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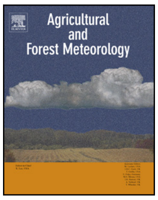

Review

A review of approaches for evapotranspiration partitioning

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ABSTRACT

Partitioning of evapotranspiration (*ET*) into evaporation from the soil (*E*) and transpiration through the stomata of plants (*T*) is challenging but important in order to assess biomass production and the allocation of increasingly scarce water resources. Generally, *T* is the desired component with the water being used to enhance plant productivity; whereas, *E* is considered a source of water loss or inefficiency. The magnitude of *E* is expected to be quite significant in sparsely vegetated systems, particularly in dry areas or in very wet systems such as surface irrigated crops and wetlands. In these cases, *ET* partitioning is fundamental to accurately monitor system hydrology and to improve water management practices. This paper aims to evaluate and summarize available methods currently used to separately determine *E* and *T* components. We presuppose that, to test the accuracy of *ET* partitioning methods (measurements and/or modeling), all three components, i.e., *E*, *T* and *ET*, must be estimated independently, but recognize that sometimes one of the components is taken as the residual of the other two. Models that were validated against measurements for their ability to partition between *E* and *T* are briefly discussed. To compare approaches, 52 *ET* partitioning studies were considered regarding estimates of the relative amount of *E* and for success of agreement in closing the $ET = E + T$ equation. The E/ET ratio was found to exceed 30% in 32 of the studies, which confirms the hypothesis that *E* often constitutes a large fraction of *ET* and deserves independent consideration. Only 20 studies estimated *E* and *T* as well as *ET*, and had varied results. A number of studies succeeded to estimate $E + T$ to within 10% of measured *ET*. Future challenges include development of models simulating the components of *ET* separately and advancement of methods for continuous measurement of *E*, *T* and/or the ratio between the two.

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1. Introduction

Evapotranspiration (*ET*) is a major unknown variable involved in the understanding of ecohydrological systems and can amount to up to 95% of the water balance in dry areas (Wilcox et al., 2003). The individual components of *ET* include evaporation from the soil (*E*) and transpiration through the stomata of plants (*T*), and in some instances evaporation of water intercepted by the plant canopy and litter layer. The function of *E* and *T* within ecosystems is distinctly different: *T* is usually associated with plant productivity, whereas *E* does not directly contribute to production. The partitioning of water into desirable and undesirable components is generally defined by the term "water use efficiency," or the less ambiguous term "water productivity" where *T* is commonly considered the more desirable component and *E* is undesirable (Agam et al., 2012; Van Halsema and Vincent, 2012).

As water limited environments currently comprise about half of the earth's land surface and are expected to continue to expand (Newman et al., 2006), the issue of accurately assessing *ET* and its components has become more acute. In addition, rising world population and associated food demand is expected to further increase the need for productive use of traditionally marginal areas (Yermiyahu et al., 2007). In agriculture, accurate *ET* estimation is fundamental to determine water management practices, design irrigation systems and irrigation regimes, and calculate crop yield (Allen et al., 1998). For example, it is estimated that 80% of the freshwater in Asia is used for irrigation, and better understanding of *ET* components can help investigate if irrigation can be improved and available water can be used more productively (Kite, 2000; Zhao et al., 2013). In some situations *ET* partitioning is used to specifically investigate *T*. For example when crops are grown under regulated drought stress (Ben-Gal et al., 2010; Farahani et al., 2007; Fereres and Soriano, 2007), or when irrigation techniques are designed to limit vigor and increase yield (García García et al., 2012). There are also situations where *E* is the main component of interest. It has been suggested that, in some cases, *E* can enhance *T* by creating a more favorable micro-climate (Kustas and Agam, 2013; Kustas and Norman, 1999), or act to regulate/reduce transpiration (Agam et al., 2012). A study by Tolk et al. (1995) reported that *T* could decrease as much as 50% as a result of evaporation associated with sprinkler irrigation.

The topic is equally important to studies on natural environments, where *ET* and its partitioning serves as an indicator of ecosystem vegetation and hydraulic dynamics, and is a critical aspect of climate modeling (Lawrence et al., 2007; Newman et al., 2006; Peñuelas et al., 2009; Wang et al., 2010). On a global scale, concerns about climate change have raised interest in the connection between *ET* and carbon sequestration (Scott et al., 2006), and the influence of *ET* partitioning on land-atmosphere patterns which affect climate simulations (Lawrence et al., 2007). Climate change is affected by *T* in multiple and opposing ways: increased *T* is associated with increased CO_2 uptake, and cooling and moistening of the atmosphere. However increased vegetation increases soil water depletion and reduces albedo, thus increasing surface temperature (Peñuelas et al., 2009). Inputs and validations of models and climate scenarios will therefore require a closer assessment of *ET* components.

In systems with full canopy cover, *ET* is often assumed to be similar enough to *T* to permit, for example, correlation of biomass with *ET*. In sparsely vegetated areas however, *E* may constitute a large fraction of *ET* due to considerable areas of exposed soil. These sparsely vegetated areas include row crops and orchards, crops in the initial growth stages and sparsely vegetated natural ecosystems. The relative importance of *E* as a part of *ET* is expected to be more pronounced when the atmospheric demand and/or the water availability in the soil is high. This is relevant in dry areas and in very wet systems such as surface irrigated crops (e.g. rice) and wetlands. In rangelands for example, *E* has been reported to account for 30–80% of the water balance (Wilcox et al., 2003). In these instances *ET* will likely not be a good indicator of the productive use of water through plant uptake, making separate assessment of *E* and *T* necessary.

Efforts to separately estimate *E* and *T* started in the 1970s with the development of crop models and initial experimentation in sparse crops (Ritchie, 1972; Tanner and Jury, 1976; Goudriaan, 1977). The invention of methods such as micro-lysimeters to measure under-canopy *E* (Boast and Robertson, 1982; Shawcroft and Gardner, 1983; Walker, 1984) and sap flow measurements of *T* (Čermák et al., 1973; Sakuratani, 1981; Granier, 1985) paved the way to more robust verification of the individual components. Shuttleworth and Wallace (1985) published the first analytical model combining *E* and *T* by formulating the different media through which evaporative flux travels as resistances. Since then, numerous numerical and analytical models have been developed that attempt to determine *E* and *T* separately. While a number of reviews have previously described *ET* research (e.g. Rana, 2000; Burt et al., 2005; Farahani et al., 2007; Shuttleworth, 2007; Li et al., 2009; Tanny, 2013), none of them specifically focused on partitioning of components. The aim of this paper is to evaluate currently available methods to separately assess *E* and *T*, taking into account different scales of interest and variety in the nature and structure of canopies. The review excludes interception losses that can be significant in forests but are usually small compared to *E* and *T* for non-forest canopies. We start by briefly reviewing some of the fundamental principles of evaporation (Section 2). An overview of methods to separately estimate *E* and *T* is given in Sections 3 and 4 respectively. In Section 5 approaches to estimate E and T simultaneously are described, along with a brief discussion of models that have been validated for ET partitioning. In Section 6, comparison of 52 studies is made regarding their calculation of relative amount of E in the system (E/ET). For 20 cases, where E, T and ET were each independently determined, the relative agreement between the sum $E+T$ and ET is evaluated for the various combinations of methods applied.

2. Theoretical foundation

The evaporation of water is fundamentally a phase transition from liquid to gas, driven by (1) available liquid water; (2) available energy to meet the latent heat requirement for the phase transition (approximately $2.5\,\mathrm{MJ\,kg^{-1}}$ to evaporate water at 15 °C); and (3) the gradient in vapor pressure between the evaporating surface and the atmosphere (Hillel, 1998; Brutsaert, 2005). Consequently, evaporation can be quantified by (1) determining removal of liquid water using a water balance; (2) the amount of energy allocated to latent heat using an energy balance; or (3) by assessing water vapor fluxes. Since during evaporation both mass and energy are transferred, ET can be expressed as evaporated mass per unit area per unit time (usually $\mathrm{kg\,m^{-2}\,d^{-1}} \approx \mathrm{mm\,d^{-1}}$), or as latent heat per unit area per unit time (usually $\mathrm{J\,s^{-1}\,m^{-2}} = \mathrm{W\,m^{-2}}$). Unless otherwise specified, evaporation in units of mass is referred to as ET, E or T, while evaporation in units of energy is referred to as λET, λE or λT where λ is the latent heat of vaporization ($\mathrm{J\,kg^{-1}}$). The approaches to quantify ET are equally applicable to independent estimation of E and T when exclusively applied to the soil surface or the plant canopy.

The energy and water balances are both conservation equations where the evaporation components are computed as the residual of the budget of a defined system of interest. The components included in the budget equations will depend on the size and time scale of the system of interest. For example, a simple representation of the water balance is the sum of inputs and outputs:

$$P + I - R - D - \Delta S - ET = 0 \tag{1}$$

where P is precipitation, I is irrigation, R is runoff, D is drainage and ΔS is change in soil storage (all in $\mathrm{mm\,d^{-1}}$). Minor water balance components that are routinely neglected include changes in plant storage, lateral flow, and capillary rise. The water balance is only practical as a tool to estimate ET when ET is relatively large, otherwise small errors in measurements of other components can result in large errors in ET (Hillel, 1998).

The surface energy balance ties into the water balance through the evaporation component and is defined as:

$$R_n - \lambda ET - H - G = 0 \tag{2}$$

where R_n is net radiation, H is sensible heat and G is soil heat flux (all in $\mathrm{W\,m^{-2}}$). Extended versions of the surface energy balance include a thermal conversion factor for CO_2 fixation; energy advection into the canopy air layer, and the rate of energy storage per unit area in the layer.

The energy balance is driven by incoming solar radiation, of which a major part is absorbed near the earth's surface. Net radiation is a result of total incoming minus reflected solar (shortwave) radiation, along with the long-wave radiation balance (absorbed minus emitted). R_n thus represents the source of energy dissipating into the other fluxes (Brutsaert, 1982).

A simple general equation can be derived for transport within a gas by either molecules, particles, or eddies, sometimes defined as "carriers", capable of transporting water vapor (or any other scalar). Even when the carriers are moving randomly, net transport in a specific direction may occur provided that the scalar decreases with distance in that direction (Monteith and Unsworth, 2008). Based on the diffusion analogy, the turbulent exchange can be described as:

$$ET = \rho \overline{w'q'} \tag{3}$$

with ET in $\mathrm{kg\,m^{-2}\,s^{-1}}$, where ρ is air density ($\mathrm{kg\,m^{-3}}$) and $\overline{w'q'}$ is the mean covariance between vertical wind speed (w; $\mathrm{m\,s^{-1}}$) and specific humidity (q; $\mathrm{kg\,kg^{-1}}$). This equation is based on the assumption that the surface boundary layer is a fully turbulent region where the vertical distribution of vapor fluxes is relatively constant. This is usually valid except when there is condensation or under stable atmospheric conditions when stratification in the vertical distribution of vapor fluxes predominates (Brutsaert, 1982).

3. Estimating evaporation from the soil

Water evaporation from a drying soil is commonly described in two or three stages (Lemon, 1956; Ritchie, 1972; Idso et al., 1974). Stage I is governed by atmospheric conditions, with E limited only by the available energy in the upper layer of the soil and by the vapor gradient between the soil and the atmosphere. During stages II and III, E becomes primarily a function of soil water content, soil hydraulic properties, and temperature gradients (Allen, 1990; Deol et al., 2012). Recent work suggests that the stages are less distinct under high atmospheric demands (Shahraeeni et al., 2012).

Some measuring and modeling methods to quantify E are more appropriate for certain stages whereas others are appropriate for all stages. Though numerous methods are available to determine bare soil E, these can be applied to assess E under plant canopies only insofar as their validity is maintained under conditions subject to root water uptake and an altered micro-climate. Validity of a method will furthermore depend on its applicability under heterogeneous conditions as a result of soil properties and wetting patterns as well as distance from a plant. Section 3.1 gives an overview of measurement methods that are suitable to estimate under-canopy E.

There are a number of available modeling methods to determine E (Kustas and Agam, 2013). It seems that no single robust model exists for independent estimation of under-canopy E, and therefore the methods simulate combined E and T (Section 5.1). We observed that most E models use meteorological data at 2 m screen height to determine the atmospheric demand, which is not representative for conditions beneath a canopy. One exception is the relative evaporation method, an energy balance model developed by Ben-Asher et al. (1983) that estimates E using soil surface temperature measurements. The model relates the daily minimum and maximum temperatures of the soil surface to minimum and maximum temperatures of a saturated and a dry soil surface. Though the original model requires wind speed data close to the surface, Kerridge et al. (2013) found that on days with light winds the model gave reasonable results for E in a drip-irrigated vineyard.

3.1. Evaporation measurements

3.1.1. Micro-lysimeter

A micro-lysimeter (ML), also named mini-lysimeter or evaporimeter, generally consists of a small cylinder, typically 0.1–0.3 m in diameter and depth, which is pushed into the soil surface to retrieve an undisturbed soil sample. The ML is then carefully excavated, sealed at the bottom and weighed. It is then placed back in the soil, sometimes inside a collar, level with the soil surface. After a period of time the ML is re-weighed; the change in mass being directly proportional to evaporation. Shawcroft and Gardner (1983) and Walker (1983) were among the first to use MLs for below-canopy E measurements. Boast and Robertson (1982) found that MLs gave accurate measurements of E provided that the soil cores were replaced at least every 24–48 h in order to minimize discrepancies with field conditions. MLs were later verified for different materials and sizes (Evett et al., 1995; Todd et al., 2000).

The MLs reported in the literature commonly follow the original design by Boast and Robertson (1982) and are weighed manually, usually on a daily basis. They are generally appreciated for simplicity and economy (e.g., Lascano et al., 1987) but are also considered time consuming (Trambouze et al., 1998). Other drawbacks include their inability to measure during irrigation or rain (Thompson et al., 1997; Flumignan et al., 2011), limited representation of field conditions due to small sample size (Daamen, 1997) and constraints in time resolution as a result of manual weighing (Trambouze et al., 1998). This last issue can be resolved by placing the ML on a continuously weighing device (Daamen et al., 1993). Efforts to further advance the use of MLs were undertaken by Thompson et al. (1997) and Herbst et al. (1996) who used the same continuously measured soil core throughout the season, while artificially removing or adding water to the ML to imitate root water uptake or irrigation/precipitation in the field. MLs are generally considered the most reliable method to measure *E* and often serve as validation for other methods.

3.1.2. Soil heat pulse

The soil heat pulse probe was initially developed to determine water content based on soil thermal properties (Campbell et al., 1991). The probe measures ambient temperature and temperature response curves to heat pulses, from which thermal properties can be derived. Evaporation can be estimated with heat pulse probes using an energy balance for a soil layer between two measurement depths by computing incoming and outgoing soil heat flux and heat storage. The energy that cannot be accounted for by the change in soil heat flux or heat storage, is attributed to latent heat flux (Heitman et al., 2008a,b). The soil heat pulse method is unique in its capability to continuously measure evaporation profiles below the surface and has yielded good results in field experiments (Heitman et al., 2008b; Sakai et al., 2011a,b; Xiao et al., 2011, 2012). Its major drawback is its inability to measure *E* during stage I evaporation, when evaporation occurs at the uppermost soil surface (Deol et al., 2012). The method would therefore be most useful to monitor evaporation over long drying periods in combination with a different measurement method for stage I.

3.1.3. Chambers

The chamber method is based on measurement of changes in gas concentration in a closed volume, from which gas exchange between the soil surface and the atmosphere is estimated (Musgrave and Moss, 1961). Chambers can be static, using an absorption agent to integrate flux over a period of time, or dynamic, measuring the differences in concentration between inflow and outflow of air (Iritz et al., 1997). The latter is more commonly used, especially as infra-red gas analyzers (IRGA) have become widely available, but is also more costly.

A chamber is generally comprised of a closed, often hemispherical, volume placed either directly on the soil surface or on a pre-installed collar. Inside the chamber is a fan or a pump that imitates air flow in the field and/or circulates gas to an external IRGA. The "rapid chamber" used by Stannard and Weltz (2006) is an example of a static chamber originally designed by Stannard (1988) that was used to measure either *E* or *ET* by placing it over bare soil or plants in a desert shrub area. Estimation of *E* was obtained using a pre-determined relationship with the maximum slope of vapor density change, measured with a psychrometer. Dynamic chambers are more complicated automated systems, aimed at regulating conditions inside the chamber to represent conditions outside. Instrumentation for dynamic chambers is commercially available and used quite widely (Raz-Yaseef et al., 2010, 2012; Domec et al., 2012).

3.1.4. Micro Bowen ratio energy balance (M-BREB)

The Bowen ratio (β; Bowen, 1926) is the ratio between *H* and λE, and can be derived from measurements of temperature and vapor pressure gradients between two heights above the surface, based on the assumption that the atmospheric transport mechanisms of vapor and heat are similar (Brutsaert, 1982). This yields:

$$\beta = \frac{H}{\lambda E} = \frac{\gamma \Delta T_a}{\Delta e} \tag{4}$$

where β is dimensionless and *H* and λE are in W m^{-2}, γ is the psychrometric constant (kPa °C^{-1}), ΔT_a (°C) and Δe (kPa) are the differences in ambient temperature and vapor pressure between two heights respectively. Combined with the energy balance equation (Eq. (2)) the latent heat is computed as:

$$\lambda E = \frac{R_n - G}{1 + \beta} \tag{5}$$

where R_n can be measured using a net radiometer underneath the canopy and *G* is most commonly quantified using a combination approach (Sauer and Horton, 2005). The Bowen ratio energy balance (BREB) is commonly used to estimate *ET* and was first tested as a method to determine *E* close to the surface ("micro" BREB) by Ashktorab et al. (1989) in a bare field. This paved the way to use the M-BREB technique to measure under-canopy *E* (Ashktorab et al., 1994). Measuring the β close to the surface is challenging as it requires high precision temperature and vapor measurements to determine gradients between heights that are typically only 5 cm apart (Ashktorab et al., 1989). The M-BREB method was successfully applied to measure under-canopy *E* in a corn crop (Zeggaf et al., 2008) and in a vineyard (Holland et al., 2013). This method is particularly noteworthy as a unique option for continuous measurement representing a relatively large surface area (compared, for example to MLs). The M-BREB method, however, is still in its developing stages, and requires further testing and adaptation under varying environmental conditions before the approach can be more broadly adopted (Holland et al., 2013).

3.1.5. Eddy covariance (EC) method

The eddy covariance (EC) technique is based on high frequency measurement, typically 10–20 Hz, of momentum, temperature and water vapor to determine evaporation (Brutsaert, 1982) with Eq. (3) as the governing equation. Three-dimensional wind speed is most commonly measured by a sonic anemometer, and vapor concentration usually with an IRGA. High frequency measurements are necessary to capture small eddies contributing to turbulent transfer (Baldocchi and Meyers, 1991). Measurements represent an area upwind from the instrument that scales with factors such as instrument height, wind speed, and atmospheric stability. Similar to the BREB method, the EC technique is mostly known for *ET* measurements, but it has also been successfully applied to measure *E* under forest canopies (Baldocchi and Meyers, 1991; Wilson et al., 2001). An attempt to use EC at 0.25 m height in a wheat field was partially successful with some modifications of theory (Denmead et al., 1996). Similarly to the M-BREB, the EC method has an advantage in that it measures continuously and represents a much larger area than, for example, MLs (Wilson et al., 2001). The method requires a homogeneous surface without disruptions between the surface and the instrument height and is therefore, considering that measurement accuracy increases with height, mostly applicable for tall canopies (Baldocchi and Meyers, 1991). Further work is necessary in order to identify conditions, including canopy height, that can allow the use of EC for under-canopy *E* measurement and to explore possible solutions for its use under less tall canopies.

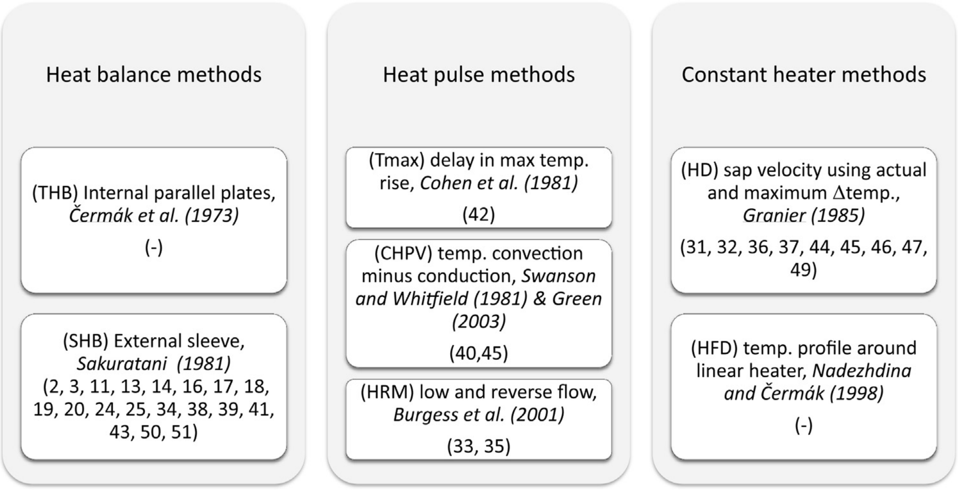

Fig. 1. Main categories of sap flow measurement techniques. Abbreviation for each of the discussed approaches is followed by a short description, references (in italics), and publications using the method (the numbers correspond to the publication numbers listed in Table 1, Section 6). Abbreviations: THB: tree heat balance, SHB: stem heat balance, CHPV: compensated heat-pulse velocity, HRM: heat ratio method, HD: heater dissipation, HFD: heat field deformation.

4. Estimating transpiration

Plant *T* is the process of water moving from soil, through the roots, stem and leaves of a plant into the atmosphere (Jones and Tardieu, 1998). Plants will differ in transpiration capacity depending on their hydraulic resistance, root and leaf water potential, and stomatal and leaf conductance. Similar to *E*, *T* is driven by atmospheric demand as well as soil water potential and hydraulic conductivity, but unlike *E*, plants regulate *T* by opening and closing the stomata (Jones and Tardieu, 1998).

Methods for directly measuring *T* generally quantify water flow at a specific interface along the soil-plant-atmosphere continuum, whereas models use varying degrees of resistance functions to characterize flow through the plant. Measurement methods include chambers that can measure *T* ranging from leaf to full plant scales and a wide range of sap flow methods (Wullschleger et al., 1998). The description of measuring methods for *T* in Section 4.1 is limited to those that allow simultaneous *E* measurements. Numerous models for estimating *T* are described in the literature (see a review by Jones and Tardieu, 1998) but there does not seem to be one single model that is widely adopted (Singer et al., 2010). A few *ET* partitioning studies (Singer et al., 2010; Williams, 2012) used the Monteith (1965) or Shuttleworth and Wallace (1985) model to scale-up stomatal conductance measurements to whole field transpiration; both were used for combined *E* and *T* estimation and are further described in Section 5.1.

4.1. *Transpiration measurements*

4.1.1. *Sap flow*

Sap flow methods are thermal based techniques to compute water flow through the stem following varying methodologies. Approaches can largely be categorized into heat balance, heat pulse and constant heater methods. Seven main methods are discussed below though numerous variations on these methods exist.

Heat balance methods are used to quantify mass flow of water based on an energy budget of energy input into the stem and subsequent losses. The two heat balance methods are trunk sector heat balance (THB) and stem heat balance (SHB). The THB method (Čermák et al., 1973, 2004) was developed for large tree trunks and consists of 3–5 plates that are inserted into the trunk in parallel, covering approximately the entire sapwood depth. The input heat is split between conductive heat losses and heating of water flowing through the trunk. No *ET* partitioning studies were found using this method, but since it was developed for large trees it has potential for partitioning in, for example, forests and orchards. The SHB method (Sakuratani, 1981, 1987) consists of a sleeve with a heater and temperature sensors wrapped around a small stem. This method is a non-invasive measurement that could theoretically be used without any calibration. It is limited by its ability to only measure stems smaller than 10–12 cm (Grime and Sinclair, 1999) and by the need to reposition the sensor regularly to prevent stem strangulation. The SHB method has been used quite often in *ET* partitioning studies (Fig. 1) and has been applied in, for example, cotton (Ham et al., 1990), grapevines (Heilman et al., 1994) and coffee (Gutiérrez and Meinzer, 1994).

Heat pulse methods allow quantification of sap flow velocity based on temperature response curves to a short heat pulse into the stem, where time delay for temperature rise is assumed to be proportional to sap flow velocity. Determination of *T* requires calibration factors to account for probe induced wounding and to calculate volumetric sap flow rates. The Tmax method (Cohen et al., 1981) is based on the delay in maximum temperature rise sensed by a probe placed a short distance above (downstream from) a line source heater. A reference probe, unaffected by the heater, is placed below (upstream) to compensate for diurnal temperature variations. The compensated heat-pulse velocity (CHPV) method (Swanson and Whitfield, 1981; Green et al., 2003) is based on similar principles, except that the reference probe upstream is placed at the same distance to the heater as the downstream probe to correct for thermal conduction. Sap flow velocity is calculated based on the time delay for the upstream and downstream probes to reach an equal temperature rise. The heat pulse methods have been tested for herbaceous plants such as soybean and corn where it proved accurate provided *T* was at least $7\,\mathrm{g\,h^{-1}}$ (Cohen et al., 1993) as well as for woody plants such as olives, apples, Asian pears, and grapevines (Fernández et al., 2007). The heat ratio method (HRM; Burgess et al., 2001) is similar to CHPV but uses the ratio of temperature increase between different points up and downstream from the heater to measure flow, allowing for measurement of low and even reverse flow (Er-Raki et al., 2010). Advantages of the heat-pulse methods include low power requirement (no constant heating) and simple instrumentation (Poblete-Echeverría and Ortega-Farias, 2012).

Constant heater methods are used to quantify sap flow velocity based on temperature dissipation from a constant heating source into the stem. Similar to the heat-pulse method sap flow velocity is then scaled up to compute *T*. The method requires a needle that is heated with constant power, and one or more needles measuring temperature at a distance from the heater. The Granier heater dissipation (HD) method (Granier, 1985) requires one or more pairs of heated and unheated probes that are inserted radially into the sap wood. The maximum temperature difference corresponds to zero flow conditions. Sap velocity is determined from the temperature differences using an empirical equation and is subsequently calibrated to plant size using sapwood area. The HD method has been used quite widely for larger stems and has been reported to give moderate to good results in, for example, pines (Domec et al., 2012), olives (Cammalleri et al., 2013), oaks in savannah steppe (Paço et al., 2009), date palms (Sperling et al., 2012) and cherries (Li et al., 2010). HD underestimated *T* in a vineyard (Ferreira et al., 2012), especially in the afternoon. The heat field deformation (HFD) method (Nadezhdina and Čermák, 1998; Čermák et al., 2004) is founded on the same principles, but the computation is based on deformation of the heat field around the source heater. The heat field is mapped by measuring temperature difference in axial and tangential directions from the heater. The HFD method allows computation of low and reverse flow and is therefore expected to be more accurate than the HD method, with particular potential for *ET* partitioning studies.

The seven main sap flow methods and the *ET* partitioning studies utilizing them are summarized in Fig. 1. Of the most widely used SHB and HD methods, SHB is more appropriate for small stems. An important limitation that applies to all heat pulse and constant heater methods, is found in scaling from sap flow to whole plant *T* (Kume et al., 2010). The two main difficulties in converting sap flow to *T* are the determination of total sapwood area (Vertessy et al., 1997) and mean sap flow over the total sapwood area (Phillips et al., 1996). These scaling issues are as crucial as the measurements themselves, and need to be considered carefully. The measurement accuracy of different sap flow methods used in *ET* partitioning studies is discussed in Section 6.

4.1.2. *Chambers*

As described in Section 3.1 for soil *E*, the chamber method is a measurement of gas fluxes in a closed volume of interest. Contrasting to most sap flow methods that are indirect indicators and require empirical factors to obtain *T*, chambers are appreciated for allowing direct measurement of actual *T*. However, the measurement process in chambers modifies micro-climatic conditions, and thus affects *T* (Denmead et al., 1993). To minimize this effect, chamber measurements of *T* should be as short as possible (especially when using static chambers) or should be conducted under very controlled conditions (dynamic chambers) that are representative of atmospheric conditions outside the chamber. Chambers used for *T* measurements range in scale from small plant chambers (Stannard and Weltz, 2006), to whole canopy grapevine chambers (Dragoni et al., 2006), all the way to full size tree canopies over 20 m^3 (Pérez-Priego et al., 2010) and even over 100 m^3 (Denmead et al., 1993). Chambers are generally considered costly, but accurate, and therefore a good method to measure *T*. However, placing the plant in an enclosure separate from the soil surface disregards interaction between *E* and *T* and can introduce errors in *ET* partitioning.

4.1.3. *Biomass–transpiration relationship*

Relative total yield has been shown to be linearly related to relative accumulated transpiration (De Wit, 1958; Hanks, 1974). This relationship has commonly been used to determine yield from measured, estimated or calculated *T*. The same relationship can be manipulated to calculate *T* based on actual measurements of biomass accumulation. Zegada-Lizarazu and Berliner (2011) estimated seasonal cumulative *T* of a mulched corn crop using a water balance. At the end of the growing season, plants were removed and their above and below ground biomass determined. The measured total seasonal *T* and biomass from the mulched treatments were used to establish the biomass – *T* ratio. This was subsequently used to calculate expected *T* in non-mulched treatments and thereby determine *ET* partitioning. The method assumes that the mulch itself does not alter the biomass-*T* ratio. The main advantage of this method is the known robustness of the biomass-*T* ratio throughout the lifespan of crops under varying environmental conditions and levels of stress (Ben-Gal et al., 2003). If shoot-root relations are assumed to be constant, the method can be simplified by only quantifying above ground biomass. The method is less suitable for smaller time-steps as it requires destructive determination of biomass.

5. Estimating evapotranspiration partitioning

Evapotranspiration partitioning can be estimated directly using isotope measurements or the correlation-based *ET* partitioning approach (Section 5.1). In addition there are numerous models and modifications of models based on a combined approach to simultaneously calculate *E* and *T*. Section 5.2 presents models that have been validated for *ET* partitioning.

5.1. *Evapotranspiration partitioning measurements*

5.1.1. *Isotopes*

The isotopic composition of water can be directly used to assess the ratio between *E* and *T*. If an absolute measurement of either *E*; *T*, or *ET* is known, quantification of *ET* and its components is achieved. The isotopic method for *ET* partitioning is based on a difference in the isotopic signature of water vapor as a result of *E* and *T*. Under natural conditions, two stable hydrogen isotopes occur: ^1H (99.9844%) and ^2H (0.0156%). Oxygen has three forms of stable isotopes: 99.762% of ^{16}O, 0.038% ^{17}O and 0.200% ^{18}O. Combinations yield nine different possible isotopic water molecules (Horita et al., 2008). In the process of evaporation, the lighter isotopes evaporate first, leaving the heavier isotopes (^2H and ^{18}O) behind (Craig and Gordon, 1965). This isotopic fractionation does not take place during root water uptake: leaf water might be enriched in the heavy isotopes as a result of evaporation through the stomata, but this reaches a steady state where the water transpiring is isotopically similar to soil water (Williams et al., 2004). Thus the isotopic compositions of *E* and *T* are distinctly different and can be used to partition between the fluxes. Although this method was first proposed several decades ago (Sheppard, 1958) and has been widely used to determine sources of water used by plants (Ehleringen and Dawson, 1992; Brunel et al., 1997) it is only slowly making its way into *ET* research, and is nearly non-existent in agricultural studies. Isotope ratios are traditionally determined using the so-called "cold-trap" sampling technique, where air is drawn into a tube immersed in liquid nitrogen or a dry-ice alcohol mixture to freeze out the vapor (Griffis, 2013; Soderberg and Good, 2012). The vapor is then injected into an isotope ratio mass spectrometer to determine the isotopic composition. A comparison between the sample composition and measured of estimated isotopic compositions of *E*, *T* and *ET* subsequently allows partitioning (Wang et al., 2010, 2012). Although the method is costly, laborious, and has a low time resolution, it has nevertheless been implemented successfully in many different studies (Griffis, 2013). Technical details regarding a number of alternative measurement techniques, including some continuous methods, can be found in reviews by Griffis (2013), Soderberg and Good (2012), Horita et al. (2008), and Dawson et al. (2002). Uncertainties stemming from the models' assumptions are discussed by Rothfuss et al. (2010). Isotopic measurements have been tested with fairly good results to assess *ET* partitioning in olives (Williams et al., 2004) and wheat (Zhang et al., 2011b). Isotopic methods are mostly applicable in dry areas with significant (>10%) evaporation. They require further validation, but appear to be appropriate for estimating *ET* partitioning at large scales (Griffis, 2013).

5.1.2. The correlation-based ET partitioning approach

A relatively new approach to measure *ET* partitioning makes use of the fact that *T* and carbon uptake by plants occur simultaneously. The relation between *ET* and CO_2 is a function of stomatal fluxes (*T* and photosynthesis) and non-stomatal fluxes (direct evaporation and respiration). Scanlon and Sahu (2008) proposed a carbon-water vapor correlation method using high frequency EC measurements. Assuming flux variance similarity between water vapor and carbon dioxide for vegetation and for the system as a whole, all the method requires is the high frequency data and a vegetation water use efficiency parameter, defined as the ratio of leaf-level carbon uptake per unit water loss at half-hourly timescales (Scanlon and Sahu, 2008; Scanlon and Kustas, 2010). The value of this method lies in its relative simplicity and the fact that EC systems are already used quite widely. Scanlon and Kustas (2012) found reasonable values using carbon-water vapor correlations over a corn field, but did not verify *E* and *T* with independent measurements.

5.2. Evapotranspiration partitioning models

Numerous models and variations of models that include *ET* partitioning are described in the literature. These are commonly categorized into mechanistic (M) and empirical (P) approaches, or analytical (A) and numerical (N) models. The following models were found to have been validated for *ET* partitioning and are briefly described: Shuttleworth–Wallace (MA); ENWATBAL (MN); Cupid-DPEVAP (MA); SWEAT (MN); TSEB (MA); FAO dual K_c model (PA); HYDRUS-1D (MN). They are presented in chronological order of their publication.

5.2.1. Shuttleworth–Wallace (S-W) model

Shuttleworth and Wallace (1985) suggested an analytical approach to *ET* partitioning based on two Penman–Monteith equations (Penman, 1948; Monteith, 1965): one for the crop (PM_C) and one for the soil surface (PM_S):

$$\lambda ET = C_c PM_c + C_s PM_s \tag{6}$$

$$PM_c = \frac{s(R_n - G) + [\rho c_p(VPD) - s r_a^c (R_n^s - G)]/(r_a^a + r_a^c)}{s + \gamma[1 + r_s^c/(r_a^a + r_a^c)]} \tag{7}$$

$$PM_s = \frac{s(R_n - G) + [\rho c_p(VPD) - s r_a^s (R_n - G) - (R_n^s - G)]/(r_a^a + r_a^s)}{s + \gamma[1 + r_s^s/(r_a^a + r_a^s)]} \tag{8}$$

where λET is in W m^{-2}, C_c and C_s are respective canopy and soil surface coefficients as functions of s, γ, ${r_a}^a$, ${r_a}^c$, ${r_s}^c$, ${r_a}^s$ and ${r_s}^s$, s is rate of change of saturated vapor pressure with air temperature (kPa °C^{-1}), c_p is specific heat of moist air (J kg^{-1} °C^{-1}) and *VPD* is vapor pressure deficit (kPa), all measured at a reference height. The additional terms to the Penman–Monteith equation are: ${R_n}^s$, net radiation at the soil surface (W m^{-2}), and a variety of resistances (r): ${r_a}^a$ is aerodynamic r between canopy and reference height, ${r_a}^c$ is bulk boundary r, ${r_s}^c$ is bulk stomatal r, ${r_a}^s$ is aerodynamic r between soil surface and canopy, and ${r_s}^s$ is soil surface r, all in s m^{-1}.

Analytical models such as the S-W model are used sporadically but form the foundation for many other *ET* partitioning models. Efforts to parameterize the resistances required for simulations were reported by Brisson et al. (1998), Lund and Soegaard (2003) and Ortega-Farías et al. (2007). Many authors (e.g., Iritz et al., 2001; Lagos et al., 2009) have suggested modifications to the S-W model. Li et al. (2010) proposed and validated a simplification of the model by using the Priestley–Taylor formula (Priestley and Taylor, 1972) to compute *E*, which requires more easily obtainable parameters and is valid for humid and sub-humid regions. Validations for partitioning of *ET* using variations of the S-W model were reported for soybean (Brisson et al., 1998), cherry (Li et al., 2010), and millet (Lund and Soegaard, 2003). The S-W model is generally considered accurate but hard to parameterize and has therefore mostly been used in a simplified format or as a validation for other models.

5.2.2. ENWATBAL

The energy and water balance (ENWATBAL) model developed by Lascano et al. (1987) is used to compute water and energy balances at the soil surface and at the plant canopy. *E* and *T* are solved numerically using inputs for soil properties (i.e. water retention, hydraulic conductivity, number and thickness of soil layers, and initial temperature and water content), plant inputs (i.e. leaf conductivity and water potential, root area with time, and depth and leaf area index (LAI) with time) and atmospheric inputs (i.e. solar radiation, air temperature, humidity, precipitation, and irrigation). These are used to quantify additional parameters that satisfy both energy and water balances (Evett and Lascano, 1993). The latent heat from the soil is defined as:

$$\lambda E = \frac{\lambda(AH_s - AH_a)}{r_a} \tag{9}$$

where λE is in W m^{-2}, *AH* is absolute humidity (kg m^{-3}) for soil (subscript *s*) and air (subscript *a*), and r_a is aerodynamic resistance (s m^{-1}). Eq. (9) is solved in combination with a below canopy energy balance equation (Eq. (2)) and additional equations (Evett and Lascano, 1993) for sensible and soil heat flux and surface and canopy temperatures. The latent heat of transpiration is defined as:

$$\lambda T = \frac{\lambda(AH_l - AH_a)}{r_{plant}} \tag{10}$$

where λT is in W m^{-2}, AH_l is leaf absolute humidity (kg m^{-3}) and r_{plant} is a plant resistance formula (s m^{-1}). This equation is combined with:

$$\lambda T = (\Psi_s + \Psi_{c\_\max} - \Psi_c) \times 1000\lambda \times \left(\frac{LAI}{r_{plant\_hyd}}\right) \tag{11}$$

where Ψ_s is soil water potential, Ψ_c and $\Psi_{c\_\max}$ are water potential and maximum water potential of the canopy, respectively (m), and $r_{\mathrm{plant\_hyd}}$ (s) is a hydraulic resistance factor of the plant. Combined with additional resistance equations (Evett and Lascano, 1993), *T* is found numerically. The capability of ENWATBAL to accurately partition *ET* has been tested in cotton (Lascano et al., 1987; Lascano, 2000) and sorghum (Qiu et al., 1999). The studies reported good agreement between measured and simulated results with a slight underestimation in calculated daily *ET*, possibly due to the effects of a dry top soil layer which introduces errors in surface temperature and energy balance calculations.

5.2.3. Cupid-DPEVAP

Thompson et al. (1993a) combined the plant-environment energy balance model, Cupid, with the water droplet evaporation–trajectory model (DPEVAP) to partition *ET* under sprinkler irrigation. The model allows partitioning of *ET* into *E* and *T* as well as the calculation of interception losses and evaporation from droplets during flight. The *ET* components are determined as a function of sprinkler characteristics, application rate, wind speed, temperature, and droplet size distribution. E is computed using a transfer coefficient validated by Sauer et al. (1995):

$$E = h_v \left(\frac{M_v}{RT_{abs}} \right) (e_0 - e_z) \tag{12}$$

where E is in kg m^{-2} s^{-1}, h_v is the surface or interfacial vapor transfer coefficient (m s^{-1}), M_v is the molecular weight of water (kg mol^{-1}), R is the gas constant (8.31 J mol^{-1} K^{-1}), T_{abs} is absolute temperature (K) and e_0 and e_z are vapor pressures at the surface and height z respectively (Pa). Transpiration is computed by dividing the canopy into layers and leaf angle classes using an upper boundary condition for air temperature, vapor pressure and wind velocity. A leaf energy balance is solved for leaves of various orientations in separated layers and then integrated over the canopy. The number of layers is determined as a function of the leaf area density distribution, which depends on the LAI (Thompson et al., 1993a,b). Thompson et al. (1997) validated Cupid-DVEVAP for E and T in corn using sap flow measurements and MLs and found good agreement between measured and modeled values, though modeled E was larger than measured E due to inability of MLs to measure during irrigation.

5.2.4. SWEAT

The soil, water, energy and transpiration (SWEAT) model was first presented by Daamen and Simmonds (1994). Interaction between E and T is quantified via a simple two-layer approach (soil and leaves) without requiring detailed information concerning canopy structure. Unlike other models, SWEAT does not require a soil resistance parameter. The basic equations of the model are:

$$\lambda ET = \frac{\lambda(AH_c - AH_a)}{r_a} \tag{13}$$

$$\lambda E = \frac{\lambda(AH_s - AH_c)}{r_{scan}} \tag{14}$$

$$\lambda T = \frac{\lambda(AH_l - AH_c)}{r_{st} + r_{lbl}} \tag{15}$$

where energy fluxes are in W m^{-2} and AH is absolute humidity (kg m^{-3}). Subscripts c, a, s and l refer to absolute humidity of the canopy, the air at reference height, the soil, and the leaf, respectively. Resistances (r) are defined for canopy to atmosphere (r_a), stomata (r_{st}), leaf boundary layer (r_{lbl}) and soil surface to canopy air (r_{scan}), all in s m^{-1}.

The sensible heat flux and λE, λT and λET are solved in SWEAT numerically to fit the energy balance (Eq. (2)). The procedure uses meteorological data and subroutines for water and heat flow described by Daamen and Simmonds (1996) in addition to measurements of LAI and crop height. The model was validated for millet (Daamen, 1997), yielding reasonable values, though the estimation of the resistances requires further improvement. It was observed that the model gave adequate results for land surfaces with LAI > 2.

5.2.5. TSEB

The two source energy balance (TSEB) model was developed to compute λET using surface temperature data that could potentially be acquired using remote sensing (Norman et al., 1995; Anderson et al., 1997; Kustas and Norman, 1999). The required inputs for the model include directional radiometric temperature of the surface, standard meteorological data, and canopy characteristics including LAI. The model is based on separate equations for soil and canopy energy balances. The respective energy balances are solved by partitioning measured R_n between soil and canopy based on LAI, a clumping factor (characterizing the canopy structure), and extinction coefficients, where G is defined as a fraction of R_n at the soil surface. Likewise, temperature inputs are divided into canopy and soil temperature to calculate H. The latent heat components are presented as:

$$\lambda ET = \lambda E + \lambda T \tag{16}$$

$$\lambda T = \alpha_{PT} f_g \frac{s}{s + \gamma} R_n^c \tag{17}$$

where α_{PT} is the Priestley–Taylor constant (α_{PT} = 1.3, Priestley and Taylor, 1972), f_g is the fraction of green vegetation in the canopy, and $R_n{}^c$ is net radiation at the canopy (W m^{-2}). This is a first approximation, assuming transpiration at potential rate, with λE computed as the residual component of the energy balance. If λT is greater than λET, resulting in negative λE, the model adjusts λT until λE becomes zero. The TSEB model has been tested for ET partitioning in a cotton field (Colaizzi et al., 2012) and is unique in that it requires relatively few input parameters and could potentially be used on large scales using remotely sensed data.

5.2.6. FAO dual-K_c model

The FAO dual-K_c model (Allen et al., 1998) computes ET of a well-watered crop using an empirically defined crop specific multiplication factor (K_c) in combination with a reference ET (ET_0). ET_0 takes into account plant response to atmospheric conditions by solving the Penman–Monteith equation (Penman, 1948; Monteith, 1965) for a reference crop (short grass or alfalfa). The dual-K_c approach divides the K_c factor into a plant component K_{cb} and a soil component K_e and is defined as:

$$ET = (K_{cb} + K_e)ET_0 \tag{18}$$

where ET and ET_0 are in mm d^{-1} and K_{cb} and K_e are dimensionless. ET_0 can be calculated from atmospheric data at 2 m height that are measured at most weather stations (Allen et al., 1998). K_{cb} and K_e are defined as:

$$K_{cb} = K_{cb(table)} + [0.04(u_2 - 2) - 0.004(RH_{\mathrm{min}} - 45)] \left(\frac{h_p}{3} \right)^{0.3} \tag{19}$$

$$K_e = K_r(K_{c\_\mathrm{max}} - K_{cb}) \le f_{ew} K_{c\_\mathrm{max}} \tag{20}$$

where $K_{cb(table)}$ is a value found in the literature that has been measured experimentally, u_2 is mean daily wind speed at 2 m height over grass (m s^{-1}); RH_{min} is mean daily minimum relative humidity (%), h_p is mean plant height (m), f_{ew} is the fraction of soil from which most evaporation occurs, K_r is a reduction factor based on soil water availability and K_{c_max} is the maximum evaporation factor based on available energy for ET at the soil surface.

The FAO-dual K_c model is the most common model used to partition ET, as it requires relatively few parameters and the results are generally accurate enough to be applied as an irrigation scheduling tool. However the model is empirical and pre-defined crop factors are not always applicable to sites in different contexts (Ferreira et al., 2012). ET partitioning using the FAO-dual K_c model has been tested for olives (Rousseaux et al., 2009; Er-Raki et al., 2010), vineyards (Ferreira et al., 2012), coffee (Flumignan et al., 2011), and peach (Paço et al., 2011). Overestimation of T was reported on days with high ET_0, as water uptake by the plants, even though well-watered, was not sufficient to meet peak hourly demand (Paço et al., 2011).

5.2.7. HYDRUS-1D

HYDRUS-1D is a public domain Windows-based modeling environment for simulation of water, heat and solute movement (Šimůnek et al., 2008). The model numerically solves the Richards equation for variably saturated media, and the convection–dispersion equation for heat and solute transport based

Table 1
Comparison and evaluation of *E* measurement methods.

	E measurements				
	ML	SHP	Chamber	MBREB	EC
Type	Water balance	Energy balance	Water vapor flux	Water vapor flux, energy balance	Water vapor flux
Measurement	Mass	Temperature	Vapor concentration	Vapor concentration, temperature, net radiation, soil heat flux	Vapor concentration, temperature, momentum
Scale	Point	Point	Point/patch	Patch	Patch/field
Main assumptions	When used on a drained soil, field conditions are accurately represented for up to 24–48 h	Latent heat is energy removed from soil layer/below surface	Flux inside chamber is representative of flux outside chamber	Atmospheric transport mechanisms of vapor and heat are similar, fluxes can be derived from gradients close to the surface	Steady state conditions, no sources and sinks between surface and measurement height, extended, level and homogeneous upwind fetch
Advantages	Simple, inexpensive, reliable	Continuous, provides *E* as a function of depth	Portable, direct measurement	Continuous	Continuous
Disadvantages	Labor intensive, only applicable on drained soil	Only applicable for stage II *E*	Expensive, complicated	Expensive, complicated high maintenance	Expensive, under tall canopy only
Common use	Validation, short-term, variety of environmental conditions	Testing stage	Forest, natural vegetation	Testing stage, used in tomato, corn, vineyard	Forest
Adaptations to original design and further developments	Continuous measurements, artificially maintaining field water content	Probes that measure closer to the surface	Dynamic: improved accuracy using IRGA, static: simpler, less expensive measurements	More accurate estimation of small fluxes; e.g. using IRGA	Adapted theory for low canopies

Abbreviations: *E*: soil evaporation, EC: eddy covariance, MBREB: micro Bowen-ratio energy balance, ML: micro lysimeter, SHP: soil heat pulse probe.

on Fick's law. The water flow equation includes a sink term to account for root water uptake of plants.

Evaporation is computed as a water flux going out of the soil system as described by Neuman et al. (1975), limited either by an atmospherically determined potential evaporation (E_{pot}), or by the rate of water that can be supplied to the soil surface. Similarly, transpiration is limited either by potential transpiration or the rate at which water can be transported to a pre-defined root zone. *E* is thus computed as:

$$E = -K\frac{\partial h}{\partial x} - K \leq E_{pot} \quad \text{at} \quad x = L \tag{21}$$

where the surface boundary pressure head (h) is:

$$h_A \leq h \quad \text{at} \quad x = L \tag{22}$$

and K is unsaturated soil hydraulic conductivity (m s^{-1}), x is the spatial coordinate (positive upwards), L is the x-coordinate of the soil surface above a certain reference plane (depth of the soil profile, m), and h_A is minimum pressure head for prevailing soil conditions (m). E_{pot} and h_A are either pre-defined by the user or calculated as a function of air humidity. E_{pot} can also be computed as a fraction of potential *ET* based on Beer's law; where potential *ET* is partitioned based on LAI.

Transpiration is defined as a function of root water uptake:

$$T = \int_{L_R} S(h, h_\varphi, x)\,dx = T_{pot}\int_{L_R} \alpha(h, h_\varphi, x)b(x)\,dx \tag{23}$$

where L_R is rooting depth (m), $S(h, h_\varphi, x)$ is the sink term defined as the volume of water removed from a unit volume of soil per unit time due to plant water uptake, h_φ is osmotic head (m), $\alpha(h, h_\varphi, x)$ is a water stress response function ($0 \leq \alpha \leq 1$), where $\alpha = 1$ implies no water stress; and $b(x)$ is normalized water uptake distribution function (m^{-1}), describing spatial variation of the potential extraction term over the root zone. The software offers options as to what function to use for $b(x)$ or $\alpha(h, h_\varphi, x)$.

HYDRUS-1D has been tested for *ET* partitioning in grass grown under laboratory conditions using isotope measurements (Sutanto et al., 2012). Though the sum of *E* and *T* for both isotope and modeling results were comparable to water balance *ET*, the partitioning was very different, indicating that both methods need further validation. Similar efforts were conducted for a teff crop in a laboratory set-up, but no conclusive partitioning results were presented (Wenninger et al., 2010). In addition to HYDRUS-1D, a 2D/3D version (Šimůnek et al., 2011) was released, allowing modeling of spatial dynamics in *ET* partitioning studies. Note, however, that HYDRUS 2D/3D is proprietary software. HYDRUS 2D/3D does not have fully coupled heat, water vapor and liquid water flow like HYDRUS-1D codes, which is important for small fluxes of evaporation. HYDRUS-2D has been used (though not validated) as a tool for *ET* partitioning in, for example, cotton (Bufon et al., 2012) and land covers ranging from native forest to tree plantation, grasslands, wheat/soybean and soybean (Nosetto et al., 2012). Advantages of the HYDRUS software include its wide-spread use and the possibility to study numerous transport processes in the soil (heat/water/solute) at once. Its ability to partition between *E* and *T* fluxes however, as well as partitioning of potential *E* and *T*, requires further validation.

6. Discussion

Studies on partitioning *ET* were done using different combinations of measurement and modeling methods depending on scale of interest, cover type, study objectives, and available resources. Within the described methods there are at least five *E* and nine *T* options, amounting to 45 possible combinations besides the two methods that measure the partitioning of *ET*. Tables 1 and 2 present a synthesis of the reviewed methods for measuring *E* and *T*, respectively. The spatial scale of the methods presented range from "point" (~0.1 m^2), to "patch" (~1–10 m^2) to "field" (~1000 m^2). The main assumptions and advantages and disadvantages are indicative

Table 2
Comparison and evaluation of *T* and *ET* partitioning measurement methods.

	T measurements			*ET* partitioning measurements	
	Sap flow	Chamber	Biomass-*T*	Isotope	CO_2–H_2O
Type	Energy balance, water balance	Water vapor flux	Plant H_2O–CO_2 exchange	Isotope	Plant H_2O–CO_2 exchange
Measurement	Temperature	Vapor concentration	Ref *T*, ref biomass, total biomass	Fractions of 'H' and 'O' isotopes	High freq. (10–20 Hz) CO_2 and H_2O data; ratio of carbon dioxide gain per unit water loss
Scale	Plant	Plant	Plant	Field	Field
Main assumptions	*T* is proportional to heat transport	Flux inside chamber is representative of flux outside chamber	Linear relationship ref biomass vs ref *T* is representative for *T* of total biomass	Preferential evaporation of lighter isotopes does not take place during root water uptake	Flux variance similarity between water vapor and CO_2 for vegetation and for the system as a whole
Advantages	Continuous	Portable, direct measurement	Simple, accurate	Large area	Continuous, EC already used for *ET*
Disadvantages	Scaling/calibration is complex	Expensive, complicated, not always suitable for partitioning	Destructive sampling, limited time resolution	Expensive	Still in testing phase
Common use	Variety of environmental conditions	Variety of environmental conditions	Used once only	Variety of environmental conditions	Testing stage
Adaptations to original design and further developments	Low and reverse fluxes, non-invasive measurements	Dynamic: improved accuracy using IRGA, static: simpler, less expensive measurements	–	Simultaneous measurement of CO_2 uptake and respiration	–

Abbreviations: EC: eddy covariance, *ET*: evapotranspiration, IRGA: infrared gas analyzer, *T*: transpiration.

of the conditions under which these methods can be used, and are augmented by information regarding common uses of the methods and past/current developments. It appears that studies aiming at partitioning *ET* have been conducted under a wide range of environmental conditions and agricultural/natural settings, using a large number of methods and combinations of methods. To date, no particular method is concluded to be the absolute most accurate, thus an absolute validation of the methods is impossible.

An indirect indication to the accuracy of the methods may be achieved through examination of the *ET* partitioning. To partition *ET* into *E* and *T*, measurements of at least two components are required. A thorough literature search resulted in 52 papers that complied with this requirement (Table 3). The level of success of the partitioning can only be evaluated if all three components (i.e., *E*, *T*, and *ET*) were measured independently. Success of *ET* partitioning was thus evaluated for 27 papers, 20 of which had measurements for all individual components and 6 that used both measurements and models to determine the components, using the ratio $[E+T]/ET$. While a good agreement between $E+T$ and *ET* provides confidence in the three methods, it does not assure that the partitioning between *E* and *T* is necessarily accurate. This remains a limitation of this analysis. It also needs to be stated that the comparisons are rough since some studies published cumulative data over a season, whereas others gave daily values, naturally resulting in different magnitudes in associated errors. If values were reported they were copied directly, otherwise they were extracted from graphically presented data. In Table 3 each component is presented as a range, allowing for seasonal changes and standard deviations in the measurements.

The most common land covers investigated were row-crops such as cotton, corn, vineyards and orchards. In five papers reporting *ET* partitioning in cotton fields, average *E* was found to account for 20–30% of *ET*. *E*/*ET* of corn, wheat and soybean fields was somewhat higher, averaging from 30 to 40%, with highly variable values. This large variability in *E*/*ET* is evident in many annual crops, as the change in canopy cover fraction from zero to full cover results in large seasonal changes. Vineyards under drip irrigation were found to be somewhat conservative with 20–30% *E*/*ET* on average, but had some of the highest *E*/*ET* ratios (50–60%) for rainfed and furrow and flood irrigated systems. *E*/*ET* seemed to be particularly high in flood irrigated and some sprinkler irrigated study sites, as well as in rainfed sites. Nine papers reported flux partitioning for forests or rangelands and generally indicated higher *E*/*ET* ratios in rangelands. Natural vegetation sites often have multiple *E* and *T* components which might explain the relatively low agreement between individual *E* and *T* measurements and *ET* measurements.

Out of the 20 studies that measured all components *E*, *T* and *ET*, the most commonly used methods were micro-lysimeters for *E* and SHB sap flow measurements for *T*. A total of 8 different combinations for $E+T$ measurements and the agreement with different *ET* measurements are shown in Fig. 2. With only one or two validations for most of the method combinations, considering dissimilarities in

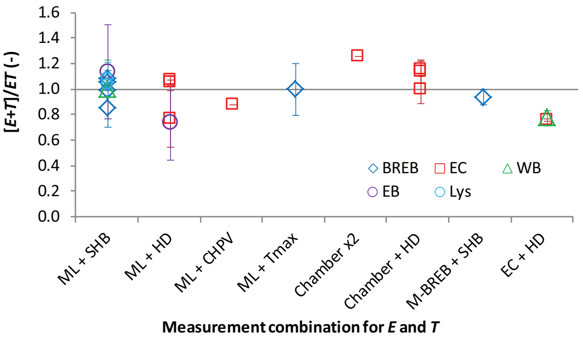

Fig. 2. An evaluation of 8 independent measurement combinations of evaporation from the soil surface (*E*) and transpiration (*T*). The combinations of *E* and *T* were compared to evapotranspiration (*ET*) measurements using the ratio $[E+T]/ET$ with the objective of deriving trends that could indicate the accuracy of the methods. Each point represents a single study. The different colors represent different methods for *ET*. Abbreviations: ML: micro-lysimeter, SHB: stem heat balance, HD: heater dissipation, CHPV: compensated heat-pulse velocity, (M)-BREB: (micro) Bowen ratio energy balance, EC: eddy covariance, EB: energy balance, Lys.: weighing lysimeter, WB: water balance.

Table 3
Overview of 52 publications regarding *ET* partitioning ($ET = E + T$) with measurements for at least two components.

#	Cover	Publication	Irrigation	E^{a}	E/ET	T^{a}	T/ET	ET^{a}	$[E+T]/ET$
Field crops									
1	Barley	Allen (1990)	NA	ML	0.67–0.77	*ET–E*	NA	WB	NA
2	Millet	Daamen et al. (1995), Daamen (1997)	NA	ML, Lys. *SWEAT*	0.03–0.78	SF (SHB) *SWEAT*	0.19–0.89	*E + T* *SWEAT*	0.92–0.97
3	Millet	Lund and Soegaard (2003)	NA	*ET–T* *S-W*	NA	SF (SHB) *S-W*	0.40–0.90	EC-EB *S-W*	NA
4	Sorghum	Qiu et al. (1999)	Sprinkler	ML, Lys. *ENWATBAL*	0.03–0.20	*ET–E* *ENWATBAL*	0.79–1.05	Lys. *ENWATBAL*	0.99–1.08
5	Wheat	Denmead et al. (1996)	NA	ML	0.10–0.85	*ET–E*	NA	EC	NA
6	Wheat	Balwinder-Singh et al. (2011)	Flood	ML	0.25–0.33	*ET-E*	NA	WB	NA
7	W-wheat	Kang et al. (2003)	?	ML	0.10–0.90	*ET–E*	NA	Lys.	NA
8	W-wheat	Zhang et al. (2002)	Furrow	ML	0.24	*ET-E*	NA	BREB, Lys.	NA
9	W-wheat	Zhang et al. (2011b)	Flood	Isotope, ML	0.18–0.40	Isotope	0.60–0.83	EC	NA
Row crops									
10	Coffee	Flumignan et al. (2011)	Sprinkler Drip NA	ML *FAO-2Kc*	0.18–0.61 0.16–0.66 0.19–0.82	*ET–E* *FAO-2Kc*	NA	Lys. *FAO-2Kc*	NA
11	Coffee	Gutiérrez and Meinzer (1994)	Drip	*ET–T*	NA	SF (SHB)	0.34–0.95	BREB	NA
12	Corn	Herbst et al. (1996)	NA	Lys.	0.00–0.22	g_s *scaled*	0.77–1.16	BREB	0.99–1.16
13	Corn	Jara et al. (1998)[b]	Furrow	ML	0.09–0.23	SF (SHB)	0.82–0.98	BREB	1.05–1.07
7	Corn	Kang et al. (2003)	?	ML	0.11–0.78	*ET–E*	NA	Lys.	NA
14	Corn	Thompson et al. (1997)	Sprinkler	ML, Lys. *Cupid*	0.28–0.58	SF (SHB) *Cupid*	0.48–0.74	Lys. *Cupid*	1.02–1.06
15	Corn	Zegada-Lizarazu and Berliner (2011)	Furrow/Drip	*ET–T*	NA	*Biomass relation*	0.61–0.63	WB	NA
16	Corn	Zeggaf et al. (2008)	Sprinkler	M-BREB	0.42–0.63	SF (SHB)	0.25–0.58	BREB, Lys.	0.88–1.00
17	Cotton	Agam et al. (2012) and Colaizzi et al. (2012)	Sprinkler	ML *TSEB*	0.13–0.21	SF (SHB) *TSEB*	0.75–1.08	Lys. *TSEB*	0.96–1.21
18	Cotton	Bufon et al. (2012)[b]	Sub-drip	*ET–T*	NA	SF (SHB)	0.82–0.90	*FAO-2Kc*	NA
19	Cotton	Ham et al. (1990)	Sprinkler	ML	0.28–0.68	SF (SHB)	0.47–0.74	BREB	1.02–1.15
20	Cotton	Lascano (2000)	Furrow	ML *ENWATBAL*	0.36	SF (SHB) *ENWATBAL*	0.64	*E + T* *ENWATBAL*	0.96–1.04
21	Cotton	Lascano et al. (1987)	?	ML *ENWATBAL*	0.30	*ET–E* *ENWATBAL*	0.70	WB *ENWATBAL*	0.93
22	Cowpea	Sepaskhah and Ilampour (1995)	Sprinkler	ML	0.52–0.59	*ET–E*	NA	WB	NA
23	Soybean	Brisson et al. (1998)[b]	Sprinkler	ML *S-W*	0.25–0.32	*ET–E* *S-W*	0.40–0.80	BREB, Lys. *S-W*	0.72–1.05
24	Soybean	Sakuratani (1987)	NA	*ET–T*	NA	SF (SHB)	0.20–0.90	BREB	NA
25	Soybean	Sauer et al. (2007)	NA	*ET–T*	NA	SF (SHB)	0.88–0.92	EC-EB	NA
26	Soybean	Singer et al. (2010)	NA	ML	0.06–0.14	g_s *scaled*	1.02–1.46	EC	1.16–1.52
27	Tomato	Ashktorab et al. (1994)	Sprinkler	M-BREB	0.01–0.51	*ET–E*	NA	Lys.	NA
28	Wheat-corn	Chen et al. (2010)	Furrow	ML	0.10–0.60	*ET–E*	NA	WB	NA
29	Wheat-corn	Fan et al. (2013)[b]	Furrow	ML	0.30–0.45	*ET–E*	NA	WB	NA
30	Wheat-corn	Liu et al. (2002)	Furrow	ML	0.30	*ET–E*	NA	Lys.	NA
Orchards and vineyards									
31	Cherry	Li et al. (2010)	Drip	ML *(S)S-W*	0.10–0.80	SF (HD) *(S)S-W*	0.20–0.90	*E + T* *(S)S-W*	0.78–1.62
32	Olive	Cammalleri et al. (2013)	Drip	*ET–T*	NA	SF (HD)	0.67–0.87	*FAO-2Kc*	NA
33	Olive	Er-Raki et al. (2010)	Flood	*ET–T* *FAO-2Kc*	0.18–0.52	SF (HRM) *FAO-2Kc*	0.51–0.79	EC-EB *FAO-2Kc*	0.97–1.03
34	Olive	Rousseaux et al. (2009)	Drip	ML *FAO-2Kc*	0.20–0.30	SF (SHB) *FAO-2Kc*	0.70–0.80	*E + T* *FAO-2Kc*	NA
35	Olive	Williams et al. (2004)	Flood	*ET–T*, Isotope	0.08–0.31	SF (HRM) Isotope	0.70–0.99	EC-EB	1.01–1.08
36	Peach	Paço et al. (2011)	Drip	ML *FAO-2Kc*	0.12	SF (HD) *FAO-2Kc*	0.88	EC *FAO-2Kc*	1.04–1.07
37	Vineyard	Ferreira et al. (2012)	Drip	ML *FAO-2Kc*	0.13	SF (HD) *FAO-2Kc*	0.87	EC-EB *FAO-2Kc*	1.05–1.10
38	Vineyard	Heilman et al. (1994)	NA	ML	0.44–0.68	SF (SHB)	0.32–0.56	BREB	0.71–1.00
39	Vineyard	Lascano et al. (1992)	Flood	*ET-T*	NA	SF (SHB), Lys.	0.23	WB	NA
40	Vineyard	Poblete-Echeverría et al. (2012)	Drip	ML	0.31	SF (CHPV)	0.69	EC-EB	>0.88

Table 3 (*Continued*)

#	Cover	Publication	Irrigation	E^a	E/ET	T^a	T/ET	ET^a	$[E+T]/ET$
41	Vineyard	Trambouze et al. (1998)[b]	NA	ML	0.22 0.25	SF (SHB)	0.55 0.81	WB EB	0.77–1.23 0.77–1.50
42	Vineyard	Yunusa et al. (2004)	Drip	ML	0.41	SF (Tmax)	0.55	BREB	0.80–1.20
43	Vineyard	Zhang et al. (2011a)	Furrow	ML	0.47	SF (SHB)	0.52	BREB	0.99
Natural vegetation									
44	Forest	Kelliher et al. (1992)	NA	ML	0.07–0.21 0.09–0.21	SF (HD)	0.28–0.76 0.35–1.07	EC EB	0.34–0.90 0.43–1.29
45	Forest	Kostner (2001)[b,c]	NA	ML, Chamber	0.05–0.15	SF (HD)	0.85–0.95	EC, WB	NA
46	Forest	Raz-Yaseef et al. (2012)[c]	NA	Chamber	0.44–0.53	SF (HD, CHPV)	0.44–0.57	EC	0.89–1.11
47	Forest	Wilson et al. (2001)[c]	NA	EC	0.32–0.35 0.31–0.38	SF (HD)	0.42–0.44 0.42–0.46	EC WB	0.77 0.72–0.84
48	Grass	Sutanto et al. (2012)	NA	Isotope *HYDRUS*	0.12–0.27	Isotope *HYDRUS*	0.64–0.78	Isotope *HYDRUS*	NA
49	Pine-4 years Pine-17 years	Domec et al. (2012)[c]	NA	Chamber	0.20–0.26 0.14–0.17	SF (HD)	0.79–1.01 0.96–1.06	EC, WB	1.05–1.23 1.10–1.22
50	Shrub	Cavanaugh et al. (2011)	NA	*ET–T*	NA	SF (SHB)	0.42–0.47	EC	NA
51	Shrub	Scott et al. (2006)	NA	*ET–T*	NA	SF (SHB)	0.58–0.70	BREB	NA
52	Shrub	Stannard and Weltz (2006)	NA	Chamber	0.16	Chamber	0.84	EC	1.26

Abbreviations: E: evaporation, ET: evapotranspiration, EB: energy balance, EC: eddy covariance, Lys.: weighing lysimeter, (M)-BREB: (micro)-Bowen ratio energy balance, ML: micro lysimeter, NA: not applicable, SF (type): sap flow (see section 4.1), T: transpiration, WB: water balance, W-wheat: winter-wheat.

[a] Methods used to estimate respective components. Models are presented in italics.

[b] Publications where data was presented with graphs only: partitioning was estimated based on visual determination of average, average minimum and average maximum values of the respective components.

[c] Partitioning for additional components: for the sake of comparison interception was added to E and all T's were summed.

data presentation between the different papers, only general trends and not hard conclusions can be deduced. Firstly, it appears that combinations using EC for E result in smaller $E+T$ compared to ET. Combinations that use EC for ET tend to realize larger $E+T$ values compared to ET. This indicates a tendency, as evidenced in the literature, for EC systems to underestimate fluxes (Twine et al., 2000). There are several method combinations that used BREB for ET and they seem to have good agreement with $E+T$; which may indicate that the individual methods for E and T give good results. It also seems that combinations using SHB sap flow measurements for T have more variable results than combinations using HD, CHPV or Tmax sap flow, however, data is too limited to be conclusive. Despite the variability in the measurements, several studies were able to achieve over 90% agreement for $ET=E+T$, implying that accurate ET partitioning is within reach of today's technology.

Interestingly, over 35% of the papers attempting ET partitioning, and satisfying our criteria for measurements of at least two of the components, were published since 2010, indicating an increasing awareness of the importance to determine ET components separately. A particularly notable increase is evident in studies on natural environments, which were mostly published in the last 10 years.

7. Conclusion

Partitioning ET is expected to become increasingly important as water resources continue to diminish and population pressure on marginal areas increases. A solid understanding of where losses occur and how much water is used beneficially through plant transpiration can help interpret the hydrological components, especially in arid and semi-arid environments, validate climate scenario predictions, and enhance agricultural water management practices.

The various methods for sap flow present a promising future for quantifying T, but analogous, simple continuous methods to measure E are lacking. MLs are used widely but are not suitable during irrigation when E may be substantial. Further investigation of novel methods such as soil heat pulse and M-BREB might allow better quantification of E in the future. Remote sensing models, such as the TSEB indicate an additional avenue for ET partitioning, but require further validation for the components under sparsely vegetated conditions and drought stress. Remote sensing models would also allow partitioning on larger scales, providing an integrated assessment of ET components, less limited by heterogeneity that causes errors when trying to understand a system using point measurements.

Two of the new methods, i.e., the biomass–transpiration relationship and the correlation-based ET partitioning approach, make use of plant CO_2 uptake to determine T. This seems an interesting development, particularly since both CO_2 and T are relevant to the understanding of ecosystems. Biomass production and allocation of water resources are essential for both agricultural and natural ecosystem sciences whereas carbon sequestration and the different feedback mechanisms associated with transpiration are very relevant to atmospheric sciences. This correlation might be further explored in, for example, chambers, that often measure CO_2 uptake as well as water vapor exchange and the MBREB technique, where some designs measure CO_2 as well as vapor and temperature fluxes. This could also be relevant in isotope studies, where H_2O and CO_2 are often determined simultaneously (Griffis, 2013; Yakir and Wang, 1996), but as yet have not been used for ET partitioning.

Partitioning ET has been evaluated for a limited amount of mostly row crops, indicating that E can account for 20–40% of ET (Table 3). This information can be valuable for the development of better management practices of, for example, deficit irrigated crops (Fereres and Soriano, 2007), the use of mulching (Adams, 1966), or could be incorporated into cost-benefit analyses of crop profitability under different irrigation or tillage regimes (Burt et al., 2005; García García et al., 2012). Results suggest that E/ET can be large for the earlier stages of full cover crops as well. Hossen et al. (2012), for example, estimated a seasonal E/ET of 30–36% for rice using an empirical equation. Despite the large fractions of E

indicated in the literature, not a single paper was found that reported a full validation of *ET* partitioning for field crops. Experimental validation is necessary to determine how much of the water allocated to *E* could potentially be saved and to validate models of plant behavior based on calculated transpiration. Similarly, results from studies on natural vegetation indicate large variability in *ET* partitioning and validation efforts suggest that attaining high accuracy is relatively challenging. Further investigation of *ET* partitioning in natural ecosystems will benefit the understanding of the hydrologic systems which affect stream flow, ground water recharge and weather conditions, as well as plant biomass production and associated carbon sequestration.

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