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Evapotranspiration partitioning at the ecosystem scale using the stable isotope method—A review

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A B S T R A C T

Terrestrial evapotranspiration (*ET*) consists of evaporation (*E*) from canopy-intercepted water, evaporation from soil and open water, and transpiration (*T*) from plants. Determining the contribution of *T* to *ET* (hereafter *T/ET*) is challenging but necessary for improving water resource management and understanding the response of ecosystem water/energy budgets to climate change. Water stable isotopes provide unique information on ecosystem processes and can be used to partition evapotranspiration at the ecosystem scale. In this paper, the aim is to review the state of the science on the isotope method for ecosystem *ET* partitioning, with a focus on uncertainties related to estimating the three isotopic end members (isotopic compositions of *ET*, *T* and *E*). The published results show larger *T/ET* variations during the growing season in croplands due to water management and rapid leaf area index (LAI) changes compared to in other natural ecosystems. Another robust result is that on average, grasslands have lower *T/ET* than woodlands. The isotopic composition of *ET* is provided by measurements, while the isotopic compositions of *T* and *E* are generally obtained using the Craig-Gordon model with appropriate modifications. Significant advances have been made in the techniques for estimating the isotopic composition of *ET*, largely due to the availability of fast-responding instruments for in situ measurements of water vapor isotopic composition. The largest source of uncertainty in the *T/ET* estimation comes from uncertainties in the isotopic composition of *ET*. Based on published results of the uncertainties in the three end members, we estimate that a typical uncertainty range for *T/ET* is ± 21% (one standard deviation). This review provides background information and theoretical references for studies on isotopic hydrology, ecosystem processes and climate change.

1. Introduction

Terrestrial evapotranspiration (*ET*) refers to the amount of water vapor evaporated from the unit area of the land surface during a unit of time and consists of evaporation (*E*) from canopy-intercepted water, evaporation from soil and open water, and transpiration (*T*) from plants. Because the *T* process directly correlates with plant growth and the carbon cycle (Scott et al., 2006), quantitative estimation of *T* in the total evapotranspiration (*T/ET*) has long been acknowledged to play a crucial role in water resource management, yield estimation, the water cycle and climate change, from plot scale to global scale (e.g., Jasechko et al., 2013; Kool et al., 2014). For example, efforts to increase water use efficiency (the ratio of carbon gain to water loss) and control evaporative loss in agricultural land requires accurate determination of the consumption of water through plant activities. Because *T* fluxes link the water and carbon cycles, they are used to calculate carbon assimilation by terrestrial vegetation, so estimating *T* fluxes is a major focus in climate and ecology studies (Dubbert et al., 2014b; Jasechko et al., 2013; Jefferson et al., 2017). Therefore, the topic of evapotranspiration partitioning has gained much attention in the scientific community (e.g., Berkelhammer et al., 2016; Lu et al., 2017; Williams et al., 2004).

Various methods have been developed to partition *ET* at different time and spatial scales. At the global and regional scales, traditional methods are mostly model-related, such as satellite-based estimations

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(Martens et al., 2017; Miralles et al., 2011; Wei et al., 2017; Zhang et al., 2016), land surface models (e.g., Wang-Erlandsson et al., 2014), and reanalysis data (Chen et al., 2014; Kochendorfer and Ramírez, 2010). Isotopic measurements (Gibson and Edwards, 2002; Good et al., 2015; Jasechko et al., 2013) have also been used to partition *ET* at these scales. There is a considerable discrepancy among global *T/ET* estimated using different methods. For example, the results of a combination of widely ranging, remotely-sensed observations showed that approximately 80% of the annual land *ET* is attributed to *T* (Miralles et al., 2011). Wei et al. (2017) quantified the global *T/ET* with a leaf area index (LAI)-based *ET* partitioning algorithm and concluded that *T* accounts for 57% of *ET*. The distinct isotope effects of *T* and *E* based on the isotopic analysis of a global dataset of large lakes and rivers showed that *T* represents 80–90% of terrestrial *ET* (Jasechko et al., 2013), although this estimate was challenged by Coenders-Gerrits et al. (2014). The results of isotope mass budget-based simulations suggested that the transpired fraction of *ET* accounts for approximately 60% of the annual land *ET* (Good et al., 2015).

At the plot scale, *T/ET* can be quantified using isotopic measurements and a combination of traditional in situ measurements, such as those from eddy covariance systems, Bowen ratio systems, weighing lysimeters, sap-flow meters, leaf conductance upscaling, chamber measurements, and the concept of underlying water use efficiency (WUE). For example, Scanlon and Sahu (2008) and Scanlon and Kustas (2010) proposed utilizing carbon dioxide (CO_2) and water vapor ecosystem fluxes to determine *T/ET*. Combinations of the eddy covariance method with sap-flow and lysimeter-based techniques have also been widely applied (e.g., Kelliher et al., 1992; Kool et al., 2014). Zhou et al. (2016) and Scott and Biederman (2017) partitioned *T/ET* using the concept of ecosystem scale water use efficiency determined from eddy covariance *ET* and gross ecosystem photosynthesis. Good et al. (2014); Hu et al. (2014) and Wei et al. (2015) partitioned *ET* based on isotopic measurements. These methods are well documented in several recent reviews (e.g., Kool et al., 2014; Schlesinger and Jasechko, 2014; Sutanto et al., 2014; Zhang et al., 2010).

Although vastly important and widely studied, *ET* partitioning is still subject to great debate (e.g., Coenders-Gerrits et al., 2014; Jasechko et al., 2013; Schlaepfer et al., 2014; Schlesinger and Jasechko, 2014; Sutanto et al., 2014). At the plot scale, *T/ET* values estimated from scaled sap-flow can be 15% lower than those estimated by the isotope approach (Williams et al., 2004). Wei et al. (2018) also reported 10–20% *T/ET* differences between estimations using isotopes and estimations using a two-source *ET* model simulation.

Among the approaches cited above, isotopic methods accounting for different kinetic fractionation effects for transpiration and evaporation processes have been used for *ET* partitioning for the past twenty years (e.g., Dubbert et al., 2013, 2014b; Williams et al., 2004; Wu et al., 2017). The saturation vapor pressure and molecular diffusivities of the minor water molecules ($^1H_2{}^{18}O$ and $^1H^2H^{16}O$) are lower than those of the most abundant water molecule ($^1H_2{}^{16}O$) (Majoube, 1971; Merlivat et al., 1963; Merlivat, 1978; Cappa et al., 2003). During the evaporation process, the lighter water molecules easily leave the liquid evaporation surface (water, soil or leaf surface), while the heavier water molecules ($^1H_2{}^{18}O$ and $^1H^2H^{16}O$) accumulate at the surface. Therefore, soil water is more isotopically enriched at the evaporating surface than at other depths (Zimmermann et al., 1966). Plant water uptake does not cause fractionation, and transpiration can often be assumed to be in an isotopic steady-state or that its isotopic composition is the same as that of the xylem water. The difference in isotopic compositions between *E* and *T* forms the basis for *ET* partitioning using isotopic methods.

The isotopic approach has been widely used for *ET* partitioning at the ecosystem (e.g., Dubbert et al., 2013, 2014b; Wang and Yakir, 2000; Williams et al., 2004; Table 1), regional (Lee et al., 2010; Jasechko et al., 2013) and global scales (Good et al., 2015; Jasechko et al., 2013). However, *T/ET* estimations based on isotopic measurements, either at the global scale or at the ecosystem scale, are generally higher than the estimations based on conventional or non-isotopic experimental observations and land surface models (Schlesinger and Jasechko, 2014; Sutanto et al., 2014). Previous studies have suggested that the isotopic compositions of *E*, *T* and *ET*, which constitute the basis of this approach, obtain large errors (e.g., Griffis, 2013; Sutanto et al., 2014; Wu et al., 2017). Although these deficiencies have been addressed in many studies (e.g., Griffis, 2013; Sutanto et al., 2014; Wu et al., 2017), the effects of uncertainties in each component (*E*, *T* and *ET*) on *T/ET* estimation are still not well known. Nevertheless, the water stable isotopes are powerful tools for partitioning *ET* because these isotopes provide unique information regarding the water in the soil-vegetation-atmosphere continuum. The stable isotopic method for *ET* partitioning is usually based on the principle of isotopic mass balance; thus, the analysis of the water stable isotopic compositions within soil, vegetation and the atmosphere is the core issue.

In this paper, the aim is to review *ET* partitioning at the ecosystem scale using the isotopic method.

In Section 2, the mass conservation principles underpinning this method are described and an overview of the relevant publications on this topic are provided. The next three sections discuss methods and theories for estimation of the three ecosystem isotopic end members: isotopic composition of *ET* (δ_{ET}, Section 3), isotopic composition of evaporation (δ_E, Section 4) and isotopic composition of transpiration (δ_T, Section 5). In Section 6, uncertainties in *T/ET* associated with errors in these end members are presented. In Section 7, we briefly discuss potential sources of discrepancies between the isotopic method and other ecosystem partitioning methods. Special emphasis is given to the key concepts and processes presented in the schematic diagram shown in Fig. 1.

2. Isotope-based *ET* partitioning at the ecosystem scale: an overview

2.1. Mass balance consideration

The isotopic method for *ET* partitioning is based on two isotopic mass balance equations: one for $^1H_2{}^{16}O$ and one for either $^1H^2H^{16}O$ or $^1H_2{}^{18}O$. At the ecosystem scale, without considering canopy interception, the isotopic two-source mixing model is the most popular isotopic method for evapotranspiration partitioning (Table 1), although several studies are based on the soil water balance principle (i.e., Ferretti et al., 2003; Hsieh et al., 1998; Robertson and Gazis, 2006; Wenninger et al., 2010) and total isotopic budget balance approaches (Sutanto et al., 2012). In this two-source framework, ecosystem evapotranspiration consists of *T* and *E*:

$$ET = E + T \tag{1}$$

The components also obey the isotopic mass balance:

$$R_{ET}ET = R_E E + R_T T \tag{2}$$

where R_{ET}, R_E and R_T are the (either oxygen or hydrogen) stable isotopic molar ratios of ecosystem evapotranspiration, soil evaporation and plant transpiration, respectively. Converting notation "*R*" to "*δ*", Eq. (2) becomes the following:

$$\delta_{ET}ET = \delta_E E + \delta_T T \tag{3}$$

where δ_{ET}, δ_E and δ_T are the (either oxygen or hydrogen) stable isotopic compositions of ecosystem evapotranspiration, soil evaporation and plant transpiration, respectively, expressed as delta notation.

The *R* and *δ* notations are related to the water vapor fluxes (*ET*, *T* or *E*) in the following manner. Let F_x represent the molar flux of $^1H_2{}^{16}O$, and $F_x{}'$ represent the molar flux of the minor isotopic water molecules ($^1H^2H^{16}O$ or $^1H_2{}^{18}O$). Their molar ratio R_x is as follows: