Title: Global synthesis of vegetation control on evapotranspiration partitioning

Running title: Vegetation and *ET* partitioning

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Abstract

Evapotranspiration (*ET*) is an important component of the global hydrological cycle. However, to what extent transpiration ratios (*T/ET*) are controlled by vegetation and the mechanisms of global-scale *T/ET* variations are not clear. We synthesized all the published papers that measured at least two of the three components (*E*, *T*, and *ET*) and leaf area index (*LAI*) simultaneously. Non-linear relationships between *T/ET* and *LAI* were identified for both the overall dataset and agricultural or natural data subsets. Large variations in *T/ET* occurred across all *LAI* ranges with wider variability at lower *LAI*. For a given *LAI*, higher *T/ET* was observed during later vegetation growing stage within a season. We developed a function relating *T/ET* to the growing stage relative to the timing of peak *LAI*. *LAI* and growing stage collectively explained 43% of the variations in the global *T/ET* dataset, providing a new way to interpret and model global *T/ET* variability.

1. Introduction

Evapotranspiration (*ET*) is an important component of hydrological cycles and may account for greater than 95% of all precipitation inputs in water-limited ecosystems [*Wilcox and Thurow*, 2006]. Evapotranspiration represents a central linkage between water and energy flux across various ecosystems [*Katul et al.*, 2012; *Wang and Dickinson*, 2012]. Evapotranspiration comprises two components: evaporation (*E*) and transpiration (*T*). Separating *ET* components and assessing the factors controlling the partitioning not only improve our knowledge of water budget but also enhance our understanding of plant water use mechanism and efficiency, which will reduce uncertainties in the interpretation of the coupling of water and carbon/nutrient cycles [*Austin et al.*, 2004]. The *T/ET* ratio has been reported to be 80-90% at the global scale (up to 95% in desert catchments) based on isotopic analyses in lake systems [*Jasechko et al.*, 2013]. The modeling assumption of that study is subject to debate [e.g., *Schlaepfer et al.*, 2014] and a larger *T/ET* range is reported in a more recent study [*Coenders-Gerrits et al.*, 2014], which emphasizes the need for more comprehensive evaluations of the global *T/ET* variations.

Because of the importance of separating *E* and *T*, there are many studies focusing on *ET* partitioning in both agricultural setting [e.g., *Harrold et al.*, 1959; *Sakuratani*, 1987; *Yunusa et al.*, 2004] and natural systems [e.g., *Sammis and Gay*, 1979; *Kelliher et al.*, 1992; *Oren et al.*, 1998; *Wilson et al.*, 2000; *Wang et al.*, 2013] from plot to ecosystem scale. Some recent works have aimed at developing new tools capable of partitioning *ET* components at the landscape scale [*Scanlon and Kustas*, 2010; *Wang et al.*, 2010; *Good et al.*, 2012]. Transpiration is directly related to vegetation activity, therefore it is not surprising that vegetation has a strong control on *ET* partitioning [e.g., *Good et al.*, 2014; *Schlesinger and Jasechko*, 2014], though factors affecting *E* also influence *T/ET*. Wang et al. [2010] provided experimental evidence of *ET* partitioning changes along with vegetation cover change, and they found that *T/ET* increased from 60% at 25% cover to 83% at 100% cover. However, it is still not clear to what extent that *T/ET* ratios are controlled by vegetation and what are the additional factors that could further explain the *T/ET* variations at a global scale. This hinders our predictions of future hydrological changes since vegetation provides a strong feedback to water cycling. To better answer these questions, we synthesized all the available literature data with simultaneous *ET* partitioning data and leaf area index (*LAI*). The objective of this study is to establish a quantitative relationship between *ET* partitioning and vegetation cover index (e.g., *LAI*) for different systems (i.e., agricultural vs. natural systems), and to explain the variations of observed *T/ET* at the global scale.

2. Materials and Methods

2.1 Data collection

We conducted article searches in ISI Web of Science and Google Scholar, and retrieved the references cited in papers. The following criteria were used to include papers in our synthesis: 1) at least two out of the three parameters (*E*, *T* and *ET*) were independently and experimentally measured; and 2) leaf area index was quantified simultaneously with *E*, *T* and *ET* measurements. As a result, 48 individual publications before May 31 2014 were included in our analysis (Auxiliary Material_text01). There were multiple *LAI* and *T/ET* information for some studies, which tracked the vegetation development. Therefore the 48 studies resulted in 334 sets of data. We extracted *E*, *T*, *ET* and *LAI* values directly from tables or text in original papers, or indirectly from figures using GraphClick software (Arizona software, USA). The units of *E*, *T* or *ET* were unified into mm d^{-1}, the unit conversion is important when using *ET* to explain the *T/ET* variations. Ancillary information including latitude, longitude, soil water potential, mean annual rainfall, ecosystem types were also recorded whenever they were available. We calculated stress level based on available soil water potential and vapor pressure deficit (*VPD*) information of each study. When the *VPD* information was not available from the individual study, it was extracted from a global forcing dataset [*Sheffield et al.*, 2006] based on the latitude and longitude of the study site.

2.2 Data analyses

The relationships between *LAI* and *T/ET* were analyzed using quantile regression [*Cade and Noon*, 2003] for agricultural settings, natural settings and the overall dataset. Quantile regression estimates multiple change rates from minimum to maximum responses, providing a more complete picture of the relationships between variables missed by other regression methods. In this study, 95% fitting [*Cade and Noon*, 2003] was established to capture the maximum constraints of *LAI* on *T/ET* for various systems. The data analyses were conducted using Matlab 8.2 (MathWorks, Natick, MA, USA).

3. Results and Discussion

Separating *ET* components, assessing the controlling factors of *ET* partitioning and predicting *ET* partitioning change under different climate regimes are important for estimating water budgets, predicting ecosystem dynamics and predicting hydrological responses to future climatic changes [*Newman et al.*, 2010; *Cavanaugh et al.*, 2011; *Wang et al.*, 2012; *Jasechko et al.*, 2013; *Wang et al.*, 2013]. Based on our synthesis, the majority of the *ET* partitioning studies focused on agricultural settings (29 out of 48 studies) and the number of studies focusing on natural setting was increasing in recent years (Auxiliary Material_text01). The studies with simultaneous measurements of *ET* partitioning and *LAI* appeared in most of the continents though the majority of the studies were conducted in US (Auxiliary Material_fs01). Based on isotopic analyses in lake systems, the *T/ET* ratio has been reported to be 80-90% at the global scale [*Jasechko et al.*, 2013]. A later study argues that such results are biased due to unrepresentative input data in the modeling and that another choice of input data could result in *T/ET* of 35-80% [*Coenders-Gerrits et al.*, 2014]. The current synthesis based on all the available data from global scale field measurements showed a range of 38-77% (Figure 1), supporting the number reported in Coenders-Gerrits et al. [2014].

The quantile regression showed that there were non-linear relationships between *LAI* and *T/ET* for both agricultural and natural systems, and for the overall dataset. The 95% quantile regression line reflects the practical upper limit of vegetation control on *T/ET* under a certain *LAI* (Figure 2a-c). The best fits between *LAI* (x) and *T/ET* (y) are $y = 0.91x^{0.07}$ for agricultural systems, $y = 0.77x^{0.10}$ for natural systems, and $y = 0.91x^{0.08}$ for the overall dataset (Figure 2a-c). The results showed that even under low *LAI* conditions (e.g., *LAI* = 0.5), *T/ET* value could be up to 0.72 and 0.90 for natural and agricultural systems, respectively (Figure 2a-c). The agricultural systems tend to have higher transpiration proportion under the same *LAI* value, which is likely due to the fact that agricultural plants are typically less constrained by environmental stress. The exponential relationship between *LAI* and *T/ET* indicates that large change in vegetation control on *T/ET* occurs over the lower *LAI* range, showing the possibility of high proportion of vegetation water use even under low *LAI* conditions.

There were large variations in *T/ET* over the entire range of *LAI* values. We used stress levels (both soil water potential and vapor pressure deficit) and *ET* levels to separate *T/ET* responses across the *LAI* range, but it did not help explain the variability in *LAI* (i.e., *T/ET* variability did not correspond to either different *ET* levels or stress levels, data not shown). Inconsistent methodology in quantifying *T/ET* across the different studies and inherent variations in plant water use characteristics may contribute to the variability. However, we hypothesize that vegetation growing stage may play a more important role since different levels of physiological activities (e.g., photosynthesis) are often seen under different growing stages [*Vries*, 1989]. To test this hypothesis regarding variations in *T/ET*, we developed a plant growing stage function (*S*),

$$S = sin(\frac{\pi}{2}\frac{DOY - DOY_{LAI_{max}}}{365})$$

where *DOY* refers to day of year; and LAI_{max} is the maximum *LAI* observed during the experiment. Basically *S* is a time function relating the time of measurement to the timing of peak *LAI*. A value of *S* = 0 refers to the peak *LAI* stage, while *S* = -1 is the beginning of the growing season and *S* = +1 is the end of the growing season.

By incorporating *LAI* and *S*, *T/ET* can be modeled by the following functions,

$$T/ET = 1 - e^{c_1 LAI + c_2 S + c_3}$$

where c_1, c_2 and c_3 are constants; and *S* is the growing stage function. These two parameters (*LAI* and *S*) collectively explained 43% of the variations in the global *T/ET* dataset (Figure 2d). The results showed that under the same *LAI* condition, the *T/ET* was affected by the growing stage. The *T/ET* was lower for the early stage and higher for the late stage during one growing season under the same *LAI* condition (Figure 2d). This is likely due to reduced evaporation under higher litter cover or crop residue after the peak *LAI* stage, similar to what is found in Wang et al. [2013] in a temperate grassland ecosystem. With the availability of frequent, global estimates of *LAI* and *ET*, it is feasible to use the *LAI* and *S* information to generate a global scale *T/ET* dataset. Continuous estimates of *T/ET* will significantly enhance our understanding of global vegetation water use and dynamics of water vapor isotopes and would be very useful to validate various global hydrological models.

This study presents a comprehensive global dataset of vegetation leaf area and *T/ET*, providing a guidance and reference for future *ET* partitioning studies. The 95% quantile regression line indicates the practical upper limit of vegetation control on *T/ET* under a fixed *LAI* value. More importantly, the study indicates that if we incorporate information of *LAI* and vegetation growing stage, almost half of the variability in *T/ET* could be explained, providing a new way to interpret and model the global *ET* partitioning variability.

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Figure legends

Figure 1. Ratio of transpiration to evapotranspiration (*T/ET*) at a global scale. Box plots are from Coenders-Gerrits et al. 2014 (A-B) and of the current study (C). The blue box indicates the 25th and 75th percentiles with the median in red. The error bars indicate the minimum and maximum values. The red crosses indicate outliers.

Figure 2. The relationship between the ratios of transpiration to evapotranspiration (*T/ET*) and leaf area index (*LAI*) for the overall dataset (A), agricultural systems, and (B) natural systems (C). The dashed lines depict the 95% quantile regression line. (D) The relationship between *T/ET* and *LAI*, plant growing stage function (*S*). The variability in *T/ET* and *LAI* relationship was partially explained by *S*.

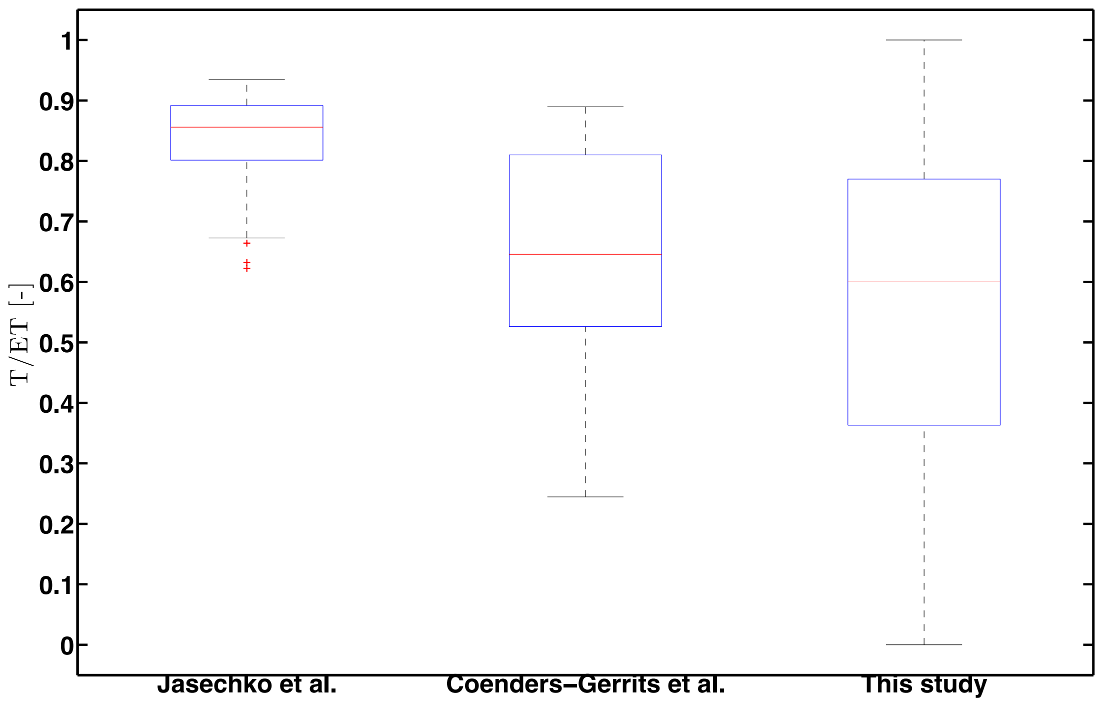
T/ET [-]
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
Jasechko et al.
Coenders–Gerrits et al.
This study

Figure 1.

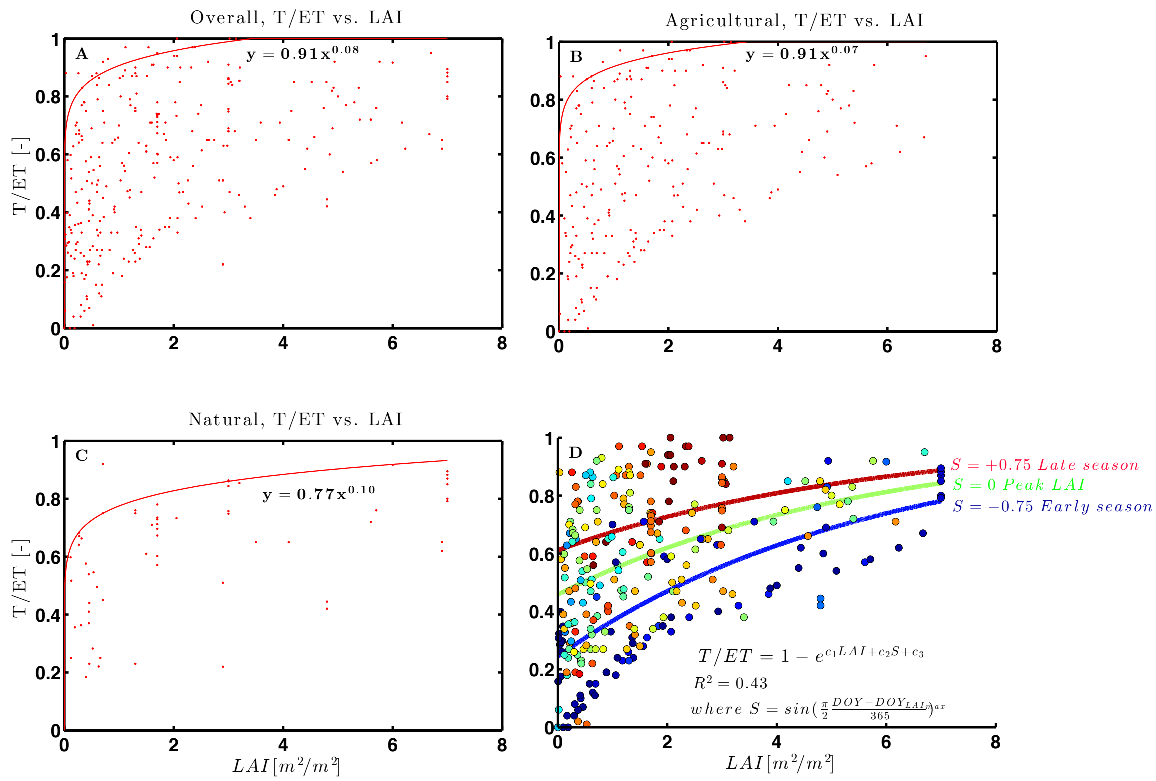
Overall, T/ET vs. LAI
A
y = 0.91x^0.08
Agricultural, T/ET vs. LAI
B
y = 0.91x^0.07
Natural, T/ET vs. LAI
C
y = 0.77x^0.10
D
S = +0.75 Late season
S = 0 Peak LAI
S = −0.75 Early season
T/ET = 1 − e^(c1 LAI + c2 S + c3)
R^2 = 0.43
where S = sin(π/2 (DOY − DOY_LAImax)/365)
T/ET [-]
LAI [m^2/m^2]

Figure 2