34
MEASURING EVAPOTRANSPIRATION

A. Christopher Oishi, Ge Sun, Lixin Wang and Kendall DeJonge

34.1 Introduction

Evapotranspiration (ET), the core of ecohydrology, represents a major component of an ecosystem's water and energy budget, reflecting multiple biophysical processes in the Earth system (1–3). This flux represents the sum of evaporation from soil and plant surface, water bodies, and plant transpiration. Accurately quantifying ET at multiple scales is increasingly recognized to be critical for water resource management and sustainable agriculture under a changing climate (3).

As with the biosphere-atmosphere exchange of other gases, ET is fundamentally unmeasurable *in situ*. This is because any *in situ* method either alters the local environment and artificially affects ET or is unable to unambiguously account for all sources of this well-mixed gas from a known area. Thus, all quantification of ET relies on estimates. Nevertheless, because of water's unique physical properties, a set of robust estimation methods exists. Water in liquid and gas phases can be described by the first principles of physics. Water molecules' polarity, which is necessary for cohesion and adhesion properties, also enables a range of sensing methods. Both hydrogen and oxygen have stable isotopes with distinct characteristics in ecohydrologic processes (4, 5). In addition, most water molecules are not transformed through chemical reactions and are fairly stable in the environment.

Despite its significance in ecohydrology, there is not a single "best" method for quantifying ET, and the "best" approach will depend on ecosystem characteristics, available resources, and objectives. In this chapter, we provide an overview of the main methodological approaches for quantifying ET, including some of the strengths and weaknesses of specific approaches (Table 34.1). We note that methods using remote sensing are addressed elsewhere in this book.

34.2 Field measurement methods

34.2.1 Water balance method

ET can be quantified at a soil column or a watershed scale using the principle of water balance. This approach assumes a one-dimensional model where ET is estimated as the residual of precipitation

DOI: 10.4324/9781003383918-40

Table 34.1 A summary of major methods for estimating ET at multiple scales

Method	*Strengths*	*Weaknesses*	*Key References*
Direct field-based approaches			
Catchment water balance	Instrumentation and analyses are relatively simple, existing monitoring networks may exist	Only long-term average is reliable, establishing new streamflow gauges can be expensive for larger catchments	(6)
Plot scale water balance	Determined by *in situ* soil water or sensor measurements	Sensors require calibration and may have time resolution limitations, soils are spatially variable, hard to characterize runoff or deep percolation	(7, 8)
Porometer and cuvette	Quantifies leaf-level physiological process	Difficult to scale up due to uncertainty of the influence of boundary layers and variability of leaf age, radiation, and humidity; high equipment costs and labor-intensive	(9)
Weighing lysimeter	Single, whole tree, or soil monolith water use	High installation and maintenance cost; for small trees or short vegetation	(10)
Heat balance/heat dissipation sap flow	Continuous estimates of transpiration at single plant scale; good detection of temporal trends	Challenges for accurately upscaling due to variability in flow at the plant, species, and community scales; tradeoffs with sensory accuracy and cost	(11–13)
Eddy covariance	Measuring fluxes continuously over moderately large areas, offering high temporal resolution data, combines water, energy, and other mass fluxes (e.g., CO_2, CH_4)	High cost in instrumentation, gap filling required, energy balance closure problems	(14–17)
Bowen ratio	Continuous estimate of ET over moderately large areas, works for both crops and natural vegetation	Relies on several assumptions, errors associated with low gradients	(18)
Surface renewal	Low cost, works for both crops and natural vegetation including forests. Can be applied close to the canopy surface	Requires extensive fetch requirements.	(19)

(*Continued*)

Table 34.1 (Continued)

Method	*Strengths*	*Weaknesses*	*Key References*
Remote sensing approaches			
MODIS, OpenET, ECOSTRESS	Provide large spatial area coverage	Uncertainties due to errors generated by measurement of sparse canopies, data mostly from clear sky conditions, snapshot of ET, large uncertainty without field correction	(20, 21)
Mathematical modeling for ET alone or the full hydrological cycles			
Theoretical models (*e.g.* Penman-Monteith equation)	Widely tested, including all conditions and scales, low cost	Require site-specific parameters, not easy to apply to data-poor regions	(22)
Isotope tracers			
Stable isotope of H and O	Process-based understanding water source of ET; Partitioning evaporation and transpiration	Cost and scaling up to stand-level	(23, 24)

(P) minus drainage (Q) measured below the root zone or at the watershed outlet, and change in water storage (ΔS):

$$P - Q - \Delta S = ET \tag{34.1}$$

Incident P can be quantified using a variety of methods. Manual precipitation gauges are simple, inexpensive methods to quantify P at a given point. Some precipitation gauging networks use a standardized approach. For example, the United States National Weather Service uses eight-inch diameter cylindrical gauges and provides guidance on deployment and operations. However, a variety of other commercial and custom-built gauges are often widely used. As the name implies, manual gauges require human effort to record water accumulation and empty the collection volume. Measurement frequency is determined by how often a person visits the site and if left unattended for too long, the gauges can either overflow or lose water through evaporation. Recording rain gauges improve upon manual gauges because they are able to log data and determine more precise timing and accumulation rate of precipitation. The most commonly used recording gauges employ one of the following mechanisms: tipping buckets, in which water is funneled into a small collection cup of a known volume that tips over once filled and triggers a pulse-counter; load-cells, in which the mass of a collection vessel is measured over time and the increase represents P; or capacitance gauges, in which the electrical capacitance of a metal rod installed in a collection vessel quantifies increases in water height. Other approaches that use optical or acoustic methods for detecting raindrops can be more accurate at quantifying small rain events and characterizing raindrop size and intensity (25, 26). For recording rain gauges, data are stored with a recording device that links P to a time of day. Early versions logged these data on paper charts, and modern dataloggers store data digitally. Depending on the spatial extent of the study area and characteristics of storm events, multiple precipitation gauges may be required. In locations where wind speed near the gauge is high, wind baffles may also be needed. Most gauges that are designed to collect liquid precipitation may include funnels or other components to limit evaporation. However, these gauges are typically not well-suited for collecting snow and ice. Because snow may be blown out of certain gauges and may sublimate over time, specialized snow gauges are often deployed where significant amounts of P are in solid form.

Where P is not measured locally, nearby weather stations associated with permanent monitoring sites or airports are often used. Additionally, several regional data products provide interpolated and/or modeled precipitation data (e.g., PRISM; https://prism.oregonstate.edu/). In agricultural systems, inputs from P may also need to be supplemented with irrigation.

Drainage (Q) from the study area can be partitioned among deep percolation below the root zone, and surface runoff, which includes overland flow as well as channel flow. Surface flow can be gauged using water stage height at a fixed point with a known channel geometry. This approach often uses experimental watersheds with weirs or flumes, or in natural basins using natural channels. United States Geological Survey (USGS) gauging stations represent perhaps the most integrated approach for continental scale streamflow monitoring for continental USA (https://dashboard.waterdata.usgs.gov/app/nwd/en/) and the US Forest Service has extensive long-term climate and streamflow data from a network of experimental forests (27). Agricultural runoff, deep percolation, and drainage can be difficult to quantify and can vary based on many characteristics, including soil type, ground cover, slope, rainfall amount and intensity, antecedent soil water condition, and engineered structures such as berms, dams, and tile drainage. The installation of streamflow gauging equipment may require substantial investments of resources; however, once operational, the approach relies on relatively simple technology to make measurements.

At some time scales, ΔS is negligible, such as if soil water storage reaches saturation or a low threshold (e.g., hygroscopic point) annually. However, ΔS can also be estimated using various types of soil water sensors or probes (e.g., neutron probe, time domain reflectometry, tensiometers), which typically measure either volumetric soil water content or matric potential (28) and can have varying levels of accuracy (29). Sensors can typically be installed with minimal disturbance to plants and soil. However, soil moisture sensors provide an estimate of soil water for a volume that extends several centimeters from the probe. The soil water content estimates from each sensor represent only a single point in space, so in heterogeneous soil media or at scales from meters to hectares, the total soil water content will be inferred from a small subsample of the actual soil. Additionally, soil water balance may not be well constrained in areas where ground or surface water is influenced by lateral inputs and outputs. In wetlands or areas with shallow ground water table, ET can be estimated by the diurnal change of the water table by the water balance Equation 34.1 (30).

34.2.2 ET chambers

Chamber-based methods for estimating ET involve enclosing a control volume, typically over a vegetated or water surface, and monitoring changes in water vapor concentration. Chambers can vary in size and complexity, depending on the spatial scale of interest and the level of control over covariates. The smallest chambers enclose a surface area on the order of centimeters to measure portions of individual leaves to tens of centimeters, capable of laboratory or *in situ* measurements of bare soil or short vegetation. These small chambers may be a part of a portable hand-held system or a semi-permanent, field-deployed automated system. Larger chambers may cover a surface area up to tens of meters and enclose a whole tree or mesocosm experiment.

Chamber systems can be roughly categorized as closed, open-top, and flow-through. Closed chambers do not allow gas exchange with the surrounding atmosphere to occur during active sampling. Thus, after accounting for temperature and pressure effects, increases in water vapor concentration are driven by ET. Chamber-based approaches may also include enclosing a soil volume to quantify water fluxes through the system. Because of the closed volume, ET will increase relative humidity and can cause feedback on subsequent ET. Therefore, closed chambers need to be periodically vented. Chambers are typically designed to allow for light to enter and maintain conditions similar to the ambient environment (31); however, proper temperature control is required to avoid artificially affecting vapor pressure deficit. For these reasons, closed chambers are typically sampled for relatively short periods at a time, on the order of several minutes, and then removed.

Open-top chambers control lateral air exchange, but allow for a limited vertical exchange of air. This approach is useful for longer-term and larger-scale experiments because it allows for better regulation of temperature and gas concentrations, as well as incoming precipitation. To quantify ET, the chamber may require modifying the chamber top to funnel gas exchange for measurements (32).

In the past ten years, a flow-through chamber method that directly measures the isotope end members of ET has been developed (33). This method is based on the basic gas exchange principles and benefits from high-frequency laser spectroscopy. This method allows continuous monitoring of both gas exchange and isotopic composition of the exchange over time. The chamber is closed but not completely sealed and allows ambient-chamber gas exchange. The advantages of the flow-through chamber method include providing a method for estimating isotope end members of ET without using complex isotope models, and no need to completely seal a chamber. The flow-through chamber method has been successfully applied to forest ecosystems (34), grassland ecosystems (35), and agricultural ecosystems (24).

If closed chambers are operated periodically for short periods, they can leave the measurement area undisturbed for most of the time and have limited effects on the underlying biophysical processes. On the other hand, open-top chambers may introduce some local decoupling from the environment but may be more suitable for applications requiring continuous, long-term measurements. The effect of the chamber on the response of ET is a caveat for this approach; however, because chambers also allow for manipulation of key drivers of ET (among other biophysical processes), it is also an advantage.

34.2.3 Weighing lysimeters

A lysimeter is defined as “a device for measuring the percolation of water through soils and for determining the soluble constituents removed in drainage” (36). For applications for quantifying ET, weighing lysimeters typically consist of a soil volume enclosed within a chamber or a tank, which allows for measurements of inputs and outputs of water (see Equation 34.1), as well as the change in the mass of the total volume. The lysimeter is typically open to the atmosphere and may contain vegetation to represent a larger soil-plant-atmosphere microcosm. As such, lysimeters can range in size from tens of square centimeters to several square meters and may be installed in a greenhouse or outdoor settings. Inputs of precipitation and irrigation can be measured using standard methods (e.g., rain gauges, flow meters) and drainage output can be measured by collecting water that percolates through the bottom of the chamber. For small, greenhouse-based experiments, weight may be measured using an electronic balance, whereas a larger-scale, field-based experiment may require specialized scales and infrastructure. The difference in inputs and drainage represents a change in soil water balance attributed to ET.

Weighing lysimeters are among the most direct methods for quantifying changes in soil water balance over time. Caution must be made to account for changes in mass over time other than water, such as carbon accumulation or loss. The relatively limited spatial scale can be beneficial for focused studies on small vegetation or individual plants, as well as controlled experimental treatments (e.g., water limitations, fertilization, temperature). However, the small size of lysimeters limits the ability to extrapolate over larger scales. Additionally, establishing a soil sample volume often requires soil disturbance and may limit the rooting depth of vegetation. Large soil monoliths can be extracted using heavy machinery to force chamber sides into the existing soil, followed by undercutting the soil to confine the lower boundary of the control volume. Such an approach can be costly and difficult if the soil has high rock content, steep topography, or large vegetation.

34.2.4 Interception and throughfall estimates

Canopy interception can return half of the precipitation as evaporation and is an important process of precipitation redistribution affecting soil water content and other fluxes (37). Interception evaporation can be inferred as the difference between precipitation and throughfall, measured with precipitation collectors beneath the vegetated canopy. Because throughfall can be highly spatially variable, ranging from near zero where the ground is blocked by vegetation to greater than total precipitation where rain is funneled to a specific point, careful consideration of the number and positioning of throughfall collectors is required. Water intercepted by the canopy may also reach the soil not as throughfall, but channeled down the plant's structure as stemflow. Stemflow can be quantified by channeling water running down the trunk of larger vegetation with flexible gutters or tubing into an automated or manual collection gauge (38). Although stemflow may only account for a small percentage of total precipitation, it can be a significant component of the hydrologic budget and supplies water directly to the base of vegetation where it is in close proximity for uptake by roots. Other methods for interception evaporation, such as leaf wetness sensors, or measurements of tree compression due to intercepted water (39) can provide more direct approaches for quantifying temporal variability but require deploying and calibrating specialized instrumentation and upscaling to the ecosystem.

34.2.5 Leaf gas exchange and sap flow

Independent estimates of transpiration from plants can be scaled up from leaf-level measurements using gas exchange systems or from stem-level measurements of sap flow.

Leaf-level transpiration can be upscaled from leaf gas exchange measurements. Gas exchange chambers can allow the user to control for leaf-level light, temperature, relative humidity, and CO_2 concentration; however, extrapolating these measurements to predict transpiration during different times of the day or the year assumes that aspects of leaf physiology, such as stomatal sensitivity or photosynthetic efficiency, are constant, and it may neglect how changes in soil water availability affect transpiration. Additionally, scaling from a small gas exchange cuvette to a canopy requires not only an accurate estimate of leaf area but also accounting for differences in sun- and shade-leaves.

Transpiration can also be estimated using sap flow methods. Sap flow methods involve small sensors installed within the tree's xylem or on the surface of a stem or branch. While multiple types of sensors can be used, the common principle involves measuring how water moving through the plant's xylem affects energy transfer from a heated probe (in this section, "probe" refers to an individual component installed in plant tissue and "sensor" refers to the integrated set of probes and wiring). Sap flow sensors can provide sub-hourly estimates of water movement through a plant's xylem, which can help quantify transpiration and identify the sensitivity of plant water uptake to environmental drivers. Sensors will measure temperature or power consumption, which can be stored on an electronic datalogger. Conversion of raw data to either a flow velocity or flux requires equations derived from thermodynamics and/or empirical relationships.

The most commonly used method is thermal dissipation (TD) (11), which consists of two small, cylindrical probes installed radially into the xylem. The difference in temperature between a downstream, continuously heated probe and an upstream unheated reference probe will reach a maximum equilibrium when sap is not moving, but this temperature decreases as flowing sap conducts heat away from the heated probe. Temperature differences are converted into sap flux density (g H_2O m^{-2} sapwood area s^{-1}, or equivalent units) using empirically derived relationships. TD sensors can be built inexpensively, which is advantageous for deploying a large number of probes with a limited budget. The constant heating requires more electrical power than some other methods, and the two-probe design cannot differentiate between normal (upward) and reverse (downward) flow. Granier's ((11)) original calibration coefficients are commonly used for a variety of tree species; however, species-specific coefficients may be required. The heat pulse (HP) method also uses small cylindrical probes, employing one heated probe that supplies a short pulse of heat to the xylem and a nearby set of probes that measure temperature. After accounting for the effect of heat conduction, which will be the dominant force when there is no flow, the probes can detect temperature changes driven by convection. A variation on the HP method is the heat ratio (HR) method that compares the ratio of upstream to downstream temperatures affected by heating (12). For the heat pulse family of methods, parameters such as wood density and tree water content are typically required to estimate sap flow velocity (m s^{-1}, or equivalent units) from measured temperatures. Compared to TD sensors, HP and HR sensors have lower power requirements and are able to detect flow direction; however, measurements are more sensitive to the spacing between individual probes. The heat deformation (HD) method characterizes changes in the shape of the heat field around a constantly heated probe (40). HD sensors typically require several probes to measure the temperature around a central heating probe. The heat balance (HB) (41) method uses a flexible heating element wrapped around a stem or branch and a series of thermocouples installed along the plant surface measuring temperature at different distances from the heating element. HB sensors are less intrusive than other methods because they do not require probes installed into the xylem and are the only method described here that estimates water movement across the entire cross-section of a stem or branch segment—all other approaches quantify flow just through the xylem around the probes. However, the HB sensor sleeve must encircle the plant and requires insulation materials to reduce the influence of external heat and this setup may damage plants if installed for long periods of time as well as limit the maximum diameter of plants that can be measured. HB typically requires constant power. Detailed descriptions of sensor principles and performance are published in several reviews (13, 42).

Most sap flow sensors (with the exception of HB sensors) provide estimates of water movement at one point with the xylem, so scaling to whole-plant or whole-ecosystem transpiration requires accounting for (1) axial and radial variability within a single plant, (2) intra-specific variability among individuals within a given area, and (3) inter-specific variability among the vegetation community.

34.2.6 Eddy covariance and micromet flux approaches

Eddy covariance methods utilize high-frequency measurements of wind velocity, water vapor concentration, and components of the energy budget to estimate the ET. For terrestrial applications, instruments are mounted on a tower, typically extending to about 1.5 times canopy height, and the processed data represent total ET fluxes from an upwind area that varies in size depending on horizontal wind velocity. Several comprehensive books have been published detailing theoretical and practical aspects of this methodology (15–17), but we provide a brief synopsis below.

Eddy covariance theory calculates the vertical flux of a gas concentration (*F*) as the mean product of dry air density (ρ_d), vertical wind speed (*w*), and dry mole fraction of a gas in air (*s*):

$$F = \overline{\rho_d w s} \qquad (34.2).$$

However, this equation can be simplified through Reynolds expansion and elimination of terms where the averaged deviation from the mean is zero and with the assumptions that short-term changes in air density are negligible and mean vertical flow is negligible for homogenous terrain, such that

$$F \approx \overline{\rho_d}\,\overline{w's'} \qquad (34.3).$$

The equation is modified when calculating the flux of water vapor as latent heat flux (LE), substituting gas concentration for water vapor pressure (e), and accounting for the latent heat of vaporization (λ), atmospheric pressure (p), and the molar masses of water and air (M_w and M_a):

This method requires sufficient vertical turbulence to estimate reliable fluxes, so although it makes continuous measurements, data are excluded under certain conditions. The theoretical underpinning of this approach assumes a uniform canopy height on flat terrain, so it is ideally suited for agricultural systems and plantation forests. However, the method can be applied in systems with complex canopy structures and topography, with appropriate consideration of how these factors affect air movement (43*,* 44).

Eddy covariance integrates total ET from the spatial area upwind of the sensor. This "footprint" can range from tens to hundreds of square meters and depends on the instrument height (taller towers have larger footprints) and the mean horizontal wind velocity. Because the size and orientation of the footprint are temporally variable, it can create some challenges for data interpretation if the surrounding ecosystem is highly spatially variable; however, this can also be leveraged as an opportunity to contrast patches with a single set of instruments.

Early implementation of eddy covariance methods began in the 1970s and progressed using a small number of custom-built systems through the 1980s (17). Subsequent advances in commercially manufactured equipment and standardized data-processing approaches have helped to expand the use of this method to a wider group of ecohydrologists. Additionally, regional and global networks for disseminating eddy covariance data have provided an important link between site-level studies and integrated multi-site syntheses and modeling studies (14*,* 45).

Eddy covariance systems can be deployed beneath the vegetated canopy to capture the understory or subcanopy ET, which includes transpiration from short vegetation along with soil surface evaporation (46, 47). In this latter case, quantifying understory transpiration using sap flow or gas exchange measurements may be prohibitively difficult, due to factors such as highly diverse herbaceous species composition or plant size limitations on sap flow methods.

The costs of instrumentation are still relatively high. These costs can be dramatically increased in ecosystems with tall canopies, because of the tower infrastructure required to install sensors. However, once installed, the systems can run continuously for multiple years with only minor, periodic maintenance. Because ET is typically calculated at half-hourly intervals, this approach provides a temporal resolution that captures sub-daily changes in ET.

In addition to cost considerations, other limitations for the use of these systems include a reliable power supply (e.g., solar panels and backup batteries or AC connection), protection from severe storms, protection from vandalism, and other safety considerations. Because some of the sensors in an eddy covariance system may not function correctly when wet, this approach may underestimate ET, particularly the evaporation of precipitation intercepted by the canopy.

34.3 Modeling approaches

As with other fluxes that are difficult to directly measure, estimates of ET are often derived from models, which can range in theoretical basis, complexity, and data input requirements. Because the process of ET is understood and explained by first principles, modeling provides a theoretically sound approach. The distinction between field measurements and modeling approaches may be blurry because neither actually measures ET, but both use data to derive an estimate of ET. For practical purposes, the previously described field methods tend to focus on attempting to follow the movement of liquid and vapor water through the ecosystem, whereas the models described below use standard meteorological and vegetation data to derive ET.

34.3.1 Penman-Monteith

Among the most commonly used is the Penman-Monteith (1965) equation, which estimates ET based on surface and aerodynamic resistances to water vapor flow. The inputs include many variables commonly measured at climate stations, including net radiation, air temperature, relative humidity, and wind speed. However, the incorporation of surface resistance by vegetation can introduce uncertainty and may incorporate simplifying assumptions about canopy physical characteristics (e.g., roughness and heterogeneity) and plant ecohydrological factors (e.g., leaf characteristics and stomatal behavior). A reference ET (ET_{ref}) is a useful concept to simplify these plant characteristics, which provides a benchmark for the environmental demand of ET. The Penman-Monteith model is recommended by the Food and Agriculture Organization (FAO) of the United Nations as the sole method for determining ET_{ref} (7) with the stipulation that "The reference surface closely resembles an extensive surface of green grass of uniform height, actively growing, completely shading the ground and with adequate water." The ET_{ref} methodology based on Penman-Monteith was later standardized to consider either short or tall (i.e., grass or alfalfa) reference surfaces, and are represented by the abbreviations ET_o and ET_r, respectively.

The ET_{ref} and crop coefficient approach (7) is a useful method to determine the crop or landscape ET, by considering both the environmental demand represented by ET_{ref} and the plant characteristics represented by a crop coefficient (K_c). The crop coefficient is multiplied by ET_{ref} to represent the actual ET (ET_a). In more detailed versions of this method, the K_c can be expanded into $K_c = K_{cb} \times K_s + K_e$, where K_{cb} represents a basal coefficient that represents transpiration, K_s is a transpiration reduction coefficient that represents water stress, and K_e is an evaporation coefficient that represents soil surface evaporation following wetting events. Details of these methodologies and their nuances are discussed in several useful references (7, 36, 48). Liu et al. (49) provide "crop coefficient" values for non-crop land covers by analyzing global flux data.

Many agricultural water balance and crop models use leaf area index (LAI) or fractional canopy cover (fc) as a basis for estimating light interception, and subsequently partitioning ET. The standardized ET_{ref} and dual crop coefficient method (7, 36) partitions crop coefficients based on their contribution to transpiration (K_{cb}) and evaporation (K_e), with more accurate results than generalized crop coefficients (K_c).

34.3.2 Priestley-Taylor

Priestley and Taylor (50) developed a simplified version of the Penman-Monteith approach utilizing only radiation observations. The Priestley-Taylor equation is expressed as

$$ET = \alpha \frac{\Delta}{\Delta + \gamma}\left(R_n - G\right) \tag{34.4}$$

where Δ is the derivative of the saturated vapor pressure (es) with respect to air temperature, γ is the psychometric constant, R_n is net radiation and G is ground heat flux. The so-called Priestley-Taylor parameter (α) is typically around 1.2–1.3 under water unstressed conditions (2). But, it can be much smaller for humid forest conditions (51). This method has been used to derive satellite-based ET estimates (e.g., ECOSTRESS ET).

34.3.3 Empirical ET models

In lieu of detailed meteorological variables or biophysical parameters, such as stomatal conductance, to apply physically based models, such as the Penman-Monteith model, various empirical ET models are derived from direct ET measurements at the ecosystem scale (49). These models may be best used as a first-order approximation under mean climatic conditions. For example, the following model was derived from 13 sites in North America and Asia (52). The model estimates monthly ET for any land cover types as a function of LAI, ET_o (mm mo^{-1}), and precipitation (mm mo^{-1}).

$$ET = 11.94 + 4.76LAI + ET_o(0.032LAI + 0.0026P + 0.15) \tag{34.5}$$

where ET_o is the FAO56 grass reference ET as discussed above.

Similarly, Fang et al. (53) provide a series of empirical monthly ET models through analyzing a FLUXNET dataset with over 250 sites. These empirical ET formulas offer a convenient way to estimate ET by land cover type with limited data.

34.4 Future directions

The methods described in this chapter provide a current snapshot of the most common methods for quantifying ET. As noted, each has limitations, but as theoretical and technological advances are made, we anticipate that many of these approaches will become more accurate, easier to use, and more affordable. We also refer readers to Chapter 44 on remote sensing, which provides information relevant to spatial scaling.

Because there is no perfect method for quantifying ET, best practices include multi-approach syntheses, where a set of independent methods are used (3). Such syntheses can advance our understanding of the complete hydrologic budget and can help to identify water fluxes that may not be observed if using one or two approaches. One of the key challenges for both eddy covariance and remote sensing data is partitioning the estimates of ET into its components (evaporation, transpiration, and interception). This is an area where many of the field-based methods described here can help to resolve some of this uncertainty.

Thus, many recent studies combine measurements that capture processes on different scales, such as pairing eddy covariance with sap flow and evaporation measurements, or leveraging data from eddy covariance networks with remote sensing products and small watershed water balance monitoring. To the end, maintaining and expanding existing networks of open data will be critical.

One key challenge for quantifying ET is scaling from an intensively measured plot to the broader landscape level. Many regions around the world are data-scarce, and we lack the field data to validate models. Data limitations may range from basic meteorological data, information on vegetation composition and structure, to field-based estimates of ET. Data-scarce regions include Africa, South America, and parts of Asia. Even in regions with abundant active ecohydrological research, we still lack information on complex terrain and wetlands.

We also acknowledge that current measurement and modeling approaches can be effective in quantifying current fluxes and identifying key drivers, but additional research is required to determine how well existing models can predict ET under future conditions.

References

1 G. G. Katul, R. Oren, S. Manzoni, C. Higgins, M. B. Parlange, Evapotranspiration: A process driving mass transport and energy exchange in the soil-plant-atmosphere-climate system. *Reviews of Geophysics* **50**, RG3002 (2012).

2 K. Wang, R. E. Dickinson, A review of global terrestrial evapotranspiration: Observation, modeling, climatology, and climatic variability. *Review in Geophysics* **50**, RG2005 (2012).

3 K. Yi, G. B. Senay, J. B. Fisher, L. Wang, K. Suvočarev, H. Chu, G. W. Moore, K. A. Novick, M. L. Barnes, T. F. Keenan, K. Mallick, X. Luo, J. E. C. Missik, K. B. Delwiche, J. A. Nelson, S. P. Good, X. Xiao, S. A. Kannenberg, A. Ahmadi, T. Wang, G. Bohrer, M. E. Litvak, D. E. Reed, A. C. Oishi, M. S. Torn, D. Baldocchi, Challenges and future directions in quantifying terrestrial evapotranspiration. *Water Resources Research* **60**, e2024WR037622 (2024).

4 J. R. Gat, Oxygen and hydrogen isotopes in the hydrologic cycle. *Annual Review of Earth and Planetary Sciences* **24**, 225–262 (1996).

5 L. Wang, K. K. Caylor, J. C. Villegas, G. A. Barron-Gafford, D. D. Breshears, T. E. Huxman, Partitioning evapotranspiration across gradients of woody plant cover: Assessment of a stable isotope technique. *Geophysical Research Letters* **37**, L09401 (2010).

6 A. Ukkola, I. Prentice, A worldwide analysis of trends in water-balance evapotranspiration. *Hydrology and Earth System Sciences* **17**, 4177–4187 (2013).

7 R. G. Allen, L. S. Pereira, D. Raes, M. Smith, Crop evapotranspiration-Guidelines for computing crop water requirements-FAO Irrigation and drainage paper 56. *Fao, Rome* **300**, D05109 (1998).

8 R. G. Allen, M. E. Jensen, ASCE Manual 70 – Second Edition: Evaporation, Evapotranspiration and Irrigation Requirements. In ASCE Manuals and Reports on Engineering Practice No. 70. (American Society of Civil Engineers, 2016).

9 B. W. Olbrich, The verification of the heat pulse velocity technique for estimating sap flow in Eucalyptus grandis. *Canadian Journal of Forest Research* **21**, 836–841 (1991).

10 J. Müller, A. Bolte, The use of lysimeters in forest hydrology research in north-east Germany. *Landbauforschung (vTI Agric. For. Res.)* **59**, 1–10 (2009).

11 A. Granier, Evaluation of transpiration in a Douglas-fir stand by means of sap flow measurements. *Tree Physiology* **3**, 309–320 (1987).

12 S. S. Burgess, M.A. Adams, N.C. Turner, C.R. Beverly, C.K. Ong, A.A.H. Khan, T.M. Bleby, An improved heat pulse method to measure low and reverse rates of sap flow in woody plants. *Tree Physiology* **21**, 589–598 (2001).
13 V. Flo, J. Martinez-Vilalta, K. Steppe, B. Schuldt, R. Poyatos, A synthesis of bias and uncertainty in sap flow methods. *Agricultural and Forest Meteorology* **271**, 362–374 (2019).
14 D. Baldocchi, E. Falge, L. Gu, R. Olson, D. Hollinger, S. Running, P. Anthoni, Ch. Bernhofer, K. Davis, R. Evans, J. Fuentes, A. Goldstein, G. Katul, B. Law, X. Lee, Y. Malhi, T. Meyers, W. Munger, W. Oechel, K. T. Paw U, K. Pilegaard, H. P. Schmid, R. Valentini, S. Verma, T. Vesala, K. Wilson, S. Wofsy, FLUXNET: A new tool to study the temporal and spatial variability of ecosystem‚ÄìScale carbon dioxide, water vapor, and energy flux densities. *Bulletin of the American Meteorological Society* **82**, 2415–2434 (2001).
15 M. Aubinet, T. Vesala, D. Papale, *Eddy covariance: A practical guide to measurement and data analysis*. (Springer, 2012).
16 G. Burba, *Eddy covariance method for scientific, regulatory, and commercial applications*. (LI-COR Biosciences, 2022).
17 M. Mauder, T. Foken, M. Aubinet, A. Ibrom, in *Springer handbook of atmospheric measurements*. (Springer, 2021), pp. 1473–1504.
18 R. Vogt, L. Jaeger, Evaporation from a pine forest-using the aerodynamic method and Bowen ratio method. *Agricultural and Forest Meteorology* **50**, 39–54 (1990).
19 M. Fischer, G. Katul, A. Noormets, G. Pozníková, J. C. Domec, M. Orság, Z. Žalud, M. Trnka, J. S. King, Merging flux-variance with surface renewal methods in the roughness sublayer and the atmospheric surface layer. *Agricultural and Forest Meteorology* **342**, 109692 (2023).
20 J. B. Fisher, B. Lee, A. J. Purdy, G. H. Halverson, M. B. Dohlen, K. Cawse-Nicholson, A. Wang, R. G. Anderson, B. Aragon, M. A. Arain, D. D. Baldocchi, J. M. Baker, H. Barral, C. J. Bernacchi, C. Bernhofer, S. C. Biraud, G. Bohrer, N. Brunsell, B. Cappelaere, S. Castro-Contreras, J. Chun, B. J. Conrad, E. Cremonese, J. Demarty, A. R. Desai, A. De Ligne, L. Foltýnová, M. L. Goulden, T. J. Griffis, T. Grünwald, M. S. Johnson, M. Kang, D. Kelbe, N. Kowalska, J.-H. Lim, I. Maïnassara, M. F. McCabe, J. E.C. Missik, B. P. Mohanty, C. E. Moore, L. Morillas, R. Morrison, J. W. Munger, G. Posse, A. D. Richardson, E. S. Russell, Y. Ryu, A. Sanchez-Azofeifa, M. Schmidt, E. Schwartz, I. Sharp, L. Šigut, Y. Tang, G. Hulley, M. Anderson, C. Hain, A. French, E. Wood, S. Hook, ECOSTRESS: NASA's next generation mission to measure evapotranspiration from the International Space Station. *Water Resources Research* **56**, e2019WR026058 (2020).
21 F. S. Melton, J. Huntington, R. Grimm, J. Herring, M. Hall, D. Rollison, T. Erickson, R. Allen, M. Anderson, J. B. Fisher, A. Kilic, G. B. Senay, J. Volk, C. Hain, L. Johnson, A. Ruhoff, P. Blankenau, M. Bromley, W. Carrara, B. Daudert, C. Doherty, C. Dunkerly, M. Friedrichs, A. Guzman, G. Halverson, J. Hansen, J. Harding, Y. Kang, D. Ketchum, B. Minor, C. Morton, S. Ortega-Salazar, T. Ott, M. Ozdogan, P. M. ReVelle, M. Schull, C. Wang, Y. Yang, R. G. Anderson, OpenET: Filling a critical data gap in water management for the western United States. *JAWRA Journal of the American Water Resources Association* **58**, 971–994 (2022).
22 T. McMahon, M. Peel, J. Szilagyi, Comment on the application of the Szilagyi–Jozsa advection–aridity model for estimating actual terrestrial evapotranspiration in" Estimating actual, potential, reference crop and pan evaporation using standard meteorological data: A pragmatic synthesis" by McMahon et al. (2013). *Hydrology and Earth System Sciences* **17**, 4865–4867 (2013).
23 S. P. Good, D. Noone, G. Bowen, Hydrologic connectivity constrains partitioning of global terrestrial water fluxes. *Science* **349**, 175–177 (2015).
24 X. Lu, L. L. Liang, L. Wang, G. D. Jenerette, M. F. McCabe, D. A. Grantz, Partitioning of evapotranspiration using a stable isotope technique in an arid and high temperature agricultural production system. *Agricultural Water Management* **179**, 103–109, (2017).
25 X. Liu, T. Gao, L. Liu, A comparison of rainfall measurements from multiple instruments. *Atmospheric Measurement Techniques* **6**, 1585–1595 (2013).
26 J. A. Nystuen, J. R. Proni, P. G. Black, J. C. Wilkerson, A comparison of automatic rain gauges. *Journal of Atmospheric and Oceanic Technology* **13**, 62–73 (1996).
27 D. Neary, D. Hayes, L. Rustad, J. Vose, G. Gottfried, S. Sebesteyn, S. Johnson, US Forest Service Experimental Forests and Ranges Network: A continental research platform for catchment-scale research. *Revisiting Experimental Catchment Studies in Forest Hydrology* **353**, 49–57 (2012).
28 R. Muñoz-Carpena, Field devices for monitoring soil water content: BUL343/AE266, 7/2004. *Edis* **2004**, (2004).

29 B. G. Leib, J. D. Jabro, G. R. Matthews, Field evaluation and performance comparison of soil moisture sensors. *Soil Science* **168**, 396–408 (2003).

30 M. L. Carlson Mazur, M. J. Wiley, D. A. Wilcox, Estimating evapotranspiration and groundwater flow from water-table fluctuations for a general wetland scenario. *Ecohydrology* **7**, 378–390 (2014).

31 D. C. Reicosky, D. B. Peters, A portable chamber for rapid evapotranspiration measurements on field plots. *Agronomy journal* **69,** 729–732 (1977).

32 P. W. Leadley, B. G. Drake, Open top chambers for exposing plant canopies to elevated CO2 concentration and for measuring net gas exchange. *Vegetatio* **104**, 3–15 (1993).

33 L. Wang, S. P. Good, K. K. Caylor, L. A. Cernusak, Direct quantification of leaf transpiration isotopic composition. *Agricultural and Forest Meteorology* **154–155**, 127–135 (2012).

34 M. Lanning, L. Wang, M. Benson, Q. Zhang, K. A. Novick, Canopy isotopic investigation reveals different water uptake dynamics of maples and oaks. *Phytochemistry* **175**, 112389 (2020).

35 J. Cui, L. Tian, Z. Wei, C. Huntingford, P. Wang, Z. Cai, N. Ma, L. Wang, Quantifying the controls on evapotranspiration partitioning in the highest alpine meadow ecosystem. *Water Resources Research* **56**, e2019WR024815 (2020).

36 S. R. Evett, T. A. Howell, Sr., A. D. Schneider, K. S. Copeland, D. A. Dusek, D. K. Brauer, J. A. Tolk, G. W. Marek, T. M. Marek, P. H. Gowda, The Bushland weighing lysimeters: A quarter century of crop ET investigations to advance sustainable irrigation. *Transactions of the ASABE* **59**, 163–179 (2016).

37 A. I. J. M. van Dijk, J. H. Gash, E. van Gorsel, P. D. Blanken, A. Cescatti, C. Emmel, B. Gielen, I. N. Harman, G. Kiely, L. Merbold, L. Montagnani, E. Moors, M. Sottocornola, A. Varlagin, C. A. Williams, G. Wohlfahrt, Rainfall interception and the coupled surface water and energy balance. *Agricultural and Forest Meteorology* **214**, 402–415 (2015).

38 Y. C. Tsai, L. Wang, C. P. Wang, T. C. Lin, Distinct epiphyte responses to drought in tropical mountain cloud forests. *Ecohydrology* **16**, e2569 (2023).

39 J. Friesen, C. Van Beek, J. Selker, H. Savenije, N. Van de Giesen, Tree rainfall interception measured by stem compression. *Water Resources Research* **44**, W00D15 (2008).

40 N. Nadezhdina, Revisiting the Heat Field Deformation (HFD) method for measuring sap flow. *iForest-Biogeosciences and Forestry* **11**, 118 (2018).

41 D. M. Smith, S. J. Allen, Measurement of sap flow in plant stems. *Journal of Experimental Botany* **47**, 1833–1844 (1996).

42 M. W. Vandegehuchte, K. Steppe, Corrigendum to: Sap-flux density measurement methods: Working principles and applicability. *Functional Plant Biology* **40**, 1088–1088 (2013).

43 D. Baldocchi, J. Finnigan, K. Wilson, K. Paw U, E. Falge, On measuring net ecosystem carbon exchange over tall vegetation on complex terrain. *Boundary-Layer Meteorology* **96**, 257–291 (2000).

44 C. Rebmann, M. Göckede, T. Foken, M. Aubinet, M. Aurela, P. Berbigier, C. Bernhofer, N. Buchmann, A. Carrara, A. Cescatti, R. Ceulemans, R. Clement, J. A. Elbers, A. Granier, T. Grünwald, D. Guyon, K. Havránková, B. Heinesch, A. Knohl, T. Laurila, B. Longdoz, B. Marcolla, T. Markkanen, F. Miglietta, J. Moncrieff, L. Montagnani, E. Moors, M. Nardino, J.-M. Ourcival, S. Rambal, Ü. Rannik, E. Rotenberg, P. Sedlak, G. Unterhuber, T. Vesala, D. Yakir, Quality analysis applied on eddy covariance measurements at complex forest sites using footprint modelling. *Theoretical and Applied Climatology* **80**, 121–141 (2005).

45 K. A. Novick, J. A. Biederman, A. R. Desai, M. E. Litvak, D. J. P. Moore, R. L. Scott, M. S. Torn, The AmeriFlux network: A coalition of the willing. *Agricultural and Forest Meteorology* **249**, 444–456 (2018).

46 R. L. Scott, C. Watts, J. Garatuza Payan, E. Edwards, D. C Goodrich, D. Williams, W. J. Shuttleworth, The understory and overstory partitioning of energy and water fluxes in an open canopy, semiarid woodland. *Agricultural and Forest Meteorology*. (2003), vol. 114, pp. 127–139.

47 S. Wolf, E. Paul-Limoges, D. Sayler, J. W. Kirchner, Dynamics of evapotranspiration from concurrent above-and below-canopy flux measurements in a montane Sierra Nevada forest. *Agricultural and Forest Meteorology* **346**, 109864 (2024).

48 K.C. DeJonge, R.G. Allen, A. Kilic, K.R. Thorp, M. Kukal, G.W. Marek, J. Altenhofen, D. Amatya, P. Blankenau, S. Datta, G. Grabow, A. Hashem, I. Kisekka, J. Kjaersgaard, T. Marek, T. Peters, D. Porter, M. Reba, D. Rudnick, G. Senay, V. Sharma, V. Sridhar, G. Sun, S. Taghvaeian, R. Trezza, T. Trout, Evapotranspiration terminology and definitions. *Irrigation and Drainage Engineering* **15**, (2025).

49 C. Liu, G. Sun, S. G. McNulty, A. Noormets, Y. Fang, Environmental controls on seasonal ecosystem evapotranspiration/potential evapotranspiration ratio as determined by the global eddy flux measurements. *Hydrol. Earth Syst. Sci.* **21**, 311–322 (2017).

50 C. H. B. Priestley, R. J. Taylor, On the assessment of surface heat flux and evaporation using large-scale parameters. *Monthly weather review* **100**, 81–92 (1972).
51 L. Rao, G. Sun, C. Ford, J. Vose, Modeling potential evapotranspiration of two forested watersheds in the southern Appalachians. *Transactions of the ASABE* **54**, 2067–2078 (2011).
52 G. Sun, K. Alstad, J. Chen, S. Chen, C.R. Ford, G. Lin, C. Liu, N. Lu, S.G. McNulty, H. Miao, A. Noormets, A general predictive model for estimating monthly ecosystem evapotranspiration. *Ecohydrology* **4**, 245–255 (2011).
53 Y. Fang, G. Sun, P. Caldwell, S.G. McNulty, A. Noormets, J.C. Domec, J. King, Z. Zhang, X. Zhang, G. Lin, G. Zhou, Monthly land cover-specific evapotranspiration models derived from global eddy flux measurements and remote sensing data. *Ecohydrology* **9**, 248–266 (2016).