



RESEARCH LETTER

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Key Points:

- A new method is developed to partition ET using multiyear carbon and water flux measurements
- The method is applied to semiarid sites and shows that E peaks at the start of rainy season and declines as the growing season progresses
- Magnitudes and trends in E and T/ET are consistent with field observations and known effects from surface and climate controls

Supporting Information:

- Supporting Information S1

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Partitioning evapotranspiration using long-term carbon dioxide and water vapor fluxes

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Abstract The separate components of evapotranspiration (ET) elucidate the pathways and time scales over which water is returned to the atmosphere, but ecosystem-scale measurements of transpiration (T) and evaporation (E) remain elusive. We propose a novel determination of E and T using multiyear eddy covariance estimates of ET and gross ecosystem photosynthesis (GEP). The method is applicable at water-limited sites over time periods during which a linear regression between GEP (abscissa) and ET (ordinate) yields a positive ET axis intercept, an estimate of E . At four summer-rainfall semiarid sites, T/ET increases to a peak coincident with maximum GEP and remains elevated as the growing season progresses, consistent with previous, direct measurements. The seasonal course of T/ET is related to increasing leaf area index and declining frequency of rainy days—an index of the wet surface conditions that promote E —suggesting both surface and climatic controls on ET partitioning.

1. Introduction

The flux of water vapor from the terrestrial surface to the atmosphere, evapotranspiration (ET), is composed of transpiration (T) from plants and evaporation (E) of water from wet surfaces. ET partitioning into E and T is critical to understanding separate abiotic and biotic ecosystem processes, illuminating, for example, how changes in vegetation and climate alter the hydrological cycle [Cao *et al.*, 2010; Huxman *et al.*, 2005; Newman *et al.*, 2006; Wilcox *et al.*, 2012]. Water use efficiency (WUE) describes the water plants lose in exchange for carbon during photosynthesis. WUE is commonly estimated by the ratio of gross ecosystem photosynthesis (GEP) and ecosystem-scale ET, which fails to account for varying amounts of E [Biederman *et al.*, 2017; Biederman *et al.*, 2016; Ponce-Campos *et al.*, 2013]. Measured ET partitioning is needed to improve land surface model estimates of evaporation components [Jasechko *et al.*, 2013; Lawrence *et al.*, 2007; Scott *et al.*, 1995; Villegas *et al.*, 2014]. Furthermore, ET partitioning reveals land-atmosphere feedbacks affecting time scales of hydrological memory, such as differential rates of wet surface evaporation versus soil moisture transpiration [Koster and Suarez, 2001; Lawrence *et al.*, 2007; Scott *et al.*, 1997]. Although combined ET can be estimated from flux measurements, catchment water balances, and satellite algorithms, the partitioned E and T remain difficult to quantify.

Studies show that ET partitioning (summarized by the ratio T/ET) is dynamic on diurnal to seasonal time scales due to both climate (precipitation and evaporative demand), especially in semiarid ecosystems [Cavanaugh *et al.*, 2011; Hu *et al.*, 2009; Moran *et al.*, 2009; Raz-Yaseef *et al.*, 2012; Scott *et al.*, 2006], and surface controls (leaf area and stomatal conductance). In water-limited systems with large evaporative demand, each rainfall pulse wets the soil and plant surfaces, supplying moisture for E . Transpiration, however, is stimulated only when rainfall is sufficient to wet the root zone and plants are upregulated [Kurc and Small, 2007; Scott *et al.*, 2006]. Therefore, ET partitioning is expected to vary with the timing and characteristics of precipitation (i.e., duration and intensity). Furthermore, modeling studies indicate that T/ET fluctuates across seasons and years due to varying responses of plant species operating on different phenological cues, plant cover, and leaf area amounts [Kemp *et al.*, 1997; Reynolds *et al.*, 2000]. Varying levels of surface and climate controls may hinder a more global understanding of T/ET based on short-term field measurements [Schlesinger and Jasechko, 2014]. Empirical models of T/ET based on leaf area index (LAI) or land cover explain only limited variability across sites [Wang *et al.*, 2014]. A broader ecohydrological understanding of T/ET would benefit from studies that can illuminate its intra-annual and interannual variability.

Several direct and indirect methods are used to partition ET. Direct methods measure E and T separately with microlysimeters or soil chambers for E and sap flow and leaf/plant chambers for T [Kool *et al.*, 2014]. Temporal upscaling of these measurements may be complicated by limited duration (weeks up to one season) or

noncontinuous nature. Another difficulty is interpreting the measurements at a useful spatial scale, such as the ecosystem. Recently, estimates of stomatal conductance and associated T have been obtained by carbonyl sulfide uptake and eddy-covariance measurements [Wehr *et al.*, 2017]. Indirect methods include using profiles of stable water isotopes in Keeling plots [Wang *et al.*, 2010; Williams *et al.*, 2004; Yepez *et al.*, 2003] and eddy covariance data [Scanlon and Kustas, 2010; Zhou *et al.*, 2016]. A recent review suggests combining isotope and micrometeorological techniques to partition ET, but major challenges remain, including dynamic isotope variation [Griffis, 2013]. The approach of Scanlon and Kustas [2010] uses widely available fast-response sonic anemometer and infrared gas analyzer data but requires the intrinsic plant WUE, which is often unknown and temporally dynamic [Sulman *et al.*, 2016]. Alternatively, Zhou *et al.* [2016] proposed that deviations of actual ecosystem-scale WUE from a maximum potential WUE, both determined from eddy covariance ET and GEP, could be used to determine T/ET . To find the potential WUE, this method requires periods when $T/ET = 1$, which may occur rarely both in water-limited and perennially wet ecosystems.

We propose a novel method to infer site-level ET partitioning from multiyear carbon dioxide (CO_2) and water vapor (H_2O) ecosystem fluxes determined by eddy covariance. Here we develop the methodology, evaluate its assumptions, and test its sensitivity to the key assumptions and the number of data years. Then, we demonstrate the approach with monthly ET partitioning over the summer growing seasons at four semiarid sites. We relate seasonal partitioning to surface and climatic drivers (LAI and number of rainy days) and compare our estimates to direct measurements made at one of the sites. Finally, we develop a simple model of early growing season T/ET based on leaf area index (LAI) and test whether its predicted T explains more of the variance in GEP than ET alone.

2. Data

We use multiyear eddy covariance and meteorological data from four AmeriFlux sites in southern Arizona USA [Scott *et al.*, 2015]. The sites comprise a desert shrubland (AmeriFlux site: US-Whs, data available 2007–2015), a savanna (US-SRM, 2004–2015), and two grasslands (US-SRG, 2008–2015 and US-Wkg, 2004–2015). To quantify green leaf area, we use LAI from the NASA Moderate Resolution Imaging Spectroradiometer (MODIS) product [Oak Ridge National Laboratory Distributed Active Archive Center, 2016] available every 16 days and interpolated onto a daily time interval. Vegetation within the 1 km MODIS pixels is very similar to that of the typical source area for the flux tower measurements (on the order 10^2 m in length) [Scott 2010].

3. Methods

Scott *et al.* [2015] proposed that positive x -intercept of a regression line of annual ET (abscissa) and GEP (ordinate) indicates a site's multiyear average E . In other words, the x -intercept is the predicted amount of ET when there is no photosynthesis. Here we clarify the assumptions behind the approach and apply it to monthly partitioning. First, we invert the regression by plotting same-month values of GEP on the x axis and ET on the y axis (Figure 1c). This defines GEP as a predictor of ET (e.g., what is ET when GEP = 0?) as follows:

$$ET = mGEP + E' \quad (1)$$

where E' is the y axis intercept and a first-order estimate of average monthly evaporation. The slope, m , is the inverse of marginal ecosystem water use efficiency, $WUE_{\text{mar}}^{-1} = \frac{\Delta ET}{\Delta GEP}$ calculated below. Given the direct relationship between transpiration and photosynthesis [Nobel, 1983; Sinclair *et al.*, 1984], T can be described by

$$T = mxGEP \quad (2)$$

where x is the ratio between the inverse of the transpirational water use efficiency, $WUE_t^{-1} = \frac{T}{GEP}$, and WUE_{mar}^{-1} . Subtracting equation (2) from equation (1) produces

$$E = E' + m(1 - x)GEP \quad (3)$$

where $m(1 - x)$ describes any change of E occurring with GEP. Such change in E could occur because we expect GEP to be higher/lower in wetter/drier years, respectively. We assume $x = 1$ in part because multiyear observations of separate E , T , and GEP are extremely limited and conflicting about how E may change in wetter or drier years and in different biomes [Raz-Yaseef *et al.*, 2012; Reynolds *et al.*, 2000]. With $x = 1$, E is

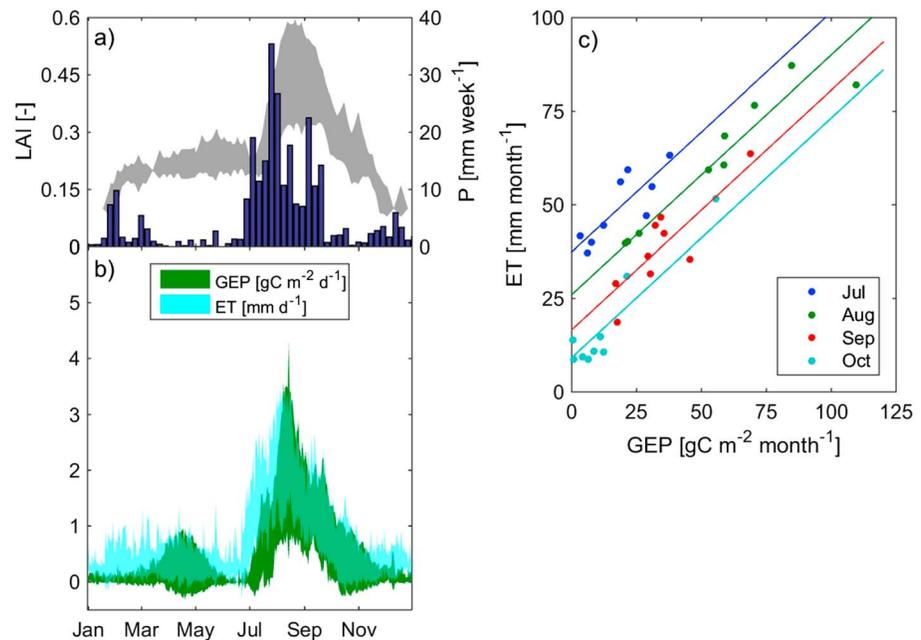


Figure 1. Data collected from 2007 through 2015 at Lucky Hills Shrubland (US-Whs). (a) Average seasonal course of leaf area index (LAI, daily mean ± 1 sigma ensembles) and precipitation (P, weekly averages). (b) Gross ecosystem photosynthesis (GEP) and evapotranspiration (ET) ensembles. (c) July–October monthly sums of GEP and ET with regression lines. Average monthly evaporation (E) rates are estimated by the regression line y axis intercept showing initially high rates that decrease through the growing season.

invariant across the years for a given month and E' represents average evaporation (illustrated in Figure S1 in the supporting information). Average monthly T/ET is determined from the mean of the ratios of calculated T (equation (2)) and measured ET. Information about the sensitivity of our results for $x \neq 1$ is given in the supporting information.

We demonstrate this approach to determine monthly E and T/ET over the summer growing season (July–October). We first determine each site’s marginal sensitivity of ET to changes in GEP, defined as the slope, m , of the regression line fit to deviations of GEP and ET from each site’s long-term mean for all the instances of a given month in the record (i.e., $m_i = \Delta ET_i / \Delta GEP_i$, where $i = \text{site}$) [Biederman *et al.*, 2016]. We compare regression slopes and y -intercepts (equivalent to average monthly E) across sites and across months at a given site using one-way analysis of covariance and the Tukey-Kramer method ($p = 0.05$; MATLAB, Natick, MA; *aocool* and *multcompare* functions).

The site slopes derived from pooled monthly data are as follows: $m_{\text{US-SRM}} = 0.53^{\text{ab}}$, $m_{\text{US-SRG}} = 0.42^{\text{b}}$, $m_{\text{US-Whs}} = 0.64^{\text{a}}$, and $m_{\text{US-Wkg}} = 0.47^{\text{ab}}$, where different letters indicate significant differences. Slopes differ between the wettest site (US-SRG, 251 mm, mean July–October precipitation) and the driest site (US-Whs, 207 mm) with the intermediate rainfall sites having intermediate slopes (US-Wkg, 220 mm; US-SRM, 230 mm). There are no significant slope differences across months at each site. Therefore, July–October site slopes are used in the regressions of GEP and ET to determine monthly y -intercepts (E). A sensitivity analysis shows that 3 years of data can be sufficient to derive E estimates similar to those using all years of data, although additional years reduce the uncertainty (Figure S3).

4. Results and Discussion

4.1. Seasonal Progression of T/ET

We begin with the shrubland site (US-Whs), where T/ET was measured for summers 2003 and 2008 using sap flow measurements of T and a Bowen ratio or eddy covariance measurement of ET [Cavanaugh *et al.* 2011; Scott *et al.* 2006]. At US-Whs and the other sites in this study, the main growing season is July–October following a foresummer drought with dry soils and downregulated plants (Figures 1a and 1b). With the

Table 1. Regression Statistics and Results of the Monthly GEP and ET Regressions Shown in Figures 1 and 2^a

Site	Month				Site	Month					
	July	August	September	October		July	August	September	October		
US-Whs	r^2	0.68	0.90	0.74	0.91	US-Wkg	r^2	0.79	0.69	0.85	0.91
	E (mm)	37 ^{aa}	26 ^b	17 ^c	9 ^c		E (mm)	33 ^a	27 ^{ab}	19 ^b	9 ^c
	ET (mm)	49	62	39	18		ET (mm)	48	66	45	19
	T/ET	0.23	0.54	0.57	0.41		T/ET	0.26	0.58	0.54	0.45
US-SRG	r^2	0.79	0.97	0.86	0.82	US-SRM	r^2	0.88	0.84	0.84	0.80
	E (mm)	32 ^a	28 ^a	26 ^a	12 ^b		E (mm)	32 ^a	21 ^b	16 ^b	8 ^c
	ET (mm)	73	84	61	27		ET (mm)	61	70	52	25
	T/ET	0.54	0.62	0.54	0.51		T/ET	0.45	0.69	0.66	0.68

^aAll correlations (r) are significant at $p < 0.01$. Values for E are all significantly different than zero, and different letters for each site indicate that the values are significantly different from each other ($p < 0.05$). T/ET is calculated as the average of yearly T/ET ratios, where T is determined from equation (2).

start of summer rainfall in July, ET rapidly increases; following a lag of about 2 weeks for plant upregulation, GEP and LAI also increase. ET and GEP typically peak in early August and then decrease in tandem to winter levels by November. At US-Whs during the growing season, y axis intercepts of the GEP and ET regressions suggest that E is highest in July and then decreases (Figure 1c). Estimated evaporation rates from these intercepts are 37, 26, 17, and 9 mm month⁻¹ (July–October, respectively), indicating increasing ratios of $T/ET = 0.23$ in July to 0.54 in August that stay elevated at 0.57 in September and decrease to 0.41 in October (Table 1). Estimated evaporation rates are highest and T/ET ratios lowest early in the growing season, consistent with (1) more frequent rainy days wetting evaporation surfaces and (2) lagged plant upregulation (fine-root, xylem, and leaf growth). Lagged upregulation is further supported by the delay of GEP and LAI behind ET (Figures 1a and 1b). By August, LAI and GEP peak, resulting in higher T/ET .

Our estimates of T/ET at US-Whs, based solely on ecosystem-scale EC measurements, agree well with the existing sparse, labor-intensive direct measurements at this site. For example, Scott *et al.* [2006] measured monthly T/ET of 0.21, 0.68, 0.70, and 0.71 across July–October 2003 (mean $T/ET = 0.57$), and Cavanaugh *et al.* [2011] found $T/ET = 0.47$ from June to October 2008 in comparison to this study's multiyear July–October average of 0.44. These studies also found that ET increases rapidly with the start of rainfall in July, but it takes 2 to 4 weeks for the shrub vegetation to fully leaf-out and transpire at peak rates. While the directly measured 2003 monthly T/ET values were higher than the 2007–2015 mean estimates (Table 1), this is to be expected as 2003 was wetter (July–October ET = 210 mm) than the average over our period (ET = 168 mm). Accordingly, our method predicts increasing T/ET in wetter years, and we can use equation (2) and published values of monthly ET and GEP from 2003 [Scott *et al.*, 2006] to predict monthly T/ET . This results in $T/ET = 0.18, 0.69, 0.73,$ and 0.90 for July–October 2003, with all but October values similar to the direct measurements.

We find similar magnitudes and consistently declining seasonal progressions of E at each of the other three sites, with E peaking in the early growing season and declining from July through October (Figures 2a–2c and Table 1). Consequently, growing season T/ET is lowest in July, peaks in August, and remains elevated through the rest of the season at all sites except US-SRG (Figure 2d), consistent with a global data synthesis indicating higher T/ET ratios later in the growing season when the plants are fully upregulated [Wang *et al.*, 2014]. As the bulk of rainfall occurs and RD is highest in July–August, increasing T/ET and LAI (Figures 2d–2f) in these months likely suggests surface control by plant upregulation [Cavanaugh *et al.*, 2011; Kemp *et al.*, 1997; Wang *et al.*, 2014]. Furthermore, higher LAI indicates increased shading of the evaporating soil surface due to leaf expansion and the infill of bare soil areas with annual plants [Wang *et al.*, 2013]. Bare ground prior to the rainy season is substantial at all these sites, from ~45 to 60% [Scott *et al.*, 2015].

In September and October, T/ET either stays elevated or decreases somewhat relative to August values (Figure 2d and Table 1). Although LAI decreases during this latter half of the growing season, the perennial plants remain upregulated while RD diminishes sharply (Figures 2e and 2f). In this latter half of the growing season, we propose that T/ET can remain elevated because decreased precipitation frequency results in less wetting of the evaporation surfaces (plants, rocks, litter, and soil) decreasing E , while plants continue transpiring any available root zone soil moisture [Raz-Yaseef *et al.*, 2012; Scott *et al.*, 2006]. The site with the most dense grass cover, US-SRG, showed the lowest variability in T/ET across the growing season (Figure 2d),

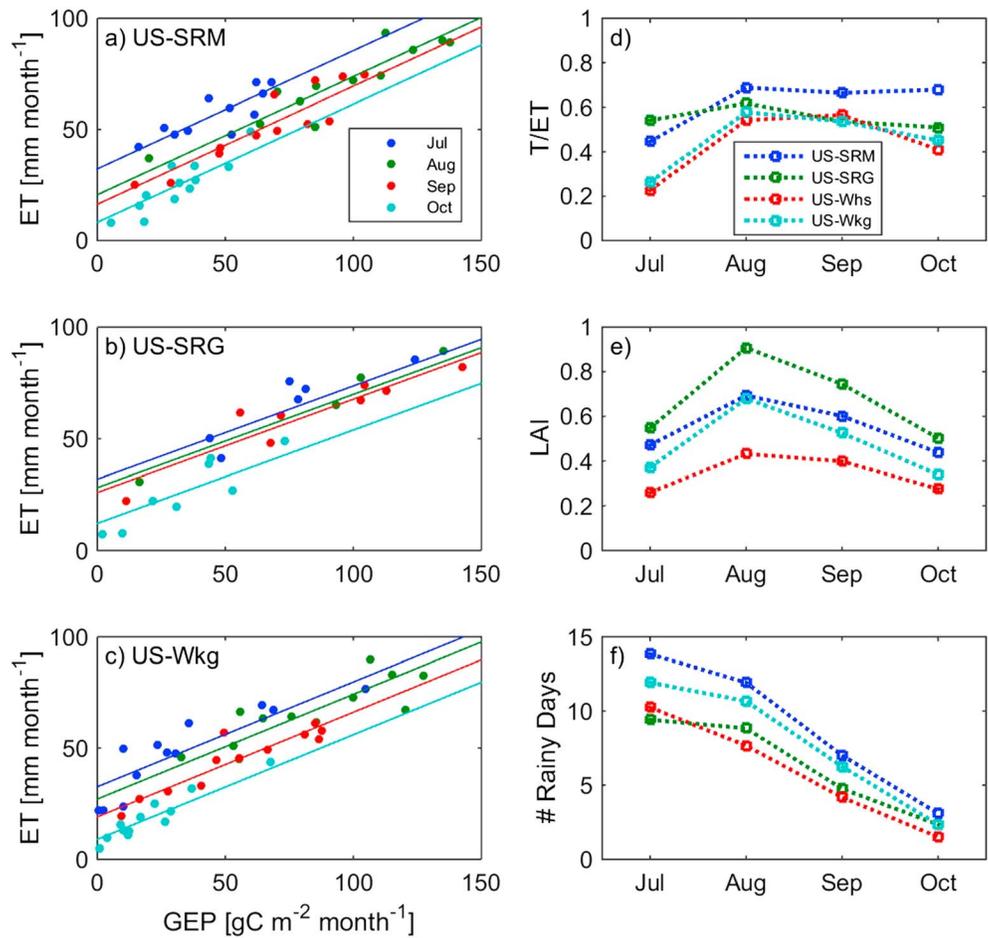


Figure 2. (a–c) July–October monthly sums of GEP and *ET* with significant ($p < 0.05$) regression lines for US-SRM, US-SRG, and US-Wkg, with colors representing months. (d–f) Resultant T/ET , monthly mean LAI, and number of rainy days per month, with colors representing sites. All sites show similar seasonal progressions of decreasing E (y axis intercept), consistent with expected effects of increasing LAI and decreasing rainy days.

possibly due to more immediate upregulation and transpiration of the grasses (as compared to the shrubs) and a more condensed seasonal growth period [Huxman *et al.*, 2004; Kurc and Small, 2007; Yezpey *et al.*, 2005].

4.2. Predicting Early Growing Season T/ET Using LAI

The hypothesized surface control of T/ET by LAI during July and August is supported by a strong relationship between LAI and T/ET for these months (Figure 3a). Sixty-nine percent of the variance in T/ET is explained by a linear relationship with LAI and 75% by a commonly used power function. The fitted power function predicts T/ET considerably below the more global, spatial shrub, and grass relationship of Wei *et al.* [2017]. While still within their 95% regression confidence intervals (not shown here), some of our estimates, notably July values at US-Whs and US-Wkg, have lower T/ET than would be predicted by Wei *et al.* Our monthly analysis captures upregulation dynamics, not captured in the seasonal to yearly data used by their study. Accordingly, seasonal averages of T/ET and LAI from our analysis plot much closer to their curve (Figure 3a, plus symbols). Furthermore, as an additional test of our method, we use our fitted power function to predict T from observed monthly ET and LAI across all instances of July and August in the data at each site (Figure 3b). The small but significant y -intercepts for US-Whs and US-Wkg result from the fitted model overestimating T/ET for low LAI. Nevertheless, regressing T instead of ET against GEP increases coefficients of variation (r^2) from a range of 0.79–0.90 to 0.92–0.95, and y axis intercepts decline from a range of 33–38 mm month⁻¹ to –3 to 8 mm month⁻¹. Thus, modeling results agree with expectations of a tight linear relationship that passes through the origin between ecosystem transpirational water vapor loss and ecosystem photosynthesis through plants [Sinclair *et al.*, 1984].

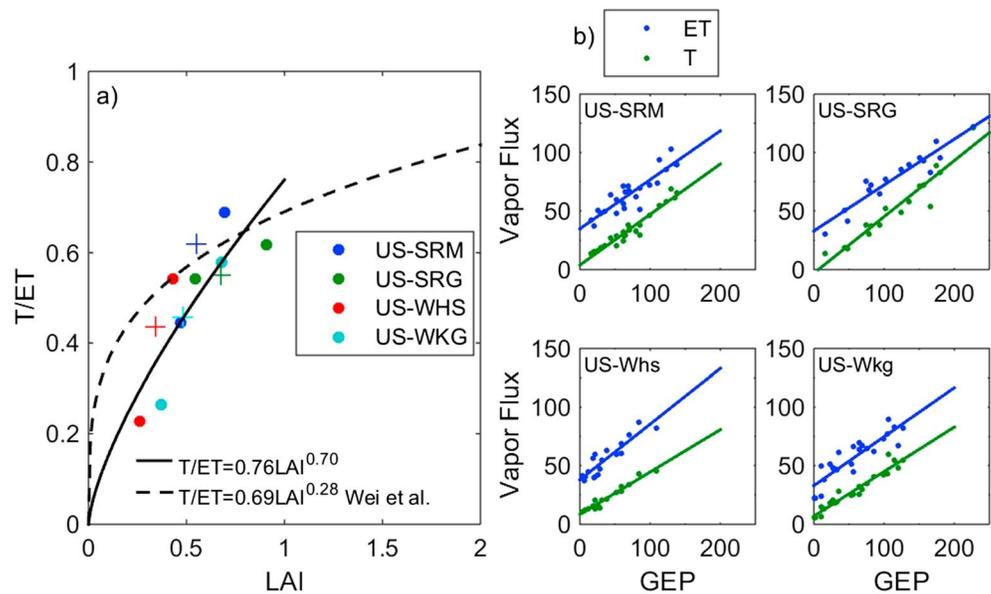


Figure 3. (a) July and August T/ET (circles) and LAI for the four sites used in this study along with a fitted power function (solid line) and the function for shrubs and grasses by *Wei et al.* [2017]. July–October seasonal averages (plus sign). (b) July and August GEP ($\text{gC m}^{-2} \text{ month}^{-1}$) and vapor fluxes, ET (blue) or T (green) (mm month^{-1}). T is computed using T/ET from the fitted equation with monthly LAI from MODIS multiplied by monthly ET. Predicted T explains more of the variability in GEP, and the regressions have x-intercepts close to the origin.

4.3. A New Tool to Quantify Long-Term T/ET

Data syntheses to explain general patterns and controls of T/ET have been hampered by differing time spans of the available observations as well as potentially high seasonal to yearly variability for some ecosystems [Schlesinger and Jasechko, 2014; Wang et al., 2014; Wei et al., 2017]. Our method can provide multiyear average partitioning at weekly to yearly levels of aggregation given flux data sets of sufficient size (ideally $n > \sim 5\text{--}7$ years, though as little as 3 years can be sufficient; Figure S3) to produce statistically significant estimates of E as demonstrated here. In our study, growing season averages were 0.44 for US-WHS, 0.46 for US-Wkg, 0.62 for US-SRM, and 0.55 for US-SRG. In comparison, Schlesinger and Jasechko [2014] compiled the measurements of both seasonal and annual T/ET and found similar mean T/ET ratios of 0.54 ± 0.18 (1 SD) for deserts and 0.57 ± 0.19 for temperate grasslands. The differences in T/ET across our sites are likely due to mean LAI differences (Figure 3a) as well as differing ecosystem structure (bare soil, interception surfaces, plant functional types, and their phenology).

The varying levels of climatic and surface controls on T/ET add additional complexity to the challenge of describing broad patterns of T/ET based on a few variables [Schlesinger and Jasechko, 2014; Wang et al., 2014]. We find that T/ET gets larger as LAI increases and the climatic forcing is relatively constant—here RD—in the first 2 months of the growing season. However, T/ET can remain elevated later in the growing season, even while LAI decreases, possibly because RD decreases, reducing the frequency of surface wetting subject to E . Thus, we expect that T/ET should be higher in regions with less rainy days (given sufficient deeper soil moisture to support plant T) and/or higher LAI. Also, T/ET should be higher in regions where the precipitation falls in periods with low evaporative demand (e.g., a Mediterranean climate) where less of the water is lost to evaporation and more is available for plants.

While this novel method of ET partitioning produces results consistent with direct methods and ecohydrological expectations at our semiarid sites, we expect that there are several cases where our approach is unsuitable. The first case would be where the regression does not produce positive y axis intercepts significantly different than zero. This can happen when there are not enough years of data to produce significant relationships or when the values of ET and GEP are too far away from the y axis (overextrapolation). Also, the site fluxes should be limited by water availability, as there is often not a strong relationship between yearly ET and GEP at nonwater-limited sites [Law et al., 2002]. Finally, the months or other periods compared across

multiple years must have similar consistency in the climate and progression of soil water availability. At our sites, there is a consistent climatology with large and rather invariant levels of radiation and vapor pressure deficit so as to not significantly affect the ecosystem marginal water use efficiency [Law *et al.*, 2002].

Our method is complimentary to and offers several advantages compared to other emerging partitioning techniques that utilize increasingly available eddy covariance measurements. Unlike the approach proposed by Scanlon and Kustas [2010], our method requires neither high-frequency (~ 10 – 20 Hz) data nor a priori knowledge of plant WUE, which is difficult to determine in the highly dynamic and spatially heterogeneous ecosystems of water-limited regions. Similar to Zhou *et al.* [2016], we assume that WUE reductions from potential WUE result from nonzero E in ET, but potential WUE is estimated differently. They use an upper percentile linear regression of 30 min ET versus $GEP * VPD^{0.5}$. This assumes that $T/ET = 1$ for the upper percentile, which may occur infrequently at water-limited sites with significant amounts of bare soil. The method of Zhou *et al.* [2016] is advantageous in that it can be used within a year and does not need multiple years of data. We, instead, use multiyear data to determine potential WUE, equal to the marginal water use efficiency ($1/m$, equation (1)) when $x = 1$ (equation (2)). Because we do not force the regression through the origin, our approach is more appropriate for water-limited sites, where it is often found that the $ET \neq 0$ (i.e., the intercept) for $GEP = 0$ [Biederman *et al.*, 2016].

Here we describe and demonstrate a new approach to partition ET that relies upon long-term eddy covariance measurements of water vapor and carbon dioxide fluxes. At four semiarid sites, this approach reveals a seasonal progression of T/ET that agrees with earlier, direct measurements as well as expectations based on surface and climatic controls. While our approach cannot be applied at all sites or for all times of year, it is useful for disentangling integrated ET measurements into its component fluxes for sites where water limitation plays a dominant role in controlling ET and GEP or for water-limited periods at more mesic sites [Jenerette *et al.*, 2012]. With the growing availability of longer term, global eddy covariance data sets (e.g., <http://fluxnet.fluxdata.org/data/fluxnet2015-dataset/>), future work will expand the application of our analysis to other sites, develop a better understanding of its limitations, and compare it with other approaches.

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