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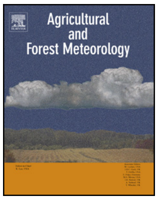

Short communication

Transpiration in the global water cycle

William H. Schlesinger[a,*], Scott Jasechko[b]

[a] Cary Institute of Ecosystem Studies, Box AB, Millbrook, NY 12545, United States
[b] Department of Earth and Planetary Sciences, University of New Mexico Albuquerque, NM 87131, United States

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ABSTRACT

A compilation of 81 studies that have partitioned evapotranspiration (ET) into its components—transpiration (T) and evaporation (E)—at the ecosystem scale indicates that T accounts for 61% (±15% s.d.) of ET and returns approximately 39 ± 10% of incident precipitation (P) to the atmosphere, creating a dominant force in the global water cycle. T as a proportion of ET is highest in tropical rainforests (70 ± 14%) and lowest in steppes, shrublands and deserts (51 ± 15%), but there is no relationship of T/ET versus P across all available data ($R^2 = 0.01$). Changes to transpiration due to increasing CO_2 concentrations, land use changes, shifting ecozones and climate warming are expected to have significant impacts upon runoff and groundwater recharge.

1. Introduction

Precipitation on the land surface is lost to runoff, groundwater, or evapotranspiration (ET) to the atmosphere. ET is seldom partitioned into its components—one physical evaporation from surfaces (E), and the other biological transpiration (T), involving root uptake of soil moisture and the loss of water vapor through plant stomates during photosynthesis. Partitioning ET in field studies is not easy. Some studies have inferred T by changes in soil moisture or runoff after the harvest of vegetation, accepting that harvest involves changing the surface area of vegetation that might otherwise intercept and evaporate water. Other studies have used a combination of eddy-covariance methods to estimate ET, and separately estimate T by measures of sap-flow in dominant trees, accepting errors associated with a small and potentially non-representative sample of trees and often ignoring subcanopy vegetation. Recently, several studies have partitioned E and T by measurements of the isotopic composition of oxygen in soil and runoff waters, recognizing that $\delta^{18}O$ is enriched by evaporation but not by transpiration (Wershaw et al., 1966). Isotope studies are affected by variations in the isotope ratio in incident precipitation and differential contributions of soil and groundwater throughout the year.

2. Results and discussion

Only a limited dataset is available for field studies that partition ET (Supplemental Table 1). Hardly any studies are available in Africa or southern and northeastern Asia (Fig. 1). We focused on studies using eddy-covariance and sap-flow measurements or isotopic approaches. Many of these studies used combinations and comparisons of methods, coupled to biophysical models to estimate E and T. We did not include estimates from FLUXNET studies that partition ET by assuming losses of water vapor from the canopy and understory represent T and E, respectively (Baldocchi and Ryu, 2011). This approach ignores the evaporation of P that is intercepted by the canopy and the transpiration of understory plants.

The proportion of precipitation (P) that is lost as T has a median value of 45% and only a few values are greater than 80%. The median value for T/ET is 59%. Weighting T/ET to either ecozone P or ET (Mu et al., 2011) yields a global T/ET estimate of 61 ± 15% (s.d.; Table 1). Several of the studies include only the growing season and presumably T/ET would be lower on an annual basis. Some crop and greenhouse studies report an increasing fraction of T/ET as plant cover increases (Ashktorab et al., 1994; Young et al., 2009; Wang et al., 2010). Among the values compiled in Appendix 1, T/ET is greater in tropical rainforests than in deserts, although there is a considerable overlap in values (Fig. 2). In forests the interception of precipitation by the canopy and its loss to evaporation is typically 10–35% of incident precipitation (Waring and Schlesinger, 1985; Wang et al., 2007). Additional evaporative loss occurs from the surface of understory vegetation and soils. This interception loss is compatible with T/P less than 65–90%.

T/ET is generally higher in wet climates (e.g., T/ET for tropical forests is 70 ± 14% (s.d.) and lower in semi-arid ecosystems (the ET-weighted T/ET value for steppe, desert and shrubland is 51% ± 15%). Nevertheless a regression of T/ET versus P shows no global trend (Fig. 3a). Differences in the partitioning of ET are important to assess the impact of anthropogenic CO_2 enrichments and land-use change. The greater role of T in tropical forests suggests that changes to

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* Corresponding author. Tel.: +1 845 677 7600x106.
E-mail address: schlesingerw@caryinstitute.org (W.H. Schlesinger).

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Table 1
Summary of compiled transpiration studies.

Ecoregion	T/ET percent average ± 1 s.d.	Land area (%)	Precipitation (mm/year)	Percent of terrestrial precipitation (%)	ET[a] (mm/year)	Percent of terrestrial ET (%)
Tropical rainforest	70 ± 14 ($n=8$)	16	1830	35	1076 (927)	33.1 (28.5)
Tropical grassland	62 ± 19 ($n=5$)	12	950	14	583 (726)	13.9 (17.3)
Temperate deciduous forests	67 ± 14 ($n=9$)	9	850	10	549 (506)	10.1 (9.3)
Boreal forest	65 ± 18 ($n=5$)	14	500	8	356 (315)	9.5 (8.4)
Temperate grassland	57 ± 19 ($n=8$)	8	470	5	332 (406)	5.4 (6.6)
Desert	54 ± 18 ($n=14$)	18	180	4	209 (186)	7.3 (6.5)
Temperate coniferous forest	55 ± 15 ($n=13$)	4	880	4	458 (404)	3.4 (3.0)
Steppe	48 ± 12 ($n=3$)	4	440	2	467 (343)	3.4 (2.5)
Mediterranean shrubland	47 ± 10 ($n=4$)	2	480	1	302 (393)	1 (1.3)

[a] Evapotranspiration (ET) data from MODIS (Mu et al., 2011) and FAO (in parentheses, from www.fao.org/geonetwork/).

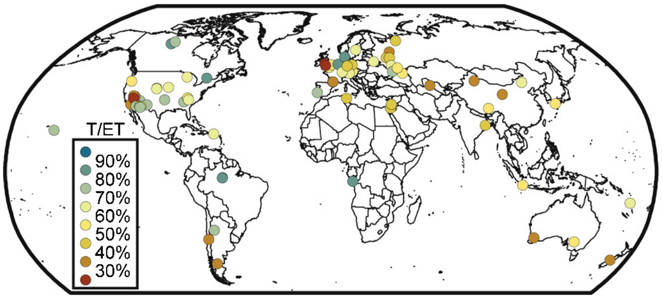

Fig. 1. Published stand-level measurements of transpiration as a proportion of total evapotranspiration (T/ET; see supplemental materials and references therein.

runoff ratios due to the CO_2 fertilization of plant growth may be greater in tropical relative to arid regions.

The values in Table 1 are lower than in the results of a recent attempt to partition ET globally, using the enrichment of $\delta^{18}O$ in surface waters that results from evaporation (Jasechko et al., 2013). The latter authors conclude that T/ET is 80–90%, which is not easy to reconcile with the values reported here. The difference in T/ET may stem from an estimate for the interception of 7% of precipitation (Miralles et al., 2010) used in Jasechko et al. (2013) compared to field measurements that suggest a global interception of ~18% of incident precipitation (median of works compiled by Wang et al., 2007; see Fig. 1 therein). Isotope approaches are often found to result in higher values for T/ET (Fig. 3b; e.g., Ferretti et al., 2003; Gibson and Edwards, 2002; Telmer and Veizer, 2000) than models driven by meteorological measurements and sap flow meters (Fig. 3b).

Isotope-based T/ET may overestimate catchment transpiration in cases of "hydrologic decoupling", whereby the isotopic signature in the runoff from high-elevation first-order streams has a disproportionate effect on the isotopic composition of downstream waters (e.g., Brooks et al., 2010). Although this process has yet to be shown to be important at a continental scale (Phillips, 2010), it may help to explain higher isotope-based T/ET relative to stand-level measurements in arid climates where this decoupling may be important (Newman et al., 1998). Conversely, stand-level T/ET may underestimate transpiration because some studies only consider only transpiration of canopy trees, neglecting potential subcanopy contributions (e.g., Tajchman, 1972; Paco et al., 2009).

Uncertainties are large in both isotope-based approaches (e.g., Fig. 2 in Jasechko et al., 2013) and stand-level measurements (e.g., T/ET estimates from two different studies for the same watershed yield 42 or 79%; Cavanaugh et al., 2011; Moran et al., 2009). Further, where the isotope-based approach may be constrained by hydrologic decoupling, stand-level measurements have are difficult to extrapolate to larger scales. Constraining the uncertainties in continental transpiration is critical given ongoing changes to plant water-use efficiency on the order of ~20% per decade (median value from Keenan et al., 2013), and are likely to benefit from both stand-level and catchment-scale isotopic approaches.

With plant transpiration accounting for 60–80% of ET on land, there is no doubt that terrestrial vegetation is a dominant force in the global water cycle. Transpiration is a major determinant of local microclimate and rainfall. Losses of vegetation in the geologic past (Steinthorsdottir et al., 2012) and ongoing now result in greater runoff, erosion, and loss of soil fertility. Decreasing plant transpiration as a response to rising atmospheric CO_2 (Keenan et al.,

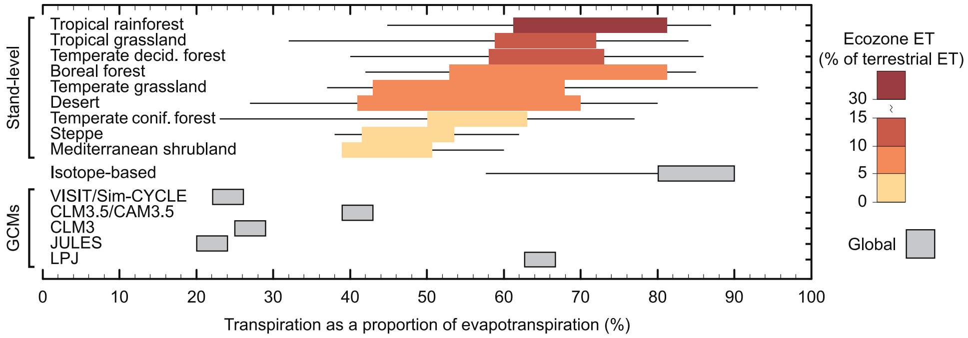

Fig. 2. Compiled estimates of transpiration as a proportion of terrestrial evapotranspiration from stand level measurements (colored bars) and global-scale calculations (gray). Colored bars represent the proportion of total terrestrial evapotranspiration (Mu et al., 2011) represented by each ecozone, with bars extending to 75th and 25th percentiles of compiled works, and whiskers showing maximum and minimum estimates. The global-scale isotope-based estimate of T/ET is derived from Jasechko et al., 2013, with error bars showing T/ET calculated using compiled interception measurements (19,000 ± 10,000 km^3/year, median ± 1 s.d. from Wang et al., 2007) instead of satellite-based estimates (7500 km^3/year Miralles et al., 2010, used in Jasechko et al., 2013). Global climate model-based estimates of T/ET are available from VISIT (Ito and Inatomi, 2012), CLM3.5/CAM3.5 (Cao et al., 2010), CLM3 (Lawrence et al., 2007), JULES (Alton et al., 2009) and LPJ (Gerten et al., 2005) models.

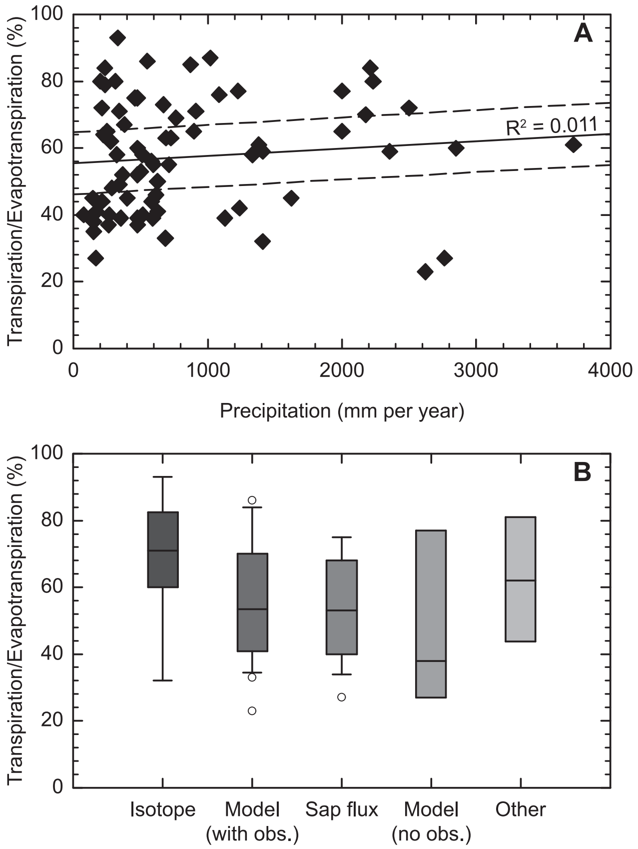

Fig. 3. Stand level T/ET values in relation to precipitation amount (a) and measurement technique (b). (a) A linear regression of T/ET and precipitation at each study site produces a weak correlation coefficient ($R^2 = 0.011$, dashed lines mark 95% confidence interval). (b) T/ET varies in relation to measurement technique, with boxes marking the 75th and 25th percentiles (median value shown as thick black line). Isotope-based approaches ($n = 9$) produce a median T/ET of 72%, evaporation models that incorporate field observations (e.g., soil moisture, meteorological measurements; $n = 31$) produce a median T/ET of 55%.

2013) is likely to increase runoff and lead to shifts in the distribution of vegetation, especially in semiarid regions.

Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.agrformet.2014.01.011.

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