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Evapotranspiration partitioning in dryland ecosystems: A global meta-analysis of *in situ* studiesXiangmin Sun^{a,*}, Bradford P. Wilcox^a, Chris B. Zou^b^a Department of Ecosystem Science and Management, Texas A&M University, College Station, TX, USA^b Department of Natural Resource Ecology and Management, Oklahoma State University, Stillwater, OK, USA

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ABSTRACT

In drylands, evapotranspiration (*ET*) is the dominant ecohydrologic process. For this reason, partitioning of *ET*—determining the relative importance of interception (*I*), soil evaporation (*E*), and plant transpiration (*T*)—is critical, but remains a challenge. Recently, however, advances in measurement technologies and data availability have triggered an upsurge in *in situ* studies focused on quantifying *T/ET*. We carried out a meta-analysis of 38 datasets drawn from 31 studies done in drylands worldwide. This analysis showed that over the growing season, *E* and *T* are roughly equivalent for most natural ecosystems, whereas *T/ET* is higher in irrigated agroecosystems. With respect to factors controlling variations in *T/ET*, we found (1) no clear correlation for annual precipitation, soil texture, or ecosystem type; (2) leaf area index is a more significant controlling factor than fractional cover; and (3) *T/ET* varies most during dynamic wetting–drying episodes. We also found that controlling factors are different for *E* and *T*. Because these two processes differ in temporal dynamics, the factors controlling *ET* partitioning vary with temporal scale. Further, when interception and shallow groundwater are substantial, including these factors is essential for accurate *T/ET* quantification. The isotopic approach, especially using laser spectroscopy, is now indispensable for such studies. However, issues related to sampling protocols and quality assurance still must be resolved. We propose three promising areas for future studies in drylands: (1) isotopic sampling of vadose-zone water vapor using laser spectroscopy; (2) improved definition/identification of diffusive pathways; and (3) robust upscaling from incongruent hydrometric and isotopic measurements.

1. Introduction

Drylands cover about 40% of the global landmass and up to 44% of cultivated lands, supporting 35% of the global population (Safriel et al., 2006). Drylands can be grouped into four categories, according to level of aridity: hyper-arid, arid, semiarid, and (dry) subhumid (Berry Sandra et al., 2006). Sustainable and efficient management of these ecosystems requires an in-depth understanding of the water cycle, and especially of the evapotranspiration (*ET*) component, which typically accounts for 90%–95% of annual precipitation (Kurc and Small, 2004; Wilcox et al., 2003; Zhang et al., 2011). The bulk *ET* flux consists of interception evaporation (*I*), soil evaporation (*E*), and plant transpiration (*T*). Partitioning of *ET*—determination of the relative importance of these constituent fluxes, usually expressed as a ratio (*T/ET* or *E/ET*)—is a challenging exercise but is essential for understanding dryland ecohydrology (Kool et al., 2014; Newman et al., 2006; Wang et al., 2010). This rationale is well supported, considering the following facts:

- Partitioning of *ET* is critical for quantifying (1) water-use efficiency (Lu et al., 2017; Williams et al., 2004), (2) ecosystem productivity (Brooks, 2015; Yopez et al., 2003) and sustainability (Raz-Yaseef et al., 2012), (3) biological water demand and its influence on the hydrologic cycle (Newman et al., 2006), and (4) the coupling of hydrologic and biogeochemical cycles (Austin et al., 2004; Jasechko, 2018; Wang et al., 2012).
- Partitioning of *ET* is essential for calibrating and validating surface–plant–atmosphere transfer models (Braud et al., 2005; Kroes et al., 2017; Sutanto et al., 2012), land surface models (Aouad et al., 2016; Wong et al., 2017), and the land–atmosphere interaction in climate models (Lawrence et al., 2007; Zhang et al., 2016).
- The processes of *I*, *E*, and *T* differ not only in timing and duration (Dickinson et al., 2003) but also with respect to the mechanisms involved in phase change—the latter differences being responsible for the dissimilarities in stable isotope composition among these constituent fluxes (Savenije, 2004).

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A clear understanding of *ET* partitioning is especially crucial for sustainable management of water resources in drylands, which are expected to be increasingly limited under climate change, mounting demographic pressures, and competition from many other socio-economic sectors. A fundamental strategy for reaching a sustainable level of agricultural water consumption is that of enhancing the “productive” component (*T*) and curtailing the “unproductive” component (*E*) (Falkenmark and Rockström, 2004).

Topics on *ET* partitioning have been summarized in a few studies: Kool et al. (2014) comprehensively reviewed methodologies available for *ET* partitioning, including both *in situ* measurement and modeling, on the basis of 52 publications; Yakir and Sternberg (2000) reviewed the isotopic approach for measuring gas exchange at the ecosystem level; Schlesinger and Jasechko (2014) compiled 81 worldwide studies on *ET* partitioning at the ecosystem scale, and found that *T/ET* is relatively lower in semiarid ecosystems ($51 \pm 15\%$ for steppe, desert, and shrublands) than in wet climates (e.g., $70 \pm 14\%$ for tropical forests); Wang et al. (2014) synthesized the relationship between *T/ET* and leaf area index (*LAI*) at a global scale, on the basis of 48 published studies; and Wei et al. (2017) further refined this relationship for different vegetation types.

To our knowledge, however, there has been no synthesis of what is known about *ET* partitioning in drylands. In this paper, on the basis of a meta-analysis of the pertinent *in situ* studies, we discuss four topics relevant to *ET* partitioning: (1) the approaches and methodologies commonly used for field studies; (2) the general trends in *ET* partitioning in dryland ecosystems; (3) emerging themes from the literature; and (4) challenges and opportunities for future investigations.

2. Literature collection

Using the Web of Science Core Collection (<http://apps.wofknowledge.com>), we searched for relevant peer-reviewed journal articles published in English from 1987 to June 2018. We used mutated combinations of the following inquiry terms: (“evapotranspiration” AND “partition*”), (“evaporation” AND “transpiration”), (“dryland” OR “water-limited”), and (“semiarid” OR “semi-arid” OR “arid”). We filtered the retrieved raw records (~200) with the following criteria: (1) quantitative separation of the *ET* flux, whether into two constituents (*E* and *T*) or three (*E*, *T*, and *I*); (2) major results obtained from *in situ* studies at the site or plot scale, rather than from modeling or remote sensing at the regional scale; and (3) at least two independent measurements, in parallel, of the three variables *ET*, *E*, and *T*.

The outcome was the selection of 31 *in situ* studies from drylands across the world (Fig. 1), which yielded 38 datasets (Tables 1 and 2). Some studies (Scott and Biederman, 2017; Yimam et al., 2015) encompassed multiple ecosystems and/or different treatments, in which case we labeled each ecosystem/treatment as a separate dataset. If exact numeric values relevant to *ET* partitioning were given only in graphs, we extracted those values with Engauge Digitizer (10.4, Mark Mitchell, Engauge Digitizer, <https://github.com/markummittchell/engauge-digitizer>).

As shown in Figs. 1 and 2, the great majority (about 80%) of the retrieved studies were conducted in semiarid climates, whereas those done in hyper-arid and subhumid climates account for only about 10% (~5% each category). On the basis of the information provided in the original records, we grouped the dryland ecosystems into the following eight types: grassland, savanna, shrubland, open woodland, forest, orchard, cropland, and marshland. Semiarid-climate grasslands and shrublands are the two most common natural ecosystems (each representing more than 15%). Agro-ecosystems (including croplands and orchards, usually irrigated) are also well represented (38%) across the spectrum of climatic aridity. The most common crops were winter wheat and maize (Table 2).

3. Approaches and methods used in the *ET* partitioning studies

Following the practice of previous studies (Laudon et al., 2004; Sutanto et al., 2014), we grouped the widely used *in situ* measurement methods for *ET* partitioning into two overarching approaches: hydrometric and isotopic (Fig. 3). Of the 31 published studies in our meta-analysis, 15 used mainly the hydrometric approach (Table 1) and 16 used mainly the isotopic approach (Table 2). However, these two approaches are usually integrated for *ET* partitioning, especially at the ecosystem or larger scales (Good et al., 2014; Williams et al., 2004; Xiao et al., 2018).

3.1. Hydrometric approach

Multiple hydrometric methods are available for measuring the bulk *ET* flux or its constituents individually. Micro-meteorological techniques—such as Bowen ratio energy budget and eddy covariance—provide only an aggregate of *ET* fluxes based on energy balance. However, multiple algebraic methods have been proposed that are capable of partitioning *ET* via additional measurements, such as ground surface temperature (Moran et al., 2009) or gross ecosystem photosynthesis (Scott and Biederman, 2017). Another recently proposed method for partitioning *ET* is based on the assumption of flux variance similarity in high-frequency eddy covariance data (Scanlon and Kustas, 2012; Skaggs et al., 2018; Wang et al., 2016b). In addition, Zhou et al. (2016) have proposed a concept called “underlying water use efficiency” (*uWUE*). This concept estimates *T/ET* as a ratio of average over potential *uWUE*, by assuming that potential *uWUE* is related to *T* and average *uWUE* is related to *ET*.

To obtain transpiration (*T*), xylem sap flow is commonly measured by various thermic techniques (Allen and Grime, 1995; Burgess et al., 2001; Granier, 1987; Poyatos et al., 2016). Gas-exchange chambers are also widely used to measure transpiration at smaller scales, such as leaf or stem (Pearcy et al., 2000; Stannard and Weltz, 2006; Yepez et al., 2005). For soil evaporation (*E*), the micro-lysimeter is an inexpensive and reliable tool when roots are excluded from the sampling soil column (Good et al., 2014); this tool is especially popular and convenient for loose and shallow soils in irrigated croplands.

Evaporation from canopy interception (*I*) is obtained by subtracting the sum of throughfall and stemflow from the measured above-canopy precipitation. Five of our retrieved studies explicitly included measurements or calculations of interception (Mitchell et al., 2009; Raz-Yaseef et al., 2010; Wang and Wang, 2017; Yaseef et al., 2010; Yimam et al., 2015). These hydrometric methods are often used in combination to measure different constituents of the *ET* flux at the site or plot scale (Table 1) or used for comparison with and validation of other methods (Perez-Priego et al., 2017; Widmoser and Wohlfahrt, 2018).

3.2. Isotopic approach

Water vapor from soil evaporation is usually lighter in isotopic composition than that from transpiration, because during soil evaporation, the liquid–vapor phase change involves a strong fractionation process. Being a substantial factor in dryland ecosystems, the isotopically lighter soil evaporation contrasts strongly with the isotopically heavier transpiration, which facilitates the practical application of the isotopic approach (Good et al., 2014).

There are two major methodologies by which the isotopic approach is used. One is the two-source mixing model, expressed as

$$\frac{T}{ET} = \frac{\delta_{ET} - \delta_E}{\delta_T - \delta_E}, \quad (1)$$

where δ_{ET} is the isotopic composition of the aggregated *ET* flux, and δ_E and δ_T are the isotopic compositions of evaporation and transpiration, respectively. Various techniques and measuring methods have been developed to quantify these three isotopic values (Table 2 and Fig. 3).

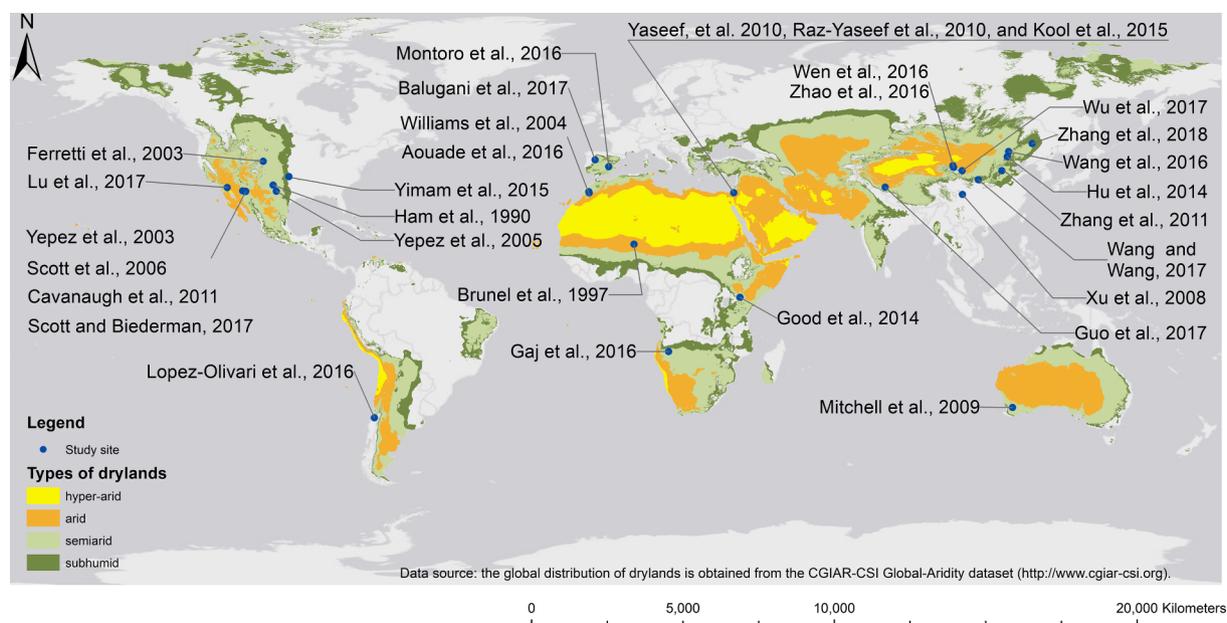


Fig. 1. Distribution of drylands and locations of study sites.

For δ_{ET} , the Keeling plot method (Keeling, 1958; Yakir and Sternberg, 2000) and the flux-gradient method (Griffis et al., 2004), both based on isotopic sampling of atmospheric water vapor within the ecosystem boundary layer, are widely used. For δ_E , the Craig–Gordon method (Craig and Gordon, 1965; Horita et al., 2008) has become a quasi-standard method. For δ_T , both steady-state theory and non-steady-state theory are often used, depending on the temporal resolution (Barnard et al., 2006; Flanagan and Ehleringer, 1991; Wang and Yakir, 1995).

The second methodology is isotopic mass balance. Under steady-state conditions, it can be simplified as

$$P * \delta_P = Q * \delta_Q + E * \delta_E + T * \delta_T, \quad (2)$$

where P and δ_P represent precipitation and its isotopic composition, while Q and δ_Q represent runoff and its isotopic composition. This method has been applied at scales ranging from that of soil profile (Ferretti et al., 2003; Gaj et al., 2016) to that of regional watershed (Guo et al., 2017). The development of the isotopic approach has been thoroughly discussed elsewhere (Kool et al., 2014; Sutanto et al., 2014; Wang et al., 2012; Xiao et al., 2018; Yakir and Sternberg, 2000; Zhang et al., 2010).

The isotopic approach requires extensive sampling of water from different reservoirs within the ecohydrologic cycle. To study the isotopic dynamics of atmospheric water vapor, cryogenic trapping systems (Barron-Gafford et al., 2017; Han et al., 2006; Helliker et al., 2002; Zhang et al., 2011) have often been used; however, the trapping method involves a slow (a few hours) and laborious process of sample collection, resulting in low temporal resolution and discreteness of the data series. In contrast to such discrete “snapshots,” field-deployable laser spectroscopy has become increasingly popular for its ability to directly sample atmospheric water vapor and to measure the isotopic composition with high temporal resolution and an accuracy comparable with that of traditional isotope ratio mass spectroscopy (Berman et al., 2013). These laser instruments greatly expand the applicability of stable water isotopologues in ecohydrologic studies (Wang et al., 2012).

For the 16 studies using the isotopic approach (Table 2), 14 studies used the single-isotope method (either ^2H or ^{18}O) and only two (Gaj et al., 2016; Yepez et al., 2003) used the double-single isotope method (^2H and ^{18}O simultaneously). The ^2H method is preferable for estimating δ_{ET} , owing to its high sensitivity (Aouade et al., 2016). In terms of labeling, two studies used artificially labeled water for ET partitioning (Good et al., 2014; Yepez et al., 2005), and one used injection of

deuterated water into the groundwater to separate the sourcing depths for transpiration (Balugani et al., 2017).

3.3. Application of the hydrometric and isotopic approaches in dryland ecosystems

The *in situ* studies reported on in our 31 retrieved publications made extensive use of the hydrometric and isotopic approaches (Fig. 4a). The measurement periods vary dramatically from one study to another—ranging from one day (Yepez et al., 2003; Zhang et al., 2011) to the length of the growing season or even a full year (Tables 1 and 2). The shorter-term investigations (most not exceeding 10 days) were classified as intermittent studies; these typically were carried out with the isotopic approach, owing to the need for extensive sampling and close human monitoring. In only two isotopic studies (in croplands) were measurements taken throughout the growing season (Lu et al., 2017; Wen et al., 2016). Long-term investigations, at either the growing season or the annual scale, are typically carried out with the hydrometric approach. One hydrometric study even used climatic records covering more than a decade (Scott and Biederman, 2017).

4. General trends in ET partitioning in dryland ecosystems

Comparison of long-term annual mean precipitation (Fig. 4b), soil texture (Fig. 4c), and ecosystem types (Fig. 5a) reveals no clear trends in ET partitioning. Results from longer-term investigations (growing season or annual scale) show that in natural ecosystems, evaporation and transpiration are largely equivalent, whereas in agro-ecosystems (usually irrigated) the transpiration fraction is relatively higher (Fig. 5a). Results for T/ET from the longer-term studies in natural ecosystems showed less variability ($0.37\text{--}0.84$ [mean value \pm standard deviation of 0.52 ± 0.13 , $n = 13$]) than those from the intermittent studies ($0.06\text{--}0.85$ [mean value \pm standard deviation of 0.47 ± 0.34 , $n = 9$]). The 0.06 minimum value for one of the intermittent studies was observed in an open woodland (7% plant coverage) under dry summer conditions (Balugani et al., 2017), indicating that T/ET is lower for woodlands with sparse vegetation canopies. Agro-ecosystems showed higher T/ET , with intermittent measurements ranging from 0.46 to 0.78 (mean value of 0.65 ± 0.13 , $n = 5$) and longer-term measurements from 0.44 to 0.90 (mean value of 0.66 ± 0.17 , $n = 9$). Maximum T/ET values are similar for natural ecosystems and agro-

Table 1
Results of ET partitioning via the hydrometric approach (15 studies).

Location	Climate	MAP ¹	Ecosystem type	Plant Canopy		Soil Texture	Study Period	Measuring Methods ²		T/ET ³		Source
				Fractional Cover	LAI			ET	E	T	I	
Texas, USA	semiarid		cotton cropland		2.39	sandy clay loam	August 8–15, 1989	BREB	lysimeter	sap	0.57	(Ham et al., 1990)
Arizona, USA	subhumid	322	Chihuahuan desert shrubland	51%		gravelly-sandy loams	summer growing season, 2003	BREB		sap	0.58	(Scott et al., 2006)
Southwestern Australia	semiarid	361	open eucalyptus woodland		0.66	sandy loams to clay	November 2005–March 2007		chamber	sap	(0.22–0.53)	(Mitchell et al., 2009)
Southern Israel	semiarid	285	open forest	60%	1.5	clay-loam	2003–2007	EC	soil chambers	sap	0.45	(Yaseef et al., 2010)
Southern Israel	semiarid	285	open forest	65%	1.5	clay-loam	October 2004–May 2007	EC	chamber	sap	(0.49)	(Raz-Yaseef et al., 2012)
Southeastern Arizona, USA	semiarid	340–345	shrubs	24–27%	0.45–0.46	sandy loam	summer 2008	EC		sap	0.42–0.47	(Cavanaugh et al., 2011)
Oklahoma, USA	subhumid	880	cropland	0–95%		loam	growing seasons of 2011–2013	Mass (soil)	FAO-56	tray	(0.72 vs 0.58)	(Yimam et al., 2015)
Central Spain	semiarid	320	grape vineyard		1.4–2		2011–2014	lysimeter		lysimeter	0.19–0.69	(Montoro et al., 2016)
Región del Maule, Chile	semiarid	602	olive orchard (irrigated)	30%	1.32	clay loam	growing seasons of 2009–2011	EC	lysimeter	sap	0.64–0.74	(Lopez-Olivari et al., 2016)
Negev highlands, Israel	hyper-arid	< 100	wine grape vineyard		< 1.71		growing season of 2012	EC	energy balance & lysimeter	sap	0.89–0.91	(Kool et al., 2016)
Northwestern China	arid	117	desert shrub	15%–20%	1.0	unconsolidated sand	growing seasons of 2008–2010	BREB	lysimeter	sap	(0.64)	(Zhao et al., 2016)
Inner Mongolia, China	semiarid	286	steppe grassland		0–1.2		growing seasons of 2005–2008	EC	— Flux variance similarity		0.50–0.74	(Wang et al., 2016a)
Spain	semiarid	586	open woodland	7%		sandy	dry summers of 2009–2010	EC	HYDRUS1D	sap	0.06	(Balugani et al., 2017)
Southern Arizona, USA	semiarid		shrubland, savanna, grasslands		0.2–0.8		summer growing seasons of 2004–2015	EC	— ET/GEP regression		0.44	(Scott and Biederman, 2017)
Northwest China	semiarid	584	orchard (apple)		1.4–2.2		May–September 2012–2014	lysimeter		sap	(0.39–0.49)	(Wang and Wang, 2017)

¹ Mean annual precipitation (mm).

² The ET flux and its constituents can be measured with the following methods: eddy covariance (EC), Bowen Ratio Energy Balance (BREB), soil moisture mass balance [Mass (Soil)], micro-lysimeter (lysimeter), simulation with the HYDRUS1D model, sap flow meter (sap), the Food and Agriculture Organization crop ET formula (FAO-56). The flux variance similarity method and regression analysis using ET and Gross Ecosystem Production (GEP) are used to partition ET obtained from EC measurement.

³ Numbers in parentheses indicate measurement of T/(E + T + D), which include measured or calculated interception (I); numbers without parentheses indicate measurement of T/(E + T) without explicit consideration of interception (I).

Table 2
Results of ET partitioning via the isotopic approach (16 studies).

Location	Climate	MAP	Ecosystem type	Plant Canopy Cover	Fractional LAI	Soil	Study Period	Sampling Soil Depth	Plant	Air ²	Calculation Methods ³				T/ET	Source
											ET	E	T	δ_{ET}		
Niger, West Africa	semiarid	550	bushland, woody shrubs	20%		sand	Early in the rainy season	0–1.2 m	twigs	3–12 m (c)	iso-mass	CG	ISS	ISS	0.21	(Brunel et al., 1997)
Southeastern Arizona, USA	semiarid	343	savanna woodland	70%	1.6 [o] ¹		July & September 2001	0–0.1 m		0.1–1 m & 3–14 m (c)	Keeling	CG	ISS	ISS	0.85	(Yepez et al., 2003)
Northeastern Colorado, USA	semiarid	320	shortgrass steppe			sandy loam	May 1999–October 2001	0.03–0.5 m					iso-mass (soil)		0.93	(Ferretti et al., 2003)
Marrakech, Morocco	semiarid	253	olive orchard				October 2001	0–0.3 m	twigs	0.1–8.9 m (c)	Keeling	CG	ISS	ISS	1.00–0.69	(Williams et al., 2004)
Southeastern Arizona, USA	semiarid		grassland		0.66 ~ 0.37	loamy sand	June 12–27, 2003	0–0.3 m	shoot bases	Chamber (c)	Keeling	CG	NSS	NSS	0.33–0.18	(Yepez et al., 2005)
Western China	semiarid	710	subalpine shrubland	> 90%	2.05 [o]	sandy loam	June 21, 24, 25, 2006	0–0.1 m	oak branches & grass stems	0.1–3 m (c)	Keeling	CG	ISS	ISS	0.66–0.97	(Xu et al., 2008)
Northern China	semiarid	480	winter wheat		2.6 (well-watered)	loam	growing season 2009	0.05–1 m	stem	0.1–10 m (c)	Keeling	CG	ISS	ISS	> 0.70	(Zhang et al., 2011)
Central Kenya	arid	600	perennial grass field	0–10%	≤ 0.1	sandy loam	February 7–21, 2011	0.01–0.2 m		0.1–10 m (l)	Keeling	CG	chamber	chamber	0.29	(Good et al., 2014)
Inner Mongolia, China	semiarid	383	temperate grassland		≤ 0.5	sandy	DOY 178–224, 2009	0.05–0.25 m	leaf & stem	0.7–1.7 m (l)	FG	CG	iso-mass	iso-mass	0.83	(Hu et al., 2014)
Northern-central Namibia	semiarid	250–500	forest			sandy	June 9–15, November 15–22, 2014			0.02–1 m within the vadose zone (l)			iso-mass (soil)		0.81	(Gaj et al., 2016)
Morocco	semiarid	240	winter wheat	85%	0–4	clayey to loamy	Five days in 2011–2013	0–0.7 m	stem	0–3 m (c)	Keeling	CG	ISS	ISS	0.69–0.80	(Aouade et al., 2016)
Northwestern China	arid	129	spring maize		5.6		May 27–September 22, 2012	0–0.8 m	leaf & root crown	0.6–3.6 m (l)	FG	CG	iso-mass & ISS	iso-mass & ISS	0.87	(Wen et al., 2016)
Southern California, USA	hyper-arid	80	forage sorghum		0.5–1.9	silty clay	July 24–August 20, 2014			Chamber (l)			Keeling & iso-mass		0.46	(Lu et al., 2017)
Northwestern China	arid	164	maize	0–4.1		loam & sandy loam	Growing season 2015	0–0.1 m	stem	1–4 m (c)	Keeling	CG & chamber	chamber	chamber	0.78	(Wu et al., 2017)
Tibetan Plateau, China	arid	82	catchment dominated by bare soil or grassland	11%		loam	2012–2015			GLDAS			iso-mass (watershed)		0.41 (annual)	(Guo et al., 2017)

(continued on next page)

Table 2 (continued)

Location	Climate	MAP	Ecosystem type	Plant Canopy	Soil	Study Period	Sampling	Calculation Methods ³					T/ET	Source			
								Fractional Cover	LAI	Soil Depth	Plant	Air ²			ET	E	T
Northeastern China	semiarid	392	marshland			June 18–19, 2013	Soil Depth 0–0.1 m	Plant stem and leaf	Air ² 0.2–1.9 m (c)	ET EC	E lysimeter	T lysimeter	δ_{ET} Keeling	δ_E CG	δ_T NSS & ISS	0.41	(Zhang et al., 2018)

¹ For LAI (m² m⁻²), “o” in brackets = overstory or upper canopy.

² (c) = cryogenic vapor trapping method (cold bath); (l) = laser spectrometer (direct *in situ* measurement).

³ ET fluxes can be obtained from a remote sensing data (GLDAS) or calculated via a mass balance (mass) method. Leaf-level transpiration can be measured with a portable photosynthesis system (photo). Isotopic compositions of δ_{ET} , δ_E , δ_T can be analyzed via two major methods: (1) the isotopic mass balance (iso-mass), either at the soil column scale (soil) or at the watershed scale (watershed); and (2) the two-source mixing model, utilizing the Keeling-plot method (Keeling), the flux-gradient method (FG), the Craig-Gordon (CG) model, or the chamber method (chamber). For δ_T , two hypotheses have been developed: the isotopic steady state (ISS) assumption and non-isotopic steady state (NSS) assumption.

ecosystems (with the exception of open woodlands)—namely, around 0.75–0.85, which agree with the maximum values of 0.72–0.90 found at the global scale for natural and agricultural systems characterized by low LAI (Wang et al., 2014).

No general trends were identified in the relationship between plant fractional cover and ecosystem type (Fig. 5b), whereas LAI (means and maximums) showed higher values in agro-ecosystems than in natural ones (Fig. 5c). The linear regression between converted T/ET and plant canopy characteristics revealed that mean and maximum LAI values explained 45% and 37%, respectively, of the variations in T/ET, whereas plant fractional cover failed to be an effective explanatory variable (Fig. 6). (All values in Fig. 6 are log-transformed because of the power-law relationship between T/ET and the vegetation-canopy parameters—see Eq. (3) in Section 5.6.) Statistically, the regression was strongly significant for mean LAI (p-value ≤ 0.01) and significant for maximum LAI (p-value ≤ 0.05). However, the coefficient of determination (R²) reported in this analysis is relatively low (Table 3), implying that the explanatory power of LAI for T/ET variability is constrained in dryland ecosystems.

5. Major themes identified via the meta-analysis

5.1. ET partitioning during dynamic wetting–drying episodes

The pattern of rare and irregular precipitation events that characterizes dryland ecosystems creates pulses of high and low biotic activity (Snyder and Tartowski, 2006). Consequently, during the dynamic wetting and drying cycles, both plant transpiration and soil evaporation can undergo rapid changes (Yepez et al., 2005). Soil evaporation is negligible when soils are dry, but after precipitation it becomes significant within a short period (usually a few days) (Hu et al., 2014; Wang et al., 2016a; Wang and Yakir, 2000); then, once it has peaked, evaporation declines rapidly. Transpiration, which is suppressed during rainfall (Evert et al., 2012), peaks more slowly and also declines more gradually after precipitation (Scott et al., 2006).

Because of the differences in temporal dynamics between soil evaporation and transpiration, the pattern of ET partitioning varies significantly during these wetting–drying episodes. As examples, a study of a semiarid forest found that soil evaporation dominated ET shortly after a rain event, with E/ET ranging between 49% and 65% (Gaj et al., 2016); a study of a semiarid shrubland with more than 90% coverage showed that daily average E/ET decreased from 34% to 3% during the first two sunny days after precipitation (Xu et al., 2008); and in a Chihuahuan desert, evaporation dominated ET at the onset of summer rains, but 2–4 weeks after the occurrence of large precipitation events, shrub vegetation recovered and began to transpire at peak rates (Cavanaugh et al., 2011; Scott and Biederman, 2017; Scott et al., 2006).

Similar phenomena were often observed for irrigated agro-ecosystems. Examples include a winter wheat field, where E/ET was 0.20 before irrigation and 0.31 after irrigation (Aouade et al., 2016); an olive (*Olea europaea* L.) orchard, where E/ET was nearly 0 prior to irrigation, then reached 0.31 by midday on the sixth day following irrigation (Williams et al., 2004); and a cotton cropland, where E/ET equaled or exceeded T/ET for four days after irrigation, but began a dramatic decrease from the fifth day (Ham et al., 1990). In contrast to this trend of increasing E/ET shortly after irrigation, an exception was reported for a semiarid sparse grassland (*Eragrostis lehmanniana*) with loamy-sandy soil, where E/ET dropped following the irrigation pulse. In such environments, soil evaporation is typically the dominant flux and transpiration the minor flux; but with the rapid infiltration of irrigation water, causing a short period of plant-available soil water in the rooting zone, transpiration increased briefly. The corresponding decrease in E/ET, to 0.57–0.65, occurred within three days after irrigation. By day 7 E/ET had again risen, to 0.78 (Yepez et al., 2005).

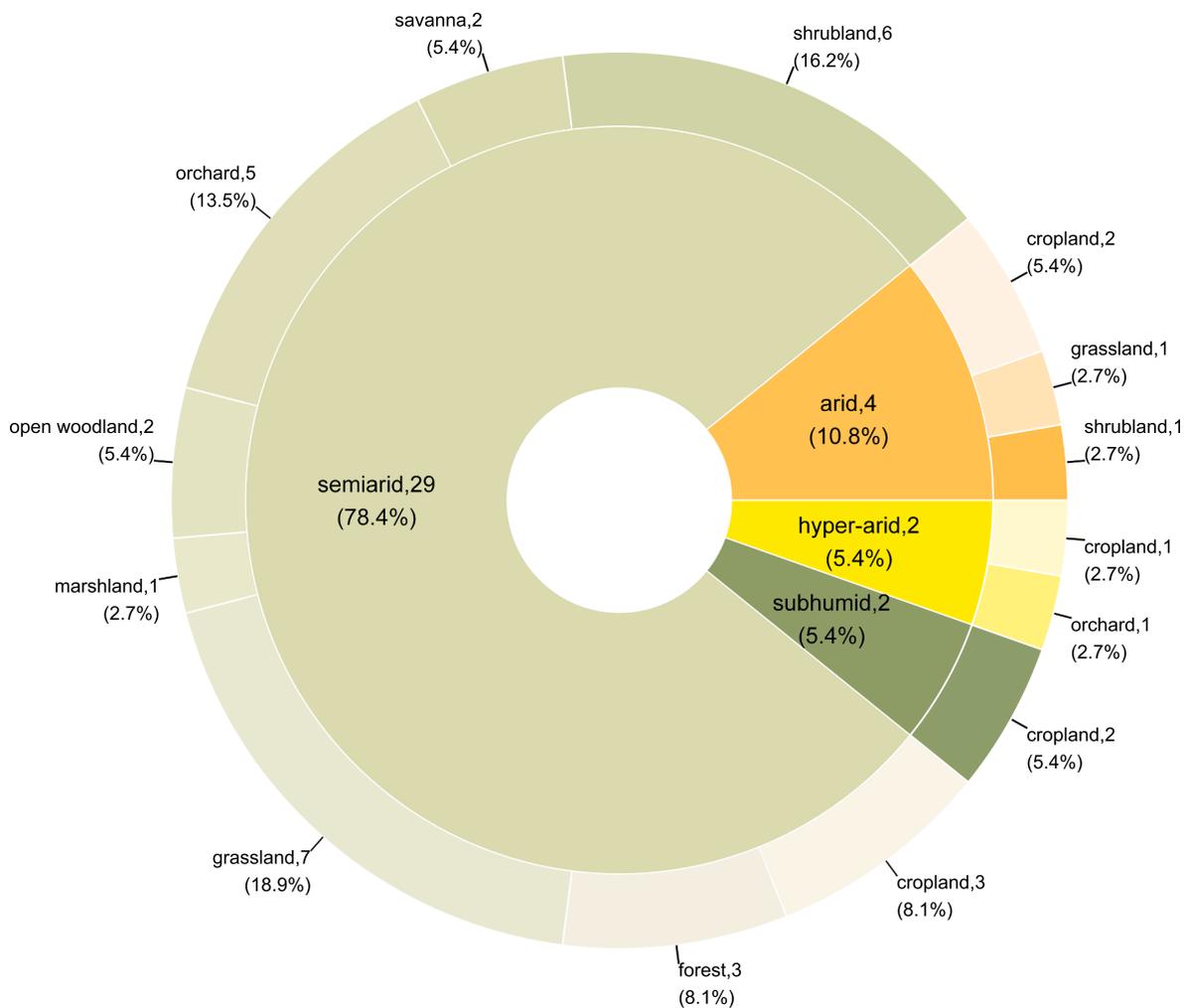


Fig. 2. Dryland climate categories and ecosystem types represented by the retrieved studies. The number following each climate category and ecosystem type indicates the number of studies from which data was drawn, and the number in parentheses indicates the corresponding percentage of the retrieved 37 records from the 30 studies done at the ecosystem level [the study done on a regional watershed (Guo et al., 2017) is not included].

5.2. Factors controlling evaporation and transpiration are different

Evaporation and transpiration are controlled by different factors. Soil evaporation is a physical process, mostly affected by abiotic factors, including vapor pressure deficit (VPD), water availability in the surface soil, and the shading effect of the vegetation canopy. Plant transpiration, on the other hand, takes place through the soil–plant–atmosphere continuum and is controlled by both abiotic and biotic factors—including plant-available soil water in the rooting zone, VPD , and physiological regulation of leaf stomata.

A study of an olive orchard (*Olea europaea* L.) showed that during wetting–drying cycles, daily rates of soil evaporation correlated positively with daily VPD , but transpiration did not (Williams et al., 2004). Seasonal-scale investigations in a semi-arid eucalyptus woodland found that daily rates of transpiration tracked seasonal changes in radiation and drainage, whereas daily rates of evaporation correlated positively with surface soil moisture content (Mitchell et al., 2009). Similar results were found in a semi-arid shrubland (Cavanaugh et al., 2011) and a pine forest (Raz-Yaseef et al., 2012), where soil evaporation was closely correlated with solar radiation and surface soil moisture, whereas transpiration was correlated with soil moisture in the deeper layers. This difference—the dependence of evaporation on shallow soil moisture and of transpiration on deeper soil moisture—was also observed in agro-ecosystems (Zhang et al., 2011).

5.3. Controlling factors differ according to temporal scale

The factors controlling ET partitioning vary at different temporal scales. Ambient atmospheric conditions show high variability at the diurnal scale, whereas plant phenology exhibits great variations across the growing season, especially with changes in the precipitation pattern (dry vs wet). For example, in a study of a semi-arid grassland, Hu et al. (2014) found that VPD was a significant factor at the diurnal scale, resulting in a U-shaped diurnal pattern of T/ET . A similar diurnal T/ET pattern was found in another dryland grassland, but over the longer timescale of a two-week period of green-up and senescence, green LAI and available soil water were the controlling factors for T/ET dynamics (Good et al., 2014). For semi-arid sites characterized by summer rainfall, T/ET reached a peak coincident with the maximum LAI , suggesting the strong effect of plant phenology and precipitation pattern on ET partitioning (Scott and Biederman, 2017). Similarly, a modeling study in grassland ecosystems concluded that T/ET was controlled by canopy stomatal conductance at the diurnal scale, and by LAI at the seasonal and annual scales (Hu et al., 2009).

5.4. Effects of precipitation and soil moisture dynamics on ET partitioning

How ET is partitioned in a given ecosystem depends on the temporal pattern of precipitation distribution—whether precipitation is concentrated into a few big events or scattered among many smaller ones

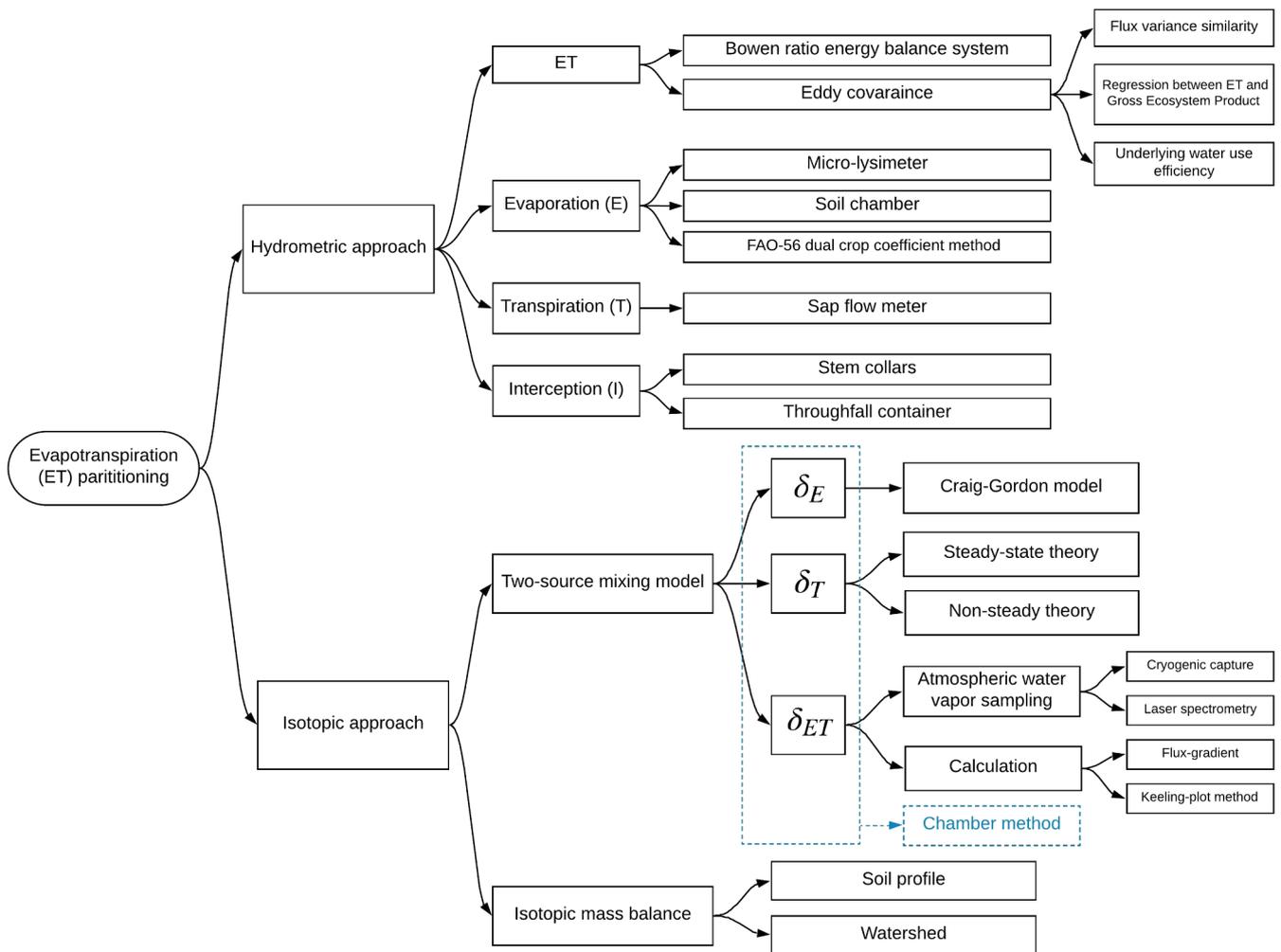


Fig. 3. Hydrometric and isotopic approaches for partitioning of ET.

(Huxman et al., 2004; Scott and Biederman, 2017). For example, a study conducted in a semiarid forest found that annual T/ET was more influenced by large storms (> 30 mm) than by the annual precipitation totals (Raz-Yaseef et al., 2012)—probably because only intense storms can result in deep infiltration and thus plant-available soil moisture for trees. A similar phenomenon was observed in semiarid grasslands and shrublands in Arizona, USA, where seasonal T/ET was found to be relatively insensitive to precipitation patterns when precipitation was near- to below-normal (Moran et al., 2009)—conditions under which deep soil water infiltration probably rarely occurred.

5.5. Effects of interception on ET partitioning

Uncertainty concerning the contribution of interception is the largest source of bias in ET partitioning (Wei et al., 2017). The amount of rainfall intercepted by the vegetation canopy and the debris layer depends on rainfall frequency and the structural characteristics and physiological properties of the vegetation. In arid and semiarid climates, sporadic and short precipitation events coupled with high VPD could result in a substantial amount of evaporation via interception (Laio et al., 2001). Examples include a semiarid eucalyptus (*E. capillosa*) woodland, where 8%–15% of the rainfall was intercepted—of which 69% evaporated and 31% was yielded as stem flow (Mitchell et al., 2009); and a semiarid pine forest, where interception accounted for 10%–12% of annual precipitation and more than 20% during the rainy season (Raz-Yaseef et al., 2010; Raz-Yaseef et al., 2012). In contrast, interception could be negligible in sparsely vegetated dryland

ecosystems, such as a desert shrubland in northern China, where interception accounted for only 3.2% of precipitation during the growing season (Zhao et al., 2016).

5.6. Effects of vegetation canopy on ET partitioning

Several researchers noted that patterns of ET partitioning are influenced by the various characteristics of the vegetation canopy, such as LAI and fractional cover (Wang et al., 2010), phenological development during the growing season (Montoro et al., 2016), and tree age (Wang and Wang, 2017). Studies of the relationship between LAI and T/ET at the global scale (Wang et al., 2014; Wei et al., 2017) suggest that LAI can be the first-order controlling factor for T/ET , as expressed in the following power-law function:

$$\frac{T}{E + T} = a LAI^b, \tag{3}$$

where coefficients a and b are specific to vegetation types (see Table 3 for results from the retrieved studies and several other pertinent investigations). It has been argued that this power-law function applies only to situations in which LAI is below a certain threshold (below that threshold, T/ET increases quickly and proportionally in response to increases in LAI; but above it, T/ET is no longer sensitive to changes in LAI). For example, an LAI threshold of 4 was found for a cropland of winter wheat and summer corn (Wang and Liu, 2007), and a threshold of approximately 2.7 for a cotton and sorghum site (Ritchie and Burnett, 1971). This threshold phenomenon may be attributable to

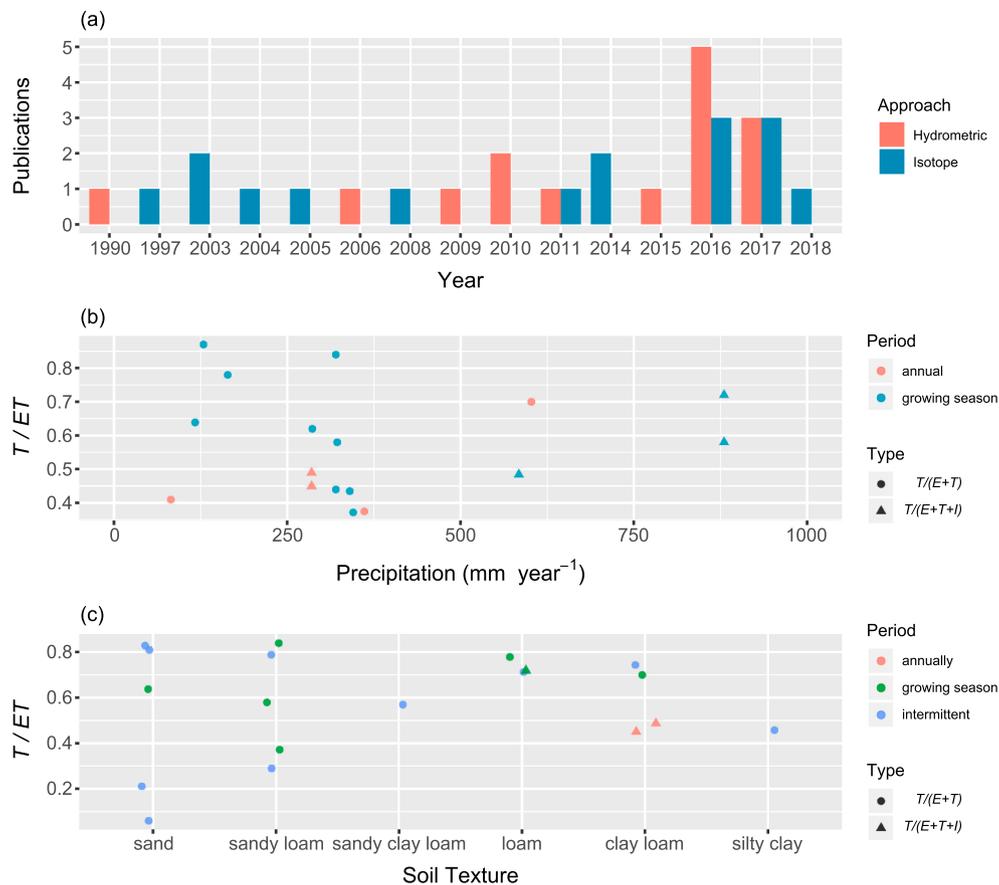


Fig. 4. Approaches used and results of the retrieved studies on ET partitioning: (a) hydrometric vs isotopic approach; (b) and (c) dependency of T/ET on long-term annual precipitation and soil texture, respectively. Mean values are used for results reported as ranges in Tables 1 and 2.

suppression of transpiration per unit of LAI for well-developed or thickened plant canopy. A simulation based on tree mosaics also revealed that as LAI increased, T/ET gradually fell below a 1:1 proportionality (Villegas et al., 2015).

The retrieved datasets show a high variability in T/ET —a range of 0.06–0.90 (Fig. 4b & c and Fig. 5a). Wide variations in T/ET were also reported at a global scale for ecosystems with low LAI (e.g., ≤ 0.5), indicating the possibility of high T/ET even under low LAI conditions (Wang et al., 2014). A modeling study of grassland ecosystems also revealed that the relationship between T/ET and LAI is more erratic in semiarid and subhumid sites than in humid sites (Hu et al., 2009). This greater variation in T/ET for low- LAI ecosystems implies that other biological or meteorological factors might play a substantial role. For example, in a semiarid steppe region of Inner Mongolia, China, in a year with normal precipitation, T/ET decreased under grazing because of the reduction in LAI (Wang et al., 2016a). In contrast, in a dry year the grazing-induced reduction in LAI did not influence T/ET because plant physiological functions were suppressed by the drought conditions.

5.7. Effects of groundwater on ET partitioning

For sites with shallow groundwater (depths of 0–10 m), groundwater evaporation and root water uptake should be explicitly considered. For example, in an oak savanna, groundwater uptake by blue oak accounted for 70%–90% of total ET during the dry summer (Miller et al., 2010). In a semiarid floodplain woodland, the ability of the dominant deep-rooted velvet mesquite (*Prosopis velutina*) to access groundwater contributed to an unusually high T/ET ratio (0.90) during the growing season (Yepez et al., 2007). Similarly, in a desert shrubland, groundwater lying about 5.7 m below the surface became the

main source for both evaporation and transpiration (Zhao et al., 2016). And in a semiarid open woodland, evaporation of shallow groundwater accounted for up to one-third of total ET , but only after soil moisture in the vadose zone had been depleted (Balugani et al., 2017).

6. Emerging technologies, challenges, and opportunities

Our understanding of ET fluxes and partitioning of ET in drylands has advanced dramatically in the past few decades, owing to enhanced capabilities in measurement technologies, data availability, and numerical modeling. At the same time, the particular nature of ecohydrologic processes in drylands—especially the heterogeneity in spatial–temporal scales—means that ET partitioning in these regions remains challenging.

6.1. Field-deployable isotopic laser spectroscopy for water vapor analysis

The isotopic approach for ET partitioning is continuing to evolve. The methods traditionally used for sampling water from soils and plants have major limitations, such as (1) the destructive nature of sampling and (2) the laborious and time-consuming procedure of cryogenic vacuum distillation. In addition, the isotopic representativeness of plant samples remains debatable (Cernusak et al., 2016; Roden et al., 2000; Rothfuss and Javaux, 2017). For drylands, a special challenge is that under very dry conditions, the negligible flux of soil evaporation might prevent reliable calculation of δ_{ET} , because of the absence of detectable vertical gradients in vapor concentrations and in the isotopic compositions of water vapor (Yepez et al., 2005). Extreme conditions of heat and aridity will decrease the equilibrium fractionation factor (Horita et al., 2008), rendering the end-members (δ_E and δ_T) insufficiently

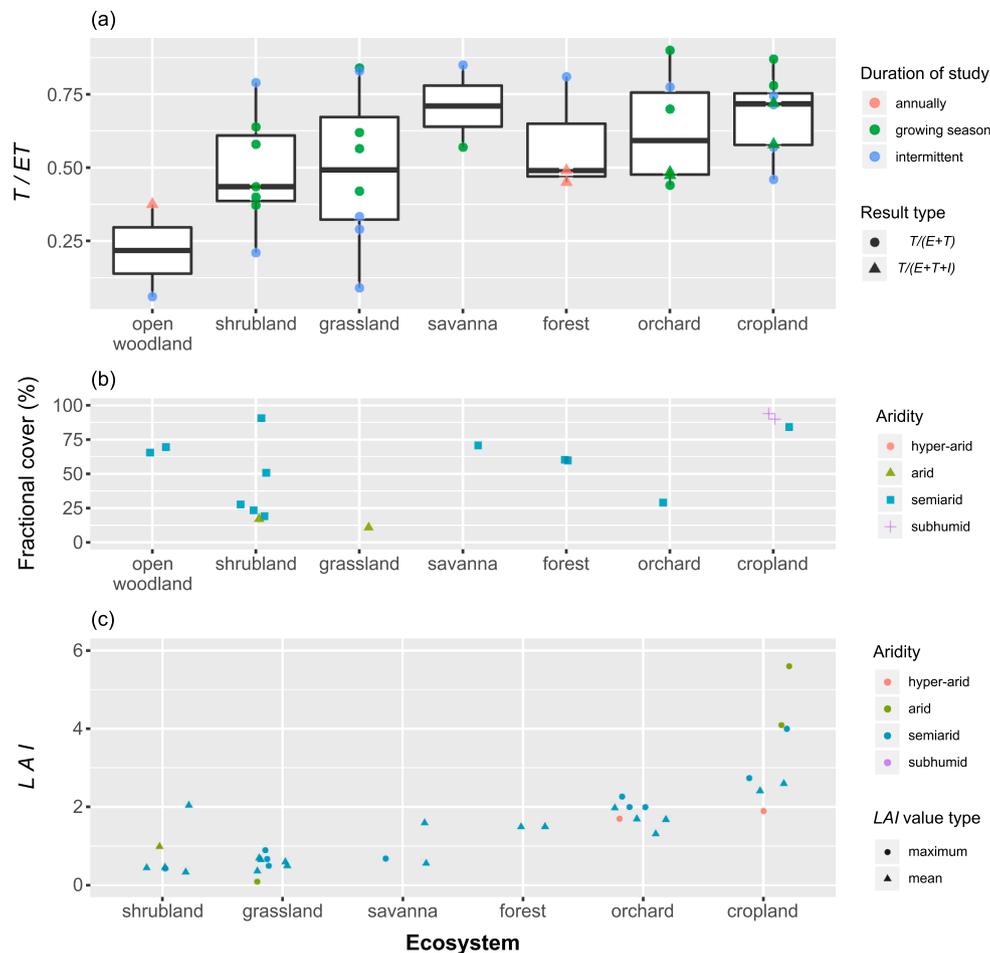


Fig. 5. ET partitioning and canopy characteristics for the different types of ecosystems. Note: The studies done on a regional watershed (Guo et al., 2017) and a marshland (Zhang et al., 2018) are not included. Mean values are used for results reported as ranges in Tables 1 and 2.

distinguishable (Lu et al., 2017), which translates to a high degree of uncertainty for the isotopic approach.

A critical question in quantifying the isotopic composition of soil evaporation is how fractionation processes affect the isotopic composition of soil water (Gaj et al., 2016)—which, under conditions of intense evaporation, exhibits high variability across the profile (Hu et al., 2014). During the dry season, vapor transport can dominate water diffusion in the vadose zone and plays a key role in mass and energy transfer within soils (Bittelli et al., 2008; Deb et al., 2011). To determine the effects of fractionation processes, then, isotopic sampling of water vapor across the soil profile is essential (Balugani et al., 2017).

A promising tool for sampling of soil water vapor in the vadose zone is field-deployable laser isotope spectroscopy, which enables direct, continuous, and non-destructive measurement (Gaj et al., 2016; Herbstritt et al., 2012; Oerter et al., 2017). *In situ* sampling of soil water vapor has been performed both to study water vapor dynamics (Gaj et al., 2016; Oerter et al., 2017; Soderberg et al., 2012; Volkmann and Weiler, 2014) and to derive the isotopic composition of liquid soil water based on the water–vapor equilibrium assumption (Herbstritt et al., 2012). This assumption is supported by a case study in a semiarid African savanna, where the liquid–vapor interface was measured *in situ* in the soil profile (Soderberg et al., 2012). The major concern during sampling of soil water vapor for isotopic analysis is fractionation caused by either inducing evaporation of liquid soil water or condensation of vapor inside the sampling apparatus (Soderberg et al., 2012). At present, standard sampling protocols with wide applicability are still under development (Stumpp et al., 2018).

6.2. Water diffusion pathways from ground to atmosphere

To be consistent and comparable, *in situ* studies on ET partitioning must identify and take into account the various diffusive pathways by which water moves from terrestrial ecosystems to the near-surface atmosphere. In the past, many field studies ignored the role of evaporation underneath the canopy, considering it to be negligible because of the shading effect (Balugani et al., 2017). An accurate quantification of under-canopy evaporation necessitates the application of either an extinction coefficient for radiation diffusion or a threshold LAI value (Wang and Liu, 2007). For two-layered ecosystems (e.g., savannas and shrublands), even though transpiration fluxes can be combined to simplify analysis (Xu et al., 2008), transpiration from the upper tree/shrub layer and from the understory herbaceous layer should be measured separately (Wei et al., 2017). Such detailed *in situ* studies are essential for quantifying the different diffusive pathways for plant transpiration and for identifying the biophysical factors that control transpiration from different functional types (Dubbart et al., 2014).

6.3. Scaling and modeling

Dryland ecosystems, characterized by scarce and sporadic precipitation as well as low vegetation coverage, exhibit considerable spatial heterogeneity along with high temporal variability in plant physiological activity (Newman et al., 2010; Raz-Yaseef et al., 2012; Villegas et al., 2014). For these reasons, upscaling of measurements from the stand or plot scale is quite challenging. For example, upscaling of sap flow is highly uncertain and error-prone—first, because the

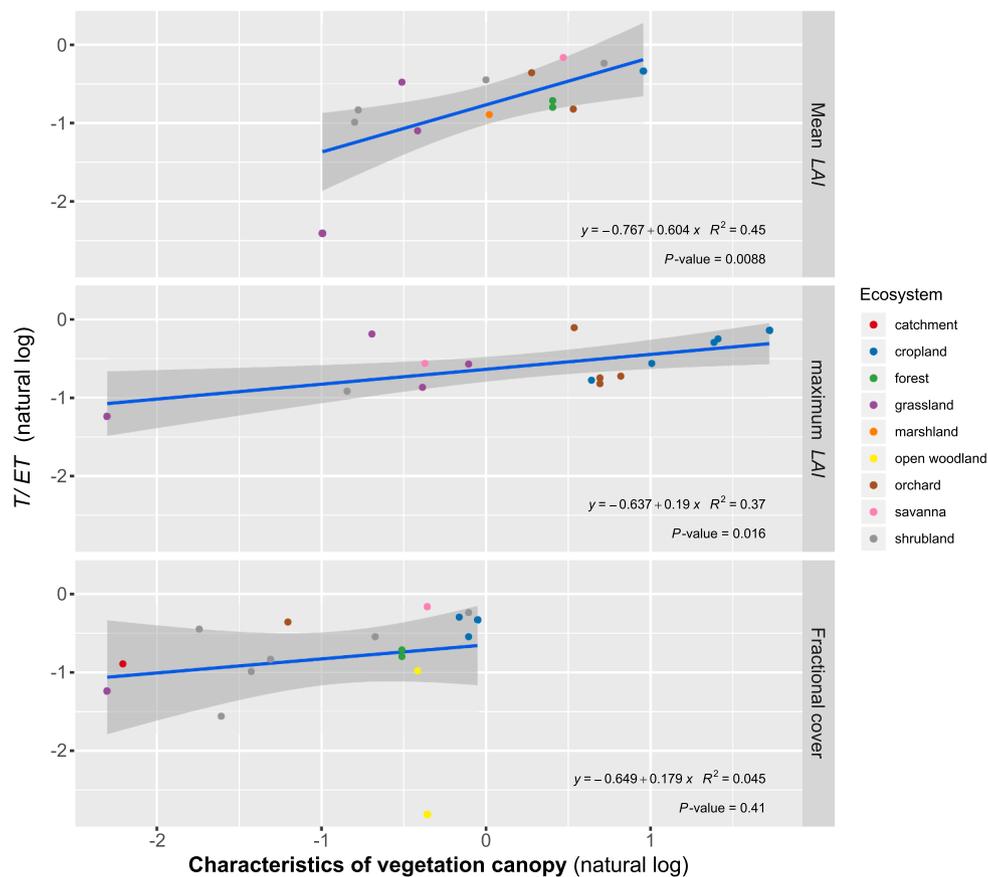


Fig. 6. Relationship between T/ET (natural log) and vegetation canopy characteristics (natural log). This analysis did include the regional catchment study (Guo et al., 2017) and the marshland study (Zhang et al., 2018). Mean values are used for results reported as ranges in Tables 1 and 2.

Table 3
Results of regression analyses for T/ET and LAI.

Ecosystem Type	Regression	Note or R^2	Citation
Winter wheat	$T/ET = 1 - e^{-0.34LAI}$	$R^2 = 0.79$	(Wang and Liu, 2007)
Summer corn	$T/ET = 1 - e^{-0.40LAI}$	$R^2 = 0.74$	(Wang and Liu, 2007)
Cotton and grain sorghum	$T/ET = -0.21 + 0.70 LAI^{0.5}$	$0.1 \leq LAI \leq 2.7$	(Ritchie and Burnett, 1971)
Cowpeas	$T/ET = 1 - e^{-0.79LAI}$	–	(Sepaskhah and Ilampour, 1995)
Maize	$T/ET = 0.71 LAI^{0.14}$	$R^2 = 0.87$	(Wu et al., 2017)
Forage sorghum	$T/ET = 0.45 LAI^{0.19}$	–	(Lu et al., 2017)
Desert ecosystems*	$T/ET = 0.76 LAI^{0.70}$	$R^2 = 0.75$	(Scott and Biederman, 2017)
Global agricultural systems	$T/ET = 0.91 LAI^{0.07}$	95% quantile regression	(Wang et al., 2014)
Global natural systems	$T/ET = 0.77 LAI^{0.10}$	Same as above	(Wang et al., 2014)
Global (overall)	$T/ET = 0.91 LAI^{0.08}$	Same as above	(Wang et al., 2014)
Drylands (this review)	$T/ET = 0.46 LAI^{0.60}$	$R^2 = 0.45$	

* Desert ecosystems in southern Arizona, USA, including shrubland, savanna, and grassland.

scaling relationships for different parameters (basal area, plant density, canopy height, canopy coverage, sapwood area, LAI) vary widely (Poyatos et al., 2016); and second, because plants of different functional types have different phenological stages (Wang et al., 2014; Yopez et al., 2003). When sap flow is being compared with ET fluxes obtained by eddy-covariance measurement, the upscaling needs to be confined to the contributing footprints of the turbulent fluxes (Williams et al., 2004).

Coupling of the eddy-covariance method with laser isotope spectroscopy could make it possible for ecosystem-level ET partitioning to be accomplished without the need for scaling (Ferretti et al., 2003; Williams et al., 2004; Xiao et al., 2018). In addition, this combined methodology can be expanded to measurement of carbon isotopes, thereby enabling the partition of CO_2 dynamics and calculation of

water-use efficiency (Good et al., 2014), both of which are essential for parameterizing and validating physical-based ecosystem models (Wang et al., 2015).

7. Conclusions

In dryland ecosystems, although ET is the largest water-loss flux, it is poorly quantified—especially at fine temporal scales. Despite the importance of accurately quantifying ET , its partitioning remains a major challenge for ecohydrologic studies in drylands. To review and summarize the current state of knowledge on this topic, we retrieved 31 publications on *in situ* studies of ET partitioning covering the past nearly three decades. We classified these studies by the length of time over which measurements were taken, ranging from “intermittent” (typically

less than 10 days, and usually done with the isotopic approach) to longer-term (done at the growing season or annual scale, and usually with the hydrometric approach). For natural ecosystems, results from the intermittent studies showed higher variability than those from the longer-term studies. Longer-term T/ET varied over a narrow range, with a mean value of 0.52—implying that soil evaporation and plant transpiration are largely equivalent in natural drylands over the long term. Agro-ecosystems (usually irrigated) exhibited a relatively higher T/ET and showed greater variability in the longer-term measurements. Maximum values of T/ET were roughly similar for natural ecosystems and agro-ecosystems. Soil evaporation and plant transpiration responded differently during dynamic wetting–drying episodes, both in timing and duration. Soil evaporation is more controlled by meteorological processes and shallow soil water, whereas transpiration is more controlled by plant phenology and water availability in the rooting zone.

The patterns of ET partitioning in drylands are influenced by multiple biometeorological factors, including the temporal distribution of precipitation, rainfall interception, soil moisture recharging, ground-water depth, and vegetation development. Atmospheric conditions and stomatal conductance dominate ET partitioning at diurnal scales, while canopy phenology (or LAI) and soil moisture dominate over longer timescales. Our regression analyses revealed that LAI (especially its mean values) is an essential factor controlling T/ET variability in dryland ecosystems, but its explanatory power might be curtailed by stomatal control under dry climatic conditions.

On the basis of our findings, we suggest three promising areas of investigation to help meet the challenges of ET partitioning in drylands: (1) employment of laser spectroscopy for intensive isotopic sampling of water vapor in the vadose zone; (2) improved identification and accurate quantification of the various pathways of water diffusion; and (3) development of methods for upscaling measurements taken at incongruent spatial/temporal scales owing to different research approaches (hydrometric vs isotopic).

Declaration of Competing Interest

None.

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Author Contributions

B.P.W., C.B.Z., and X.S. conceived and developed the original perspectives and framework, X.S. wrote the paper, and B.P.W. and C.B.Z. contributed to and edited the manuscript.

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