub-daily time scales the controlling variables are different, with plants responding much more strongly to meteorological variables and soil moisture limitations (e.g., Scott et al., 2009; Barron-Gifford et al., 2012). However, over longer time scales of months to years plants tend to adjust leaf area to match the environments capacity to support photosynthesis (Field, 1991; Goldstein et al., 2008; Huxman et al., 2004; Paruelo et al., 1999), so constraints on productivity are incorporated into the EVI signal. Field (1991) pointed out, if selection favors a limited number of mechanisms by which plants adapt to a given stress factor, the challenge of predicting plant responses from limited amounts of remote sensing data might be feasible. The present results support this hypothesis.

The final ET algorithm contained only EVI and $ET_{o\text{-}BC}$ as predictive variables. Given the low correlation between $ET_{o\text{-}PM}$ or R_n with ET and the significant correlation with T_{air}, use of the temperature-derived $ET_{o\text{-}BC}$ formula for ET_o is justified. The sigmoidal response of ET to $ET_{o\text{-}BC}$ or T_{air} indicates there is a minimum temperature below which ET approaches zero, a mid-region in which ET responds to the increase in atmospheric water demand as a function of T_{air}, and a maximum temperature above which ET does not increase due to an increase in physiological resistance (Jones, 1983; Monteith and Unsworth, 1990). Hence, when calibrated to local conditions and combined with ground data, MODIS EVI imagery can provide accurate annual estimates of ET across shrublands, mesquite savannas and grasslands in monsoon-driven drylands (see also Bunting et al., 2014).

By contrast, the global MODIS ET product, MOD16A2, seriously underestimated ET in these semiarid ecosystems. Velpouri et al. (2013) reported underestimates of monthly ET of 31–55% by MOD16A2 compared to gridded FLUXNET estimates for sparsely vegetated grasslands and shrublands, similar to our results. One reason for the underestimates could be in the way stomatal conductance is calculated in the MOD16A2 algorithm (Mu et al.,

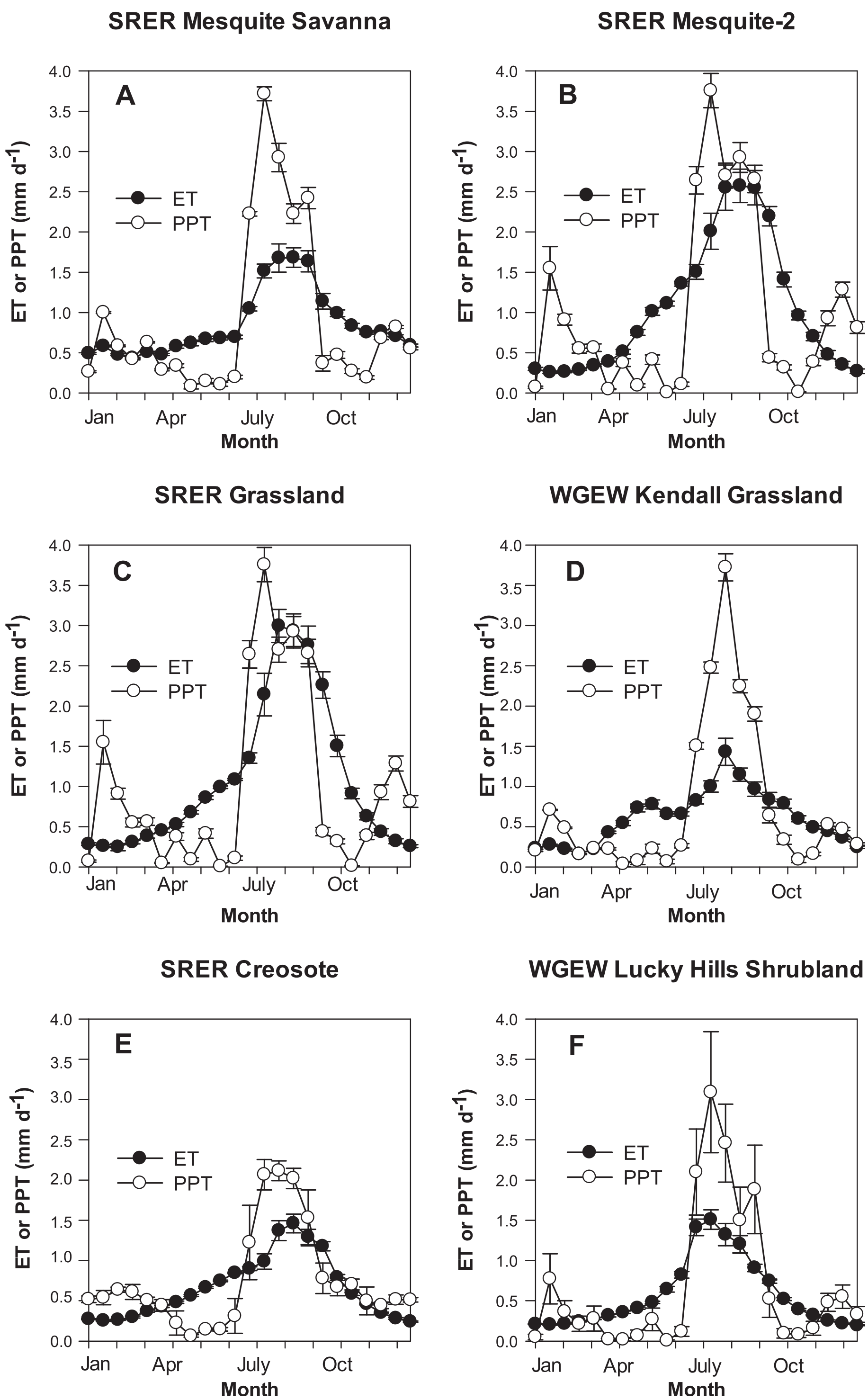

Fig. 4. MODIS ET (closed circles) and precipitation (open circles) over wide area sites centered on the SRER Mesquite Savanna (A), SRER Mesquite-2 (B), SRER Grassland (C), WGEW Kendall Grassland (D), SRER Creosote (E) and SRER Shrubland (F) sites. Data points are monthly means across years (2004–2012); error bars are standard errors of means.

2011). It includes a term to reduce stomatal conductance when VPD of the atmosphere is high; however, we found no depression of ET for these plant communities as a function of VPD. Mesquites, grasses and shrubs in WGEW had substantial rates of ET so long as water was available even when VPD exceeded 4.0 kPa (Serrat-Capdevila et al., 2011), whereas MOD16A2 assumes nearly complete stomatal closure for open shrubland ecosystems at a VPD of 4.4.

The algorithm in Equation (3) allowed us to scale essentially point measurements of ET at tower sites (footprint areas of several thousand square meters) over much wider areas (4–36 km^2) representing whole plant communities. Flux tower sites are chosen to represent flat terrain and homogeneous canopy conditions, hence they do not necessarily represent wide-area conditions, and the use of satellite imagery is useful in scaling tower data over mixed plant communities (Bunting et al., 2014). Application of these methods to

Table 5
Comparison of ET, PPT and ET/PPT for sites used in this study. ET was for wide-area sites and was calculated from MODIS EVI and ET_{o-BC}. Different letters within a column denote significant differences in means at $P < 0.05$ one-way ANOVA and Tukey's mean difference test within each column. Numbers in parenthesis are standard errors of means. F and P statistics are given for the one-way ANOVA for each variable with site as the categorical variable.

	Years	ET (mm yr^{-1})	PPT (mm yr^{-1})	ET/PPT
SRER Mesquite – 2	5	364 (41)a	374 (50)a	0.996 (0.063)a
SRER Grass	5	358 (30)a	374 (50)a	0.996 (0.037)a
SRER Mesquite	9	306 (19)a	331 (21)a,b	0.923 (0.001)a
Kendall Grass	9	234 (16)b	271 (20)b	0.875 (0.037)a,b
LH Shrub	7	223 (19)b	257 (24)b	0.885 (0.064)a,b
SRER Creosote	9	190 (5)b	272 (12)b	0.707 (0.034)b
Statistics: F, P	–	11.9, <0.001	3.52, 0.01	5.78, <0.001

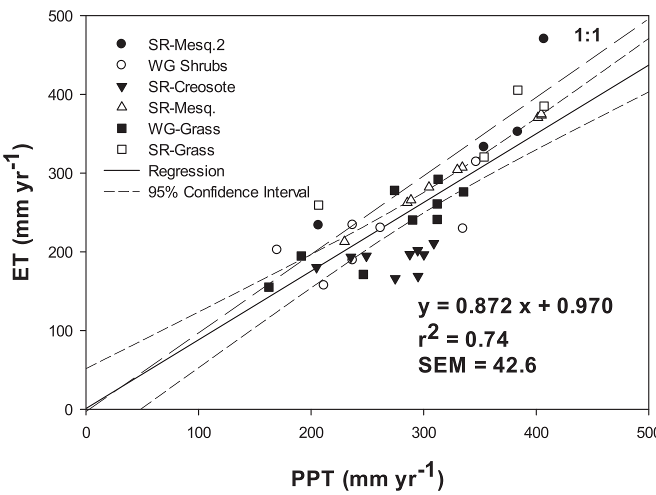

Fig. 5. Annual MODIS ET versus precipitation for six wide-area sites in southern Arizona rangelands. Plot shows regression line (solid line), 95% confidence intervals (short dashed lines) and the 1:1 line (long dashed line).

other dryland areas would require that the algorithm be calibrated to local conditions with flux tower and meteorological data. The present algorithm can only be expected to be accurate with the range of EVI and meteorological conditions found in WGEW and SRER. The algorithm does not explicitly estimate bare soil evaporation, and in sparser plant communities bare soil evaporation would become increasing important in determining ET. Morillas et al. (2013) tested three methods for inferring bare soil evaporation at two semiarid sites in southern Spain. They reported that applying a drying equation to the top 5 cm of soil following a rainfall event was a promising method to incorporate direct evaporation into remote sensing estimates of ET by optical band methods as used here.

The present study suggests that the amount of green plant cover, as determined by EVI or other satellite VIs, is more important than type of plant cover in determining ET and its response to environmental variables in dryland ecosystems. VIs provide an integrated measurement of canopy “greenness” across differences in fractional cover, leaf area index and chlorophyll contents in different plant communities (Glenn et al., 2008). Thus they provide tools for wide-area monitoring of ecohydrological processes over mixed landscapes. However, a source of potential error in projecting ET/PPT over wide areas is inaccuracy in PPT estimates, as rainfall is spatially and temporally variable over these monsoon-dependent ecosystems. PPT cannot be directly determined by remote sensing, but patterns of VIs can indirectly reveal the spatial and temporal variability of rainfall events in dryland ecosystems (Grist et al., 1997). Hence, in some cases VIs can be surrogates for PPT, and by inverting the multiple regression equation developed in the present study to solve for PPT it might be possible to construct spatially-distributed PPT maps based on EVI in these ecosystems. Use of multiyear and wide-area data sets can also help offset the spatial and temporal variability of PPT in determining overall trends.

In WGEW there is dispute about the nature of the vegetation community changes as well as their impacts on the regional water balance, particularly their ability to contribute stream flow to the Upper San Pedro River. A portion of this river is part of the protected San Pedro National Riparian Conservation Area but has suffered a 60% reduction in surface flows over the past 80 years. Goodrich et al. (2004) concluded that infiltration along ephemeral channels of monsoonal precipitation contributes 15–40% of basin aquifer recharge, which, along with mountain front recharge from adjacent mountain ranges, maintains base flows in the river. Kepner et al. (2000, 2002), used Landsat imagery from 1973, 1986 and 1993 to infer an increase in *P. velutina* in the uplands in the Sierra Vista and Benson subwatersheds. They attributed the decrease in flows in the Upper San Pedro to increased upland ET due to mesquite encroachment (Nie et al. 2012). Thomas and Pool (2006) also concluded that increases in both upland and riparian ET were likely responsible for decreased river flows. However, King et al. (2008), using archival photography as well as satellite imagery, concluded that any large-scale changes in vegetation within WGEW occurred before 1967, while stream flow has continued to decrease up to the present. Other studies have suggested that the reduction in river flows is due to interception of mountain front recharge by well pumping to support urban growth in the watershed (e.g., Mac Nish et al., 2009). The present study shows no major difference in ET/PPT between grasslands and mesquite savannas, hence it does not support the argument that woody plant encroachment can explain the reduction in San Pedro river flows. Nguyen et al. (2014), using annual, pre-monsoon Landsat imagery, showed an overall decrease in both upland and riparian NDVI and presumably ET from 1984 to 2012 in WGEW even while river base flows continued to decrease.

Another change that has taken place in WGEW as well as SRER is replacement of native C4 grasses by *E. lehmanniana*. Several studies have suggested that *E. lehmanniana* has greater water use than native C4 grasses due to its ability to utilize soil water during parts of the year when native species are dormant and to extract water from the soil profile to very low water contents (e.g., Frasier and Cox, 1994). It also is reported to have higher biomass production than native grasses (Anable et al., 1992). However, studies in WGEW and SRER have shown that while T/ET ratios can shift, replacement of native grasses by *E. lehmanniana* does not necessarily result in altered ET/PPT either during the cool-season (Hamerlynck et al., 2012) or on an annual basis (Moran et al., 2009a). Polyakov et al. (2010), studying runoff during the years in which the Kendall Grassland site converted from a native grass dominated site to an *E. lehmanniana* dominated site, reported that sediment runoff yields were 0.06 t ha^{-1} yr^{-1} under both native bunchgrasses and replacement *E. lehmanniana* plants, but rose to

Table 6
Comparison of EVI, ET, PPT and ET/PPT for the Kendall Grassland site before (2000–2005) and after (2006–2012) replacement of native grasses with introduced *E. lehmanniana*. 2006 was a transition year and was not included. P values were based on one-way ANOVA with Period as the categorical variable.

Period	EVI	ET mm yr^{-1}	PPT mm yr^{-1}	ET/PPT
2000–2005	0.131 (0.008)	234 (39)	260 (49)	0.90 (0.171)
2007–2012	0.132 (0.055)	261 (17)	301 (12)	0.87 (0.031)
P	0.95	0.53	0.46	0.52

1.64 t ha^{-1} yr^{-1} during the transition year in 2006. For the Kendall Grassland site, we found that mean annual EVI, ET and ET/PPT were similar ($P > 0.05$) before (2000–2005) and after (2007–2012) replacement of native *Bouteloua* spp. with *E. lehmanniana*.

The present study supports the cautions articulated by Huxman et al. (2005) with respect to expectations of higher ET/PPT for tree savanna versus grassland sites (Zhang et al., 2001). Grassland and mesquite savannas had ET/PPT greater than 0.99 in SRER, supporting tower results from previous studies (e.g., Krishnan et al., 2012). However, in a grassland ecosystem with higher annual PPT (474 mm) than the present sites, ET/PPT was only 0.84 compared to near 1.0 for the Kendall Grassland site (PPT = 340 mm yr^{-1}) measured in the same study (Krishnan et al., 2012). More intense monsoon rain events tended to produce more runoff in the higher-PPT grassland, despite higher NDVI and plant cover compared to the Kendall Grassland site. Similarly, we found a 13% deviation from the 1:1 line when ET was plotted against PPT in our study, with the proportion of PPT discharged as ET decreasing with increasing PPT. Hence, the Zhang et al. (2001) model appears to be valid for higher-PPT ecosystems.

The two shrub sites in the present study differed from each other. Both were more sparely vegetated than the grassland or mesquite sites judging by lower EVI values. Nevertheless, the WGEW Lucky Hills Shrubland site had ET/PPT of 0.89 compared to only 0.71 for the SRER Creosote site. At this site, water not immediately consumed in ET was apparently able to infiltrate into the soil and support further ET through the winter and spring. On the other hand slope or soil conditions at the SRER Creosote site presumably led to a larger proportion of water lost to runoff compared to the WGEW Lucky Hills Shrubland site. In general, sparsely vegetated shrublands tend to have more runoff than more heavily vegetated grassland and savanna sites. In small plot studies in natural stands of rangeland plants in Arizona and New Mexico, Tromble (1988) measured runoff rates of 16–20% for acacia and creosote plots, compared to only 2% for in well-developed stands of *Boutelua gracilis* and other native grasses.

Encroachment of mesquites into grasslands (e.g., Breshears, 2006; Barron-Gifford et al., 2012) or conversion of native grasslands to exotic-dominated grasslands (e.g., Moran et al., 2009a) can have profound impacts on carbon cycling, primary productivity, T/ET ratios and species diversity but do not necessarily result in changes in the local hydrological cycles so long as plant cover is maintained. The susceptibility of plant communities to degradation is in part dependent on the rainfall regime. Mendez-Barroso et al. (2009) showed that EVI increased linearly with PPT along a gradient from 280 to 400 mm yr^{-1} in a monsoon region in northwestern Mexico, similar to our plot of ET versus PPT (Fig. 5). Ecosystem resilience measured as ability to maintain high primary productivity increased with increasing PPT.

On the other hand, vegetation conversion can have more ecological and hydrological consequences at the low end of the precipitation gradient. Kurc and Small (2004, 2007), working in the Sevilleta National Wildlife Refuge (SNWR) with about 230 mm yr^{-1} precipitation, found that the conversion of grasslands to creosote shrublands resulted in changes in the surface energy balance and primary productivity but not necessarily changes in ET/PPT, because direct evaporation rather than T was the main factor in controlling ET during the summer monsoon season. Turnbull et al. (2010) and Brazier et al. (2014), also working at SNWR, showed that the conversion of grassland to creosote shrublands resulted in increased runoff and erosion and loss of organic carbon from the soil. Conversion of grasslands into more sparsely vegetated shrublands can reduce ET/PPT, as is apparently the case at the SRER Creosote site, but results will be site specific depending on local soil and slope conditions.

Acknowledgements

Any use of trade, product, or firm names is for descriptive purposes only and does not imply endorsement by the U.S. Government.

References

Allen, R.G., Pereira, L.S., Howell, T.A., Jensen, M.E., 2011. Evapotranspiration information reporting: I. Factors governing measurement accuracy. Agric. Water Manag. 98, 899–920.
Allen, R., Pereira, L., Rais, D., Smith, M., Solomon, K., O'Halloran, T., 1998. Crop Evapotranspiration—guidelines for Computing Crop Water Requirements—FAO Irrigation and Drainage Paper 56. Food and Agriculture Organization of the United Nations, Rome, Italy.
Anable, E.A., McClaran, M.P., Ruyle, G.B., 1992. Spread of introduced Lehmann lovegrass *Eragrostis lehmanniana* Nees. in Southern Arizona, USA. Biol. Conserv. 61, 181–188.
Baldocchi, D.D., Xu, L., Kiang, N., 2004. How plant functional-type, weather, seasonal drought, and soil physical properties alter water and energy fluxes of an oak-grass savanna and an annual grassland. Agric. For. Meteorol. 123, 13–39.
Barron-Gifford, G.A., Scott, R.L., Jenerette, G.D., Hamerlynck, E.P., Huxman, T.E., 2012. Temperature and precipitation controls over leaf- and ecosystem-level CO_2 flux along a woody plant encroachment gradient. Glob. Change Biol. 18, 1389–1400.
Bausch, W.C., Neale, C.M.U., 1987. Crop coefficients derived from reflected canopy radiation: a concept. T ASAE 30, 703–709.
Biedenbender, S.H., Mclaran, M.P., Quade, J., Weltz, M.A., 2004. Landscape patterns of vegetation change indicated by soil carbon isotope composition. Geoderma 119, 69–83.
Brazier, R.E., Turnbull, L., Wainwright, J., Bol, R., 2014. Carbon loss by water erosion in drylands: implications from a study of vegetation change in the south-west USA. Hydrol. Process 28, 2212–2222.
Breshears, D.D., 2006. The grassland-forest continuum: trends in ecosystem properties for woody plant mosaics? Front. Ecol. Environ. 4, 96–104.
Breshlof, C.J., Nguyen, U., Glenn, E.P., Waugh, J., Nagler, P.L., 2013. Effects of grazing on leaf area index, fractional cover and evapotranspiration by a desert phreatophyte community at a former uranium mill site on the Colorado Plateau. J. Environ. Manag. 114, 92–104.
Brouwer, C., Heibloem, M., 1986. Irrigation Water Management. Training Manual No. 3. Part II, Chapter 3: Crop Water Needs. FAO Corporate Document Repository, available on-line at. http://www.fao.org/docrep/s2022e/s2022e07.htm.
Bunting, D.P., Kurc, S.A., Glenn, E.P., Nagler, P.L., Scott, R.L., 2014. Insights for empirically modeling evapotranspiration influenced by riparian and upland vegetation in semiarid regions. J. Arid. Environ. 111, 42–52.
Cavanaugh, M.L., Kurc, S.A., Scott, R.L., 2011. Evapotranspiration partitioning in semiarid shrubland ecosystems: a two-site evaluation of soil moisture control on transpiration. Ecohydrology 4, 671–561.
Choudhury, B.J., 1987. Relationships between vegetation indices, radiation absorption, and net photosynthesis evaluated by a sensitivity analysis. Remote Sens. Environ. 22, 209–233.
Cohen, J., Cohen, P., West, S.G., Aiken, L.S., 2003. Applied Multiple Regression/Correlation Analysis for the Behavioral Sciences, third ed. Lawrence Earlbaum Associates, Mahwah, NJ.
Dugas, W.A., Hicks, R.A., Gibbons, R.P., 1996. Structure and function of C3 and C4 Chihuahuan Desert plant communities. Energy balance components. J. Arid. Environ. 34, 63–79.
Dugas, W.A., Hicks, R.A., Wright, P., 1998. Effect of removal of *Juniperus ashei* on evapotranspiration and runoff in the Seco Creek watershed. Water Resour. Res. 34, 1499–1506.
Emmerich, W.E., 2003. Carbon dioxide fluxes in a semiarid environment with high carbonate soils. Agric. For. Meteorol. 116, 91–102.
Farley, K.A., Jobba, E.G., Jackson, R.B., 2005. Effects of afforestion on water yield: a global synthesis with implications for policy. Glob. Change Biol. 11, 1565–1576.
Field, C.B., 1991. Ecological scaling of carbon gain to stress and resource availability. In: Mooney, H.A., Winner, W.E., Pell, E.J. (Eds.), Response of Plants to Multiple Stresses. Academic Press, Inc., San Diego, CA, pp. 35–66.
Frasier, G.W., Cox, J.R., 1994. Water balance in pure stand of Lehmann lovegrass. J. Range Manag. 47, 373–378.
Glenn, E.P., Huete, A.R., Nagler, P.L., Nelson, S.G., 2008. Relationship between remotely-sensed vegetation indices, canopy attributes and plant physiological processes: what vegetation indices can and cannot tell us about the landscape. Sensors 8, 2136–2160.
Glenn, E.P., Neale, C.M.U., Hunsaker, D.J., Nagler, P.L., 2011. Vegetation index-based crop coefficients to estimate evapotranspiration by remote sensing in agricultural and natural ecosystems. Hydrol. Process 25, 4050–4062.
Goldstein, G., Meinzer, F.C., Bucci, S.J., Scholz, F.G., Franco, A.C., Hoffmann, W.A., 2008. Water economy of Neotropical savanna trees: six paradigms revisited. Tree Physiol. 28, 395–404.
Goodrich, D.C., Unkrich, C.L., Keefer, T.O., Nichols, M.H., Stone, J.J., Levick, L.R., Scott, R.L., 2008. Event to multidecadal persistence in rainfall and runoff in southeast Arizona. Water Resour. Res. 44 http://dx.doi.org/10.1029/

2007WR006222.
Goodrich, D.C., Williams, D.G., Unkrich, C.L., Hogan, J.F., Scott, R.L., Hultine, K.R., Poo, D., Coes, A.L., Miller, S., 2004. Comparison of methods to estimate ephemeral channel recharge, Walnut Gulch, San Pedro River Basin, Arizona. Water Sci. Appl. 9, 77–99.
Grist, J., Nicholson, S.E., Mpolokang, A., 1997. On the use of NDVI for estimating rainfall fields in the Kalahari of Botswana. J. Arid. Environ. 36, 195–214.
Hamerlynck, E.P., Scott, R.L., Barron-Gifford, G.A., Cavanaugh, M.L., Moran, S.M., Huxman, T.E., 2012. Cool-season whole-plant gas exchange of exotic and native semiarid bunchgrasses. Plant Ecol. 213, 1229–1239.
Heilman, J.L., Litvak, M.E., McInnes, K.J., Kjelgaard, J.F., Kamps, R.H., Schwiining, S., 2014. Water-storage capacity controls energy partitioning and water use in karst ecosystems on the Edwards Plataeu, Texas. Ecohydrology 7, 127–138.
Huete, A., Didan, K., van Leeuwen, W., Miura, T., Glenn, E., 2011. MODIS vegetation indices. In: Ramachandran, B., Justice, C.O., Abrams, M.J. (Eds.), Land Remote Sensing and Global Environmental Change: NASA's Earth Observing System and the Science of ASTER and MODIS. Springer, New York, pp. 579–602.
Huxman, T.E., Smith, M.D., Fay, P.A., Knapp, A.K., Shaw, M.R., Loik, M.E., Smith, S.D., Tissue, D.T., Zak, J.C., Wltzin, J.F., Pockman, W.T., Sala, O.E., Haddad, B.M., Harte, J., Koch, G.W., Schwinning, S., Small, E.E., Williams, D.G., 2004. Convergence across biomes to a common rain-use efficiency. Nature 429, 651–654.
Huxman, T.E., Wilcox, B.P., Breshears, D.D., Scott, R.L., Snyder, K.A., Small, E.E., Hultine, K., Pockman, W.T., Jackson, R.B., 2005. Ecological implications of woody plant encroachment. Ecology 86, 308–319.
Jones, H., 1983. Plants and Microclimate: a Quantitative Approach to Environmental Plant Physiology. Cambridge University Press, Cambridge, UK.
Kemp, P.R., Reynolds, J.F., Pachepsky, Y., Chen, J.L., 1997. A comparative modeling study of soil water dynamics in a desert ecosystem. Water Resour. Res. 33, 73–90.
Kepner, W.G., Edmonds, C.M., Watts, C.J., 2002. Remote Sensing and Geographic Information Systems for Decision Analysis in Public Resource Administration: a Case Study of 25 Years of Landscape Change in a Southwestern Watershed. EPA 600 R-12/039. U.S. Environmental Protection Agency, Office of Research and Development, Las Vegag, NV.
Kepner, W.G., Watts, C.J., Edmonds, C.M., Maingi, J.K., Marsh, S.E., Luna, G., 2000. A landscape approach for detecting and evaluating change in a semi-arid environment. Environ. Monit. Assess. 64, 179–195.
King, D.M., Skirvin, S.M., Collins, C.D., Moran, M.S., Biedenbender, S.H., Kidwell, M.R., et al., 2008. Assessing vegetation change temporally and spatially in southeastern Arizona. Water Resour. Res. 44, W05S15.
Krishnan, P., Meyers, T.P., Scott, R.L., Kennedy, L., Heuera, M., 2012. Energy exchange and evapotranspiration over two temperate semi-arid grasslands in North America. Agric. For. Meteorol. 153, 31–44.
Kurc, S.A., Small, E.E., 2004. Dynamics of evapotranspiration in semiarid grassland and shrubland ecosystems during the summer monsoon season, central New Mexico. Water Resour. Res. 40 http://dx.doi.org/10.1029/2004WR003068.
Kurc, S.A., Small, E.E., 2007. Soil moisture variations and ecosystem-scale fluxes of water and carbon in semiarid grassland and shrubland. Water Resour. Res. 43 http://dx.doi.org/10.1029/2006WR005011.
Mac Nish, R., Baird, K.J., Maddock, T., 2009. Groundwater hydrology of the San Pedro River Basin. In: Stromberg, J.C., Tellman, B. (Eds.), Ecology and Conservation of the San Pedro River. University of Arizona Press, Tucson, AZ, pp. 285–299.
McClaran, M.P., 2003. A century of vegetation change on the Santa Rita experimental range. In: Santa Rita Experimental Range: 100 Years (1903–2003) of Accomplishments and Contributions, Conference Proceedings. USDA Forest Service Rocky Mountain Research Station Proceedings 30, pp. 16–33.
Mendez-Barroso, L.A., Vivoni, E.R., Watts, C.J., Rodriquez, J.C., 2009. Seasonal and interannual relationships between precipitation, surface soil moisture and vegetation dynamics in the North American monsoon region. J. Hydrol. 277, 59–70.
Milly, P.C.D., 1994. Climate, soil water storage and the average annual water budget. Water Resour. Res. 30, 2143–2156.
Monteith, J.L., Unsworth, M., 1990. Principles of Environmental Physics, second ed. Edward Arnold, London, UK.
Montgomery, D.C., Peck, E.A., Vining, G.G., 2012. Introduction to Linear Regression Analysis, fifth ed. Wiley, Inc., New York.
Moran, M.S., Emmerich, W.E., Goodrich, D.C., Hielman, P., Collins, C., Keefer, T.O., Nearing, M.A., Nichols, M.H., Renard, K.G., Scott, R.L., 2008. Preface to special section on fifty years of research and data collection: U.S. Department of Agirculture Walnut Gulch Experimental Watershed. Water Resour. Res. 44 http://dx.doi.org/10.1029/2007WR0060834.
Moore, G.W., Hielman, J.L., 2012. Proposed principles governing how vegetation changes affect transpiration. Ecohydrology 4, 351–358.
Moran, M.S., Scott, R.L., Hamerlynck, E.P., Green, K.N., Emmerich, W.E., Holifield Collins, C.D., 2009a. Soil evaporation response to Lehmann lovegrass (*Eragrostis lehmanniana*) invasion in a semiarid watershed. Agric. For. Meteorol. 149, 2133–2142.
Moran, M.S., Scott, R.L., Keefer, T.O., Emmerich, W.E., Hernandez, M., Nearing, G.S., Paige, G.B., Cosh, M.H., O'Neal, P.E., 2009b. Partitioning evapotranspiration in semiarid grassland and shrubland ecosystems using time series of soil surface temperature. Agric. For. Meteorol. 149, 59–72.
Morillas, L., Leuning, R., Villagarcia, L., Garcia, M., Serrano-Ortiz, P., Domingo, F., 2013. Improving evapotranspiration estimates in Mediterranean drylands: the role of soil evaporation. Water Resour. Res. 49, 6572–6586.
Mu, Q., Zhao, M., Running, S.W., 2011. Improvements to a MODIS global terrestrial evapotranspiration algorithm. Remote Sens. Environ. 115, 1781–1800.
Nagler, P.L., Glenn, E.P., Kim, H., Emmerich, W., Scott, R.L., Huxman, T.E., Huete, A.R., 2007. Relationship between evapotranspiration and precipitation pulses in a semiarid rangeland estimated by moisture flux towers and MODIS vegetation indices. J. Arid. Environ. 70, 443–462.
Nagler, P.L., Scott, R.L., Westenburg, C., Cleverly, J.R., Glenn, E.P., Huete, A.R., 2005. Evapotranspiration on western US rivers estimated using the Enhanced Vegetation Index from MODIS and data from eddy covariance and Bowen ratio flux towers. Remote Sens. Environ. 97, 337–351.
Nguyen, U., Glenn, E.P., Nagler, P.L., Scott, R.L., 2014. Long-term decrease in satellite vegetation indices in response to environmental variables in an iconic desert riparian ecosystem: the Upper San Pedro, Arizona, United States. Ecohydrology. http://dx.doi.org/10.1002/eco.1529 (on-line first).
Nichols, M.H., Renard, K., 2007. History of the USDA-ARS Walnut Gulch experimental watershed. In: Rogers, J.R. (Ed.), Environmental and Water Resources: Milestones in Engineering History. ASCE. Available on-line at: http://dx.doi.org/10.1061/9780784409282.
Nie, W., Yuan, Y., Kepner, W., Erickson, C., Jackson, M., 2012. Hydrological impacts of mesquite encroachment in the upper San Pedro watershed. J. Arid. Environ. 82, 147–155.
ORNL DAAC (2014) Oak Ridge, TN, USA On-line at http://daac.ornl.gov/cgi-bin/MODIS/GLBVIZ_1_Glb/modis_subset_order_global_col5.pl.
Paruelo, J.M., Jobba, E.G., Sala, O.E., Lauenroth, W.K., Burke, I., 1999. Functional and structural convergence of temperate grassland and shrubland ecosystems. Ecol. Appl. 8, 194–206.
Polyakov, V.O., Nearing, M.A., Stone, J.J., Hamerlynck, E.P., Nichols, M.H., Holifield, C.D., Scott, R.L., 2010. Runoff and erosional responses to a drought-induced shift in a desert grassland community composition. J. Geophys Res. Biogeosci. 115 http://dx.doi.org/10.1029/2010JG001386.
Ravi, S., Breshears, D.D., Huxman, T.E., D'Odorico, P., 2010. Land degradation in the drylands: interactions among hydrologic-aeolian erosion and vegetation dynamics. Geomorph 116, 236–245.
Ritchie, J.C., Nearing, M.A., Nichols, M.H., Ritchie, C.A., 2005. Patterns of soil erosion and redeposition on lucky Hills watershed, Walnut gulch experimental watershed, Arizona. Catena 61, 122–130.
Sayre, N.F., 2003. Recognizing history in range ecology: 100 years of science and management on the Santa Rita experimental Range. In: Santa Rita Experimental Range: 100 Years (1903–2003) of Accomplishments and Contributions, Conference Proceedings. USDA Forest Service Rocky Mountain Research Station Proceedings 30, pp. 1–15.
Scott, R.L., 2010. Using watershed water balance to evaluate the accuracy of eddy covariance evaporation measurements for three semiarid ecosystems. Agric. For. Meteorol. 150, 219–225.
Scott, R.L., Hamerlynck, E.P., Jenerette, G.D., Moran, M.S., Barron-Gafford, G., 2010. Carbon dioxide exchange in a semidesert grassland through drought-induced vegetation change. J. Geophys Res.-Biogeosci. 115, G03026. http://dx.doi.org/10.1029/2010JG001348.
Scott, R.L., Huxman, T.E., Cable, W.L., Emmerich, W.E., 2006. Partitioning of evapotranspiration and its relation to carbon dioxide exchange in a Chihuahuan Desert shrubland. Hydrol. Process 20, 3227–3243.
Scott, R.L., Jenerette, G.D., Potts, D.L., Huxman, T.E., 2009. Effects of seasonal drought on net carbon dioxide exchange from a woody-plant encroached semiarid grassland. J. Geophys Res. 114 http://dx.doi.org/10.1029/2008JG000900.
Serrat-Capdevila, A.S., Scott, R.L., Shuttleworth, W.J., Valdes, J.B., 2011. Estimating evapotranspiration under warmer climates: insights from a semi-arid riparian system. J. Hydrol. 399, 1–11.
Tennesen, M., 2008. When juniper and other woody plants invade, water may retreat. Science 322, 1630–1631.
Thomas, B.E., Pool, D.R., 2006. Trends in Streamflow of the San Pedro River, Southeastern Arizona, and Trends in Precipitation and Streamflow in Northwestern New Mexico and Southeastern Arizona, p. 79. U.S. Geological Survey Professional Paper 1712, Reston, VI.
Tromble, J.M., 1988. Water budget for creosotebush-infested rangeland. J. Arid. Environ. 15, 71–74.
Turnbull, L., Wainwright, J., Brazier, R.E., 2010. Changes in hydrology and erosion over a transition from grassland to shrubland. Hydrol. Process 24, 393–414.
Twine, T.E., Kustas, W.P., Norman, J.M., Cook, D.R., Houser, P.R., Meyers, T.P., Prueger, J.H., Starks, P.J., Wesley, M.L., 2000. Correcting eddy-covariance flux underestimates over a grassland. Agric. For. Meteorol. 103, 279–300.
Velpouri, N.M., Senay, G.B., Singh, R.K., Bohms, S., Verdin, J.P., 2013. A comprehensive evaluation of two MODIS evapotranspiration products over the conterminous United States: using point and gridded FLUXNET and water balance ET. Remote Sens. Environ. 139, 35–49.
Yathereendradas, S., Wagener, T., Gupta, H., Unkrich, C., Goodrich, D., Schaffner, M., Stewart, A., 2008. Understanding uncertainty in distributed flash flood forecasting for semiarid regions. Water Resour. Res. 44 http://dx.doi.org/10.1029/2007WR005940.
Zhang, L., Dawes, W.R., Walker, G.R., 2001. Response of mean annual evapotranspiration to vegetation changes at catchment scale. Water Resour. Res. 37, 701–708.