3 Forest Evapotranspiration: Processes and Quantification

G. Sun[1]*, J. -C. Domec[2,3] and D. M. Amatya[4]
[1]Eastern Forest Environmental Threat Assessment Center, USDA Forest Service, Research Triangle Park, North Carolina, USA; [2]Bordeaux Sciences Agro, Gradignan Cedex, France; [3]Nicholas School of the Environment, Duke University, Durham, North Carolina, USA; [4]Santee Experimental Forest, Southern Research Station, USDA Forest Service, Cordesville, South Carolina, USA

Abstract
Next to precipitation, evapotranspiration (ET) is the second largest flux in forest hydrological cycles. Forest ET rates are generally higher than other vegetated ecosystems under the same climatic conditions. ET serves as the nexus of the carbon, water and energy balances in forests. Understanding ET dynamics is critical for quantifying forest–water relationships and ecosystem services (e.g. carbon sequestration, climate and streamflow flow moderation, biodiversity) at multiple scales. This chapter describes the basic ET processes, which include forest canopy and litter interception, tree transpiration and soil evaporation. Finally, practical methods for measuring and modeling ET at tree, watershed and regional levels are presented to show the challenges in accurately quantifying ET under a changing environment.

3.1 Introduction

Forest evapotranspiration (ET) refers to the sum of evaporation from the soil, canopy and litter interception and plant transpiration, and is critical to understanding of effects of forest change (Bosch and Hewlett, 1982) and the energy, water and biogeochemical cycles in forests (Yi *et al*., 2024). Compared with traditional hydrology, the science of forest hydrology is rooted in understanding the 'forest influences' on microclimate and has a relatively long history of studying the effects of forest vegetation change in regulating the water cycles through ET (Sun *et al*., 2016). The importance of ET in understanding forest ecohydrological processes, quantifying ecosystem services and developing 'nature-based solutions' for climate change mitigation and adaptation has been increasingly recognized (Hao *et al*., 2023; Yang *et al*., 2023).

The linkage among energy, water and carbon balances at a forest stand level over a long time period (Fig. 3.1), in which ET plays a key role, can be described conceptually in the following interlinked formulae (Sun *et al*., 2011a):

Water balance:

$$P = ET + Q \pm \Delta S \tag{3.1}$$

where ET = litter interception + evaporation from the soil + plant transpiration.

Energy balance:

*Corresponding author: ge.sun@usda.gov

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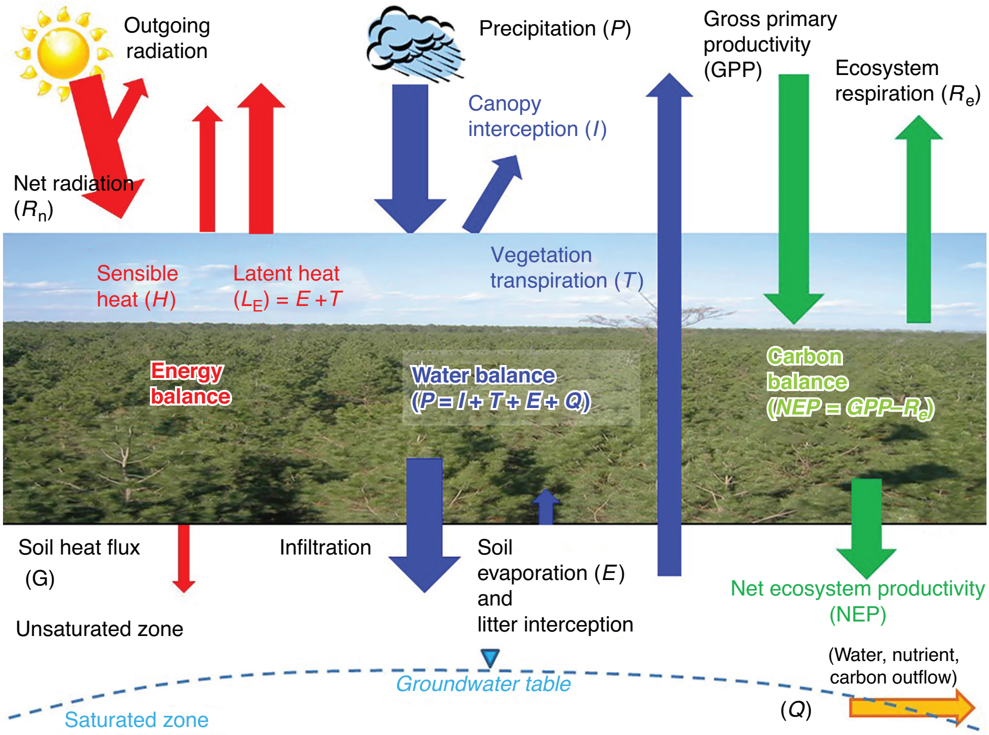

Fig. 3.1. Linkages among energy, water and carbon cycles in a forest ecosystem on the lower coastal plain of North Carolina in the USA. Note that net radiation (R_n) is a result of total incoming minus reflected shortwave radiation, along with the absorbed minus emitted longwave radiations.

$$R_n = L_E + H = ET \times L + H \quad (3.2)$$

Carbon balance:

$$EP = GPP - R_e - L_c = E \times WUE - R_e - L_c \quad (3.3)$$

In the above, *P* is precipitation (mm), *Q* is runoff (mm), *E* is given as mm or kg or m^3 of water/m^2, ΔS is change in soil water storage (mm), R_n is net radiation (W/m^2; 1 W = 1 Joule per second, J/s), L_E is latent heat (W/m^2) representing the energy needed to evaporate the amount of water, assuming a constant conversion factor called latent heat of vaporization of water (L = 2.256 × 10^6 J/kg H_2O) and *H* is sensible heat (W/m^2) representing the loss of energy to heat the air within/near the forest canopies. The net ecosystem productivity (*NEP*, g carbon (C)/m^2) is the carbon balance between carbon gain by gross ecosystem productivity (i.e.plant photosynthesis) and carbon loss by ecosystem respiration (R_e, g C/m^2) and by lateral stream runoff (L_c, g C/m^2). The magnitude of both gross primary productivity (*GPP*, g C m^2) and R_e are much larger than *NEP* and L_c, and all four variables are influenced by stand soil moisture and the hydrology. ET explains most of the seasonal variability of GPP for all ecosystems (Sun *et al.*, 2011a). The ratio of GPP:ET is termed water-use efficiency (WUE) and has been used as an important variable to understand water–carbon coupling and for quantifying the trade-offs between water yield and carbon sequestration (Zhang *et al.*, 2023).

ET is a key variable linking meteorology (Baldocchi *et al.*, 2001), hydrology (Asbjornsen *et al.*, 2011; Ukkola and Prentice, 2013) and ecosystem sciences (Sun *et al.*, 2017). ET is the only variable that links hydrology and biological processes in many ecosystem models. ET is also highly linked to ecosystem productivity (Beer *et al.*, 2007) and net ecosystem exchange of CO_2 because both photosynthesis and ecosystem respiration are controlled by soil water availability (Jackson *et al.*, 2005; Sun *et al.*, 2011a). Most of the water lost through tree transpiration is used to cool leaves when air temperature increases (Taborski *et al.*, 2022), and thus the ET processes are closely linked to energy partitioning and micro- and macro-climate systems (Fig. 3.1) (Bonan, 2008) and climate change (Jackson *et al.*, 2008). Global climate change, in turn, affects the local forest water resources directly (e.g.precipitation and runoff forms and patterns) (Amatya *et al.*, 2024) or indirectly (e.g.ecosystem structure) by affecting all ET components (Duarte *et al.*, 2024). ET has long been regarded as an index to represent the available environmental water and energy resources and ecosystem productivity by bioclimatologists (Stephenson, 1998). Thus, ET has been used to explain the large regional variations in plant and animal distribution and species richness (Currie and Paquin, 1987; Currie, 1991; Stephenson, 1998; Hawkins *et al.*, 2003).

3.2 ET Processes

Both physiological (e.g.stomata control) and physical (e.g.water potential control) processes influence water movements from the plant organs of roots, xylem, and leaves to stands (Domec *et al.*, 2012a) and landscapes (i.e.watersheds). Soil evaporation can be a large part of the total ET for young plantation forests or forests with sparse canopies (Younger *et al.*, 2023). Soil evaporation is minor in closed canopy forests (Domec *et al.*, 2012b) so this chapter focuses on the processes that control canopy and litter interception and transpiration. Partitioning ET to soil evaporation, canopy interception and transpiration is important to understand the ecosystem functional response such as carbon sequestration to climate change and how plants adapt to novel soil moisture and atmospheric regimes (Wang and Dickinson, 2012; Wei *et al.*, 2017; Stoy *et al.*, 2019).

3.2.1 Canopy and litter interception

There is a long history of studying forest canopy interception in forest hydrology (Fischer *et al.*, 2023). The quantity of canopy and litter interception in forests can be a large component of the ET and water balances, depending on forest stand age (Sadeghi *et al.*, 2024), structure characteristics such as leaf area index (LAI), canopy holding capacity, and the amount of litter and litter water holding capacity (Deguchi *et al.*, 2006), as well as soil moisture. In addition, the frequency of storms and the drying and wetting cycles affect total canopy and litter interception (Lian *et al.*, 2022).

The earliest studies by Horton (1919) showed that forest interception rates are highly variable between and across species, with the spruce/fir/hemlock forest type the highest, followed by pines and then hardwoods. Helvey (1971) reported annual canopy interception of 17% for red pine (*Pinus resinosa* Ait.), 16% for ponderosa pine (*Pinus ponderosa* Dougl. ex. Laws.), 19% for eastern white pine and 28% for the spruce/fir/hemlock forest type. Summer rates of deciduous forests in the south-eastern USA ranged from 8% to 33%, with a mean of 17%, and winter rates ranged from 5% to 22%, with a mean of 12% (Helvey and Patric, 1965). Annual canopy interception rates were 18% for wetland sites, 20% for hardwood sites and a longleaf pine (*Pinus palustus* Mill.) plantation, and 23% for pine-dominated forests in the south-eastern USA (Bryant *et al.*, 2005). Interception rates vary from 10% to 35% and from 5% to 25% for unthinned and thinned loblolly pine stands, respectively (Gavazzi *et al.*, 2016). In the USA, reported annual litter interception rate values for eastern forests varied by about 2–5%, generally less than 50 mm per year (Helvey and Patric, 1965). However, litter interception may be higher than canopy interception in other forest ecosystems (Gerrits *et al.*, 2007). The mean canopy interception rates for pine forests decrease as precipitation increases at both event and longer timescale (Fig. 3.2) (Gavazzi *et al.*, 2016).

3.2.2 Transpiration

The transpiration process represents water uptake from the root zone to its loss through the leaf stomata, the tiny openings found on one or both sides of the tree leaves in the canopies

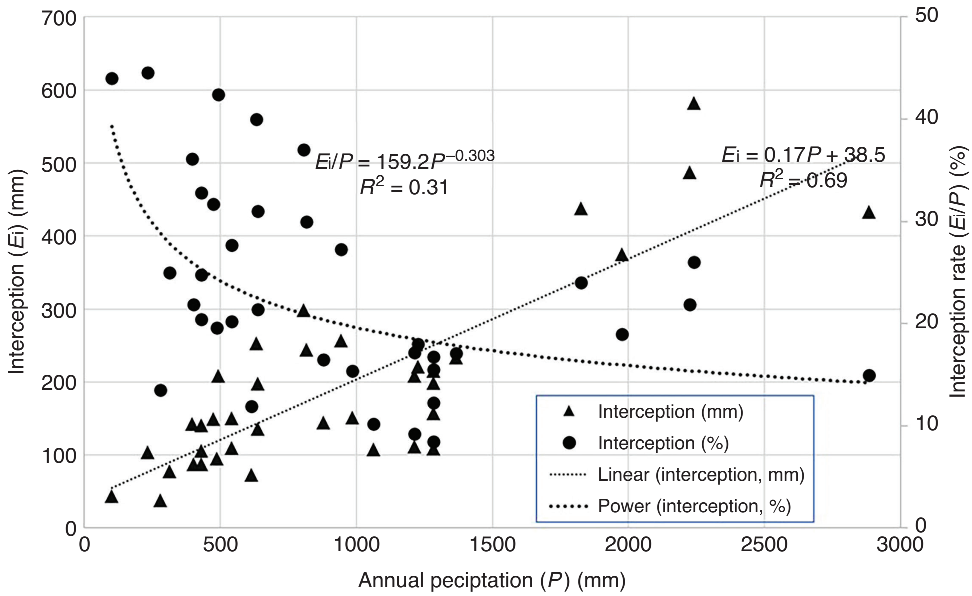

Fig. 3.2. Large variability in canopy interception rates among pine forests. In general, annual accumulative pine forest interception rates decrease with an increase in precipitation. Each dot represents one global study site.

(Canny, 1998). In most plants, transpiration is controlled largely by the vapor pressure deficit of the atmosphere and soil moisture. Because transpiration is an inevitable consequence of CO_2 assimilation by plants through photosynthesis and maintaining leaf tissue turgidity and water uptake, together with soil evaporation, transpiration represents an ecosystem water loss and thus is a 'necessary evil' (Curtis, 1926) that benefits plants from cooling leaf surfaces to nutrient transport from the root zone to the top of the canopies. In fact, less than 5% of the water taken by up roots is used to assimilate CO_2 and used for growth of the trees, with the remaining 95% returning to the atmosphere through the stomata (Steudle, 2002). A global synthesis indicated that transpiration accounts for 61 ± 15% of ET, and returns approximately 39 ± 10% of incident precipitation to the atmosphere, playing an important role in the global water cycle (Schlesinger and Jasechko, 2014), which is consistent with a study by Good *et al*. (2015) who reported that globally transpiration is 64 ± 13% (mean ± 1 standard deviation) of evapotranspiration. The transpiration:ET ratios are highest in tropical rainforests (70 ± 14%) and lowest in steppes, shrub lands and deserts (51 ± 15%). Thus, biophysical parameters such as stomatal conductance and leaf area that control transpiration have important implications for total ET (Jasechko *et al*., 2013). Therefore, changes in transpiration due to increasing CO_2 concentrations, land-use changes, shifting ecozones, air pollution, climate warming and drought may have significant impacts on ET and water balances (Schlesinger and Jasechko, 2014).

Transpiration is an active water translocation process that occurs only when water exists continuously along the soil–root–stem–branch–leaf–stomata flow pathways (Kumagai, 2011). However, transpiration rates differ tremendously among different tree species and ages (Fig. 3.3). For example, *Quercus rubra* trees with a 50 cm diameter transpire an average of 30 kg/day, but *Betula lenta* can transpire as much as 110 kg/day under the same climate in the southern Appalachians of the eastern USA (Vose *et al*., 2011). A review of 52 whole-tree water-use studies for 67 tree species worldwide

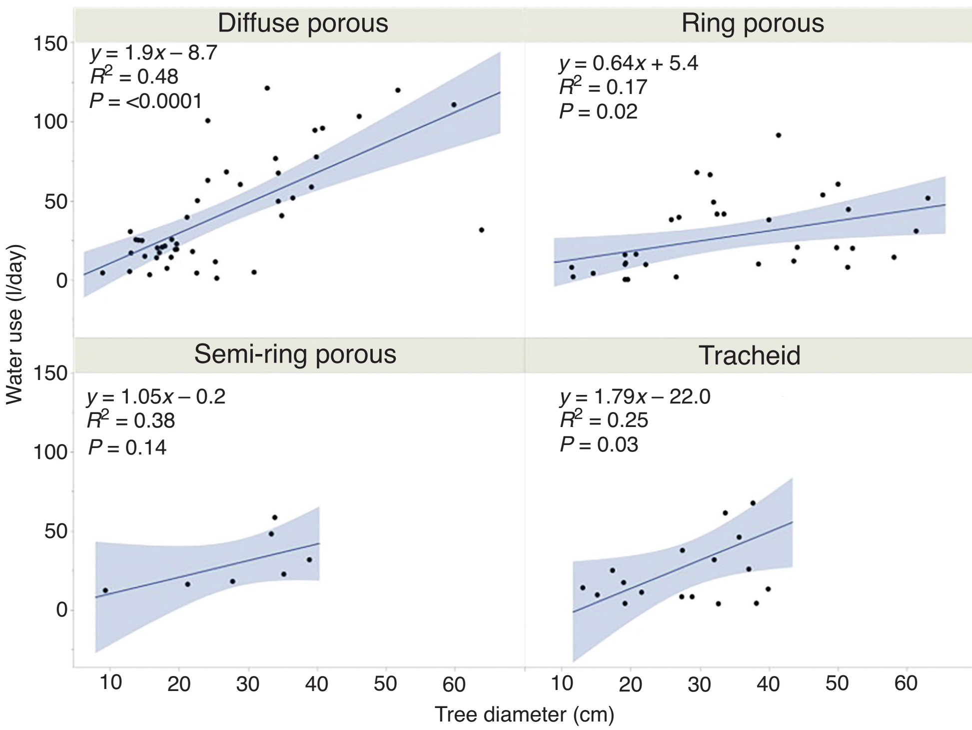

Fig. 3.3. Measured growing season daily mean sapflow rates (tree transpiration) grouped by xylem anatomy and tree diameter at breast height for major species in the USA. The shaded area depictsthe 95% confidence intervals for the trend. Diffuse porous species: red maple (*Acer rubrum*), sugar maple (*Acer saccharum*), birch (*Betula* spp.), hackberry (*Celtis laevigata*), dogwood (*Cornus florida*), American beech (*Fagus grandifolia*), European beech (*Fagus sylvatica*), sweetgum (*Liquidambar styraciflua*), tulip poplar (*Liriodendron tulipifera*), blackgum (*Nyssa sylvatica*), hop hornbeam (*Ostrya virginiana*), sycamore (*Platanus occidentalis*), American basswood (*Tilia americana*) and catalpa (*Catalpa speciosa*); ring porose species: green ash (*Fraxinus pennsylvanica*) and oak (*Quercus* spp.); semi- porous species: hickory (*Carya* spp.), aspen (*Populus* spp.) and black cherry (*Prunus serotina*); tracheid-bearing species: balsam fir (*Abies balsamea*), oneseed juniper (*Juniperus monosperma*), white spruce (*Picea glauca*), pine (*Pinus* spp.), northern white cedar (*Thuja occidentalis*) and eastern hemlock (*Tsuga canadensis*).

using different techniques concluded that maximum daily water-use rates for trees averaging 21m in height were within 10–200 kg/day (Wullschleger *et al*., 1998).

Tree transpiration rates are controlled by numerous biophysical factors such as microclimate, atmospheric CO_2 concentration, soil water potential, stand characteristics (e.g.leaf area, sapwood area, species compositions, tree density) and hydraulic transport properties of plant tissues (Table 3.1) (Domec *et al*., 2010, 2012a, b). The species composition changes over space and time due to natural regeneration or the response to climatic change or human activities such as silviculture (i.e.reforestation, afforestation). In addition, the forest ecosystem structure may change dramatically over time in both above- and belowground characteristics including leaf (i.e.leaf biomass, LAI, morphology), stem (i.e.sapwood area) (Domec *et al*., 2012a; Komatsu and Kume, 2015), and belowground factors (i.e.root biomass).

Forest canopies have a complex vertical structure, and the understorey vegetation may be an important component of a forest stand by intercepting and transpiring a significant amount of water. For example, over 20% of the total ET for a 17-year-old pine plantation was

Table 3.1. A comparison of major methods for estimating evapotranspiration (ET) at multiple scales

	Method	Strength	Weakness	Source
Direct field-based	Porometer and cuvette	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	Olbrich (1991)
	Weighing lysimeter	Single whole-tree water use	High maintenance cost for small trees	Müller and Bolte (2009)
	Heat balance/heat dissipation sapflow	Allows routine unsupervised measurement accurately at single plant scale	Large-scale measurement errors are determined by the sample size and variability of samples	Granier (1987)
	Eddy covariance	Measuring fluxes continuously, offering high temporal resolution data	High cost of instrumentation, gap filling required, energy imbalance problems	Baldocchi *et al*. (2001)
	Bowen ratio	Low cost; works for both crops and natural vegetation	Relies on several assumptions; errors associated with low gradients	Vogt and Jaeger (1990)
	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	Fischer *et al*. (2023)
	Catchment water balance	Easy to measure; low cost	Only long-term average is reliable	Ukkola and Prentice (2013)
Remote sensing	MODIS, OpenET	Provides spatial, continuous and temporal scale high-resolution data	Uncertainties due to errors generated by measurement of sparse canopies; data mostly from clear-sky conditions	Melton *et al*. (2022)
Mathematical modeling for ET alone or the full hydrological cycles	Theoretical models (e.g.Penman–Monteith equation)	Widely tested, including all conditions; low cost	Requires site-specific parameters; not easy to apply to data-poor regions	McMahon *et al*. (2013)

Continued

Table 3.1. Continued

	Method	Strength	Weakness	Source
Isotopes	Stable isotopes of hydrogen (H) and oxygen (O)	Process-based understanding of water source of ET; partitioning evaporation and transpiration	Cost and scaling up to stand level	Good *et al*. (2015)

from understories (Domec *et al.*, 2012b) and as much as one-third of the total ET during the growing season in temperate and boreal forests (Balandier *et al.*, 2022). Emergent understorey vegetation soon after harvest in the humid coastal plain was shown to have substantial LAI, potentially affecting water balance for 4–5 years until the planted pine seedlings dominated the understorey (Sampson *et al.*, 2011).

3.2.3 Hydraulic redistribution by roots: exchange of water at the soil–root interface

Plants can reduce water stress by extracting water from deeper and moister soil layers through their roots and storing it in the upper, drier soil layers for use by shallow roots. The bidirectional (upward and downward) process is termed 'hydraulic redistribution' (HR) (Burgess *et al.*, 1998). The HR process occurs widely in all water-limited vegetated environments (Neumann and Cardon, 2012). HR is a passive process that depends on the soil suction head and the root distribution within the soil column. HR by roots acts as a large water capacitor, increasing the efficiency of whole-plant water transport, buffering the seasonality of ET against water stress during seasonal water deficits, and representing 20–40% of whole-stand water use (Domec *et al.*, 2010; Asensio *et al.*, 2020). Even when HR only represents a relatively small amount of ecosystem water use (<0.5 mm/day) and just a fraction (5–10%) of total ET during dry period, the partial recharge of upper soil moisture by HR is important to slow down the decline of soil water content and thus maintain water availability in the top soil horizons (Warren *et al.*, 2007). The influx of soil water maintains root water uptake capacity and extends root functioning later into the drought period, influencing forest productivity (Domec *et al.*, 2010).

3.2.4 Total ET

The ET rates at the ecosystem, watershed or regional level are controlled mainly by energy and water availability (Zhang *et al.*, 2001; Aguilos *et al.*, 2024), but are also influenced by other management factors such as chemical fertilization, CO_2 'fertilization effects' and nitrogen deposition tree genetic improvement, species conversion, artificial drainage and irrigation (Tian *et al.*, 2012). During the forest stand development, site-level energy and water availability also vary, resulting in dramatic seasonal changes in total ET and the partitioning of ET. For example, ET of a loblolly pine plantation stand on the lower coastal plain of the southeastern USA increased dramatically prior to age 10 but stabilized around years 10–15 (Fig. 3.4).

Forested watershed ET generally decreases and water yield increases soon after tree removal by harvesting (Bosch and Hewlett, 1982). Other natural disturbances such as hurricanes (Jayakaran *et al.*, 2014), wildfires (Boden *et al.*, 2023; Mankin and Patel, 2023), invasive species, defoliation due to insects and diseases (Sidhu *et al.*, 2024), wind and snowstorms, and urbanization also alter ET as a result of reduced canopy interception and transpiration and soil disturbances (Diem *et al.*, 2023). However, the hydrological responses vary depending on season and local conditions, and ET generally tends to increase soon after afforestation or reforestation and after natural regeneration from disturbances. Such changes in ET are often estimated as the differences between measured precipitation and streamflow runoff, assuming the change in soil water storage is

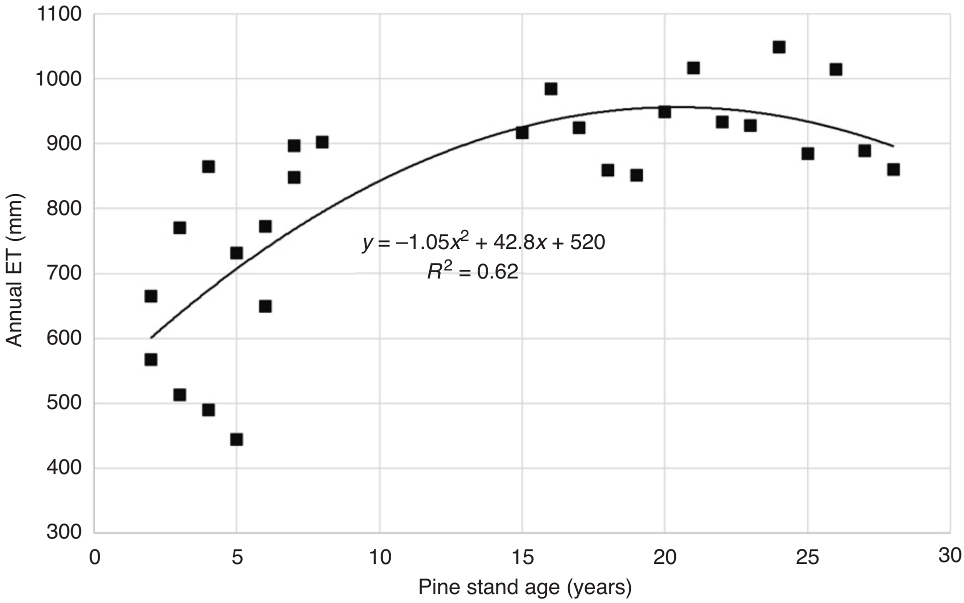

Fig. 3.4. A general curve showing that evapotranspiration (ET) rates of a loblolly pine (*Pinus taeda*) plantation increase with stand age, especially from seedlings to 15 years old. The ET data (2005–2018) were collected using an eddy flux method for stands with multiple ages in the lower coastal plain of North Carolina in the south-eastern USA (Domec *et al*., 2012; Aguilos *et al*., 2024).

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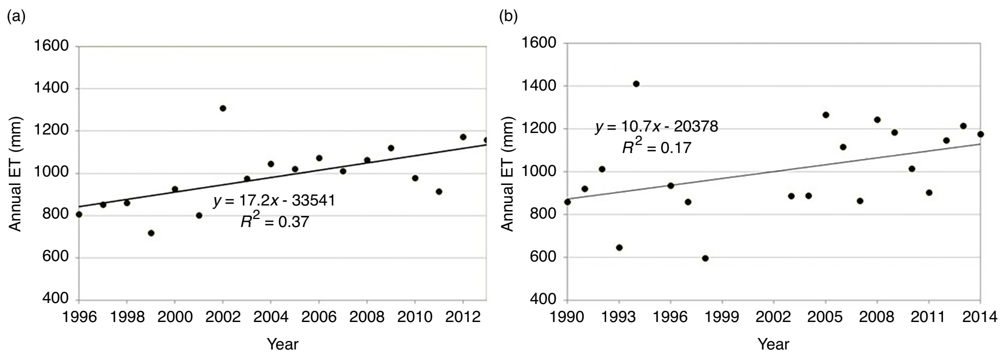

Fig. 3.5. Annual watershed forest ecosystem evapotranspiration (ET) calculated as the differences between measured precipitation and measured streamflow for an experimental watershed recovering gradually after disturbances: (a) following harvesting in 1995 and replanting with loblolly pine in 1997 in Carteret County, coastal North Carolina, USA, and (b) a mixed forest naturally regenerated after the impact of Hurricane Hugo in 1989 at Santee Experimental Forest in coastal South Carolina, USA.

negligible (Fig. 3.5). The inter-annual variability of ET is a result of variability of both the precipitation and potential ET (Ukkola and Prentice, 2013). Direct ET measurements using the eddy covariance over a full stand rotation (Aguilos *et al*., 2024) and remote sensing-based estimates (Yang *et al*., 2017) provide insights of the ET dynamics over space and time.

Forest ET rates also vary dramatically across a heterogeneous terrain with significant topographical gradients that modify natural water and energy availability (Boggs *et al.*, 2021). For example, ET rates of a forest stand are higher on the sunny side and/or near the ridges on a mountain watershed due to more available solar radiation (Emanuel *et al.*, 2010). Forest thinning practices reduce forest biomass, and thus canopy interception and transpiration from the remaining trees, but do not necessarily reduce total ET until the thinning treatment exceeds a threshold (del Campo *et al.*, 2022). The long-term effects of forest disturbances on ET and water yield by wildland fires and insects and diseases appear to be rather variable in the western USA (Goeking and Tarboton, 2022).

3.3 Direct ET Measurement

Forest ET processes can be quantified at multiple temporal (from subhourly to annual) and spatial scales from leaf to watershed, and even to a global scale using various methods from hand-held cuvette to remote sensing (Table 3.1). Because canopy and litter interception are important components of total forest ET, throughfall measurements under forest canopies are essential. For tree transpiration, the porometer method has been used to measure leaf water use for understanding the environmental control of gas exchange (CO_2 and H_2O) at the leaf level (Olbrich, 1991). Other methods to quantity tree transpiration include ventilated chambers (Denmead *et al.*, 1993), large lysimeters (Müller, 2009), sap flux density based on thermal dissipation and heat transport theories (Granier *et al.*, 1996).

The sapflow technique has the advantage of being economical, easy to install, and applicable to forests with multiple tree species and on heterogenous landscapes (Ford *et al.*, 2007; Boggs *et al.*, 2021). The ET of forest understories can be determined by direct measurements with the eddy covariance method with a short tower or by calculating the differences between total ET measured by the eddy covariance method above the tree canopy and tree sapflow (Domec *et al.*, 2012a). Sapflow measurements provide a powerful tool for quantifying plant water use and the physiological responses of plants to environmental change. SAPFLUXNET (Poyatos *et al.*, 2021) is a global database that compiles global sapflow data for understanding environmental and biological controls on water use across species and extreme climates such as drought and heatwaves (Ahongshangbam *et al.*, 2023). In contrast, the eddy covariance technique measures forest ET by calculating the covariance between fluctuations in vertical eddy velocity and the specific water vapor content above forest canopies (Baldocchi and Ryu, 2011). The method is designed to understand the gas exchange at the boundary layer between vegetation and the atmosphere and to answer landscape-scale (the footprint of the flux tower) questions (Baldocchi *et al.*, 2001). Global participation in the flux measurements through FLUXNET (over 900 sites) or other regional networks in different countries since the 2000s has been a major driving force for advancing ET science. However, the recent literature suggests that the eddy covariance measurement method may result in a large underestimation of ET for forests (Volk *et al.*, 2024). Most of the discrepancy can be explained by an underestimation of turbulent fluxes, at which data are most affected during rainfall conditions, as well as insufficient closure correction during interception episodes (Fischer *et al.*, 2023; Pluntke *et al.*, 2023).

The Bowen ratio energy balance method and, more recently, the surface renewal biometeorological technique have been used for quantifying ET in croplands and forests, and have similar accuracy to the eddy flux methods (Vogt and Jaeger, 1990; Fisher *et al.*, 2023). These methods estimate ET based on the ratio of sensible heat to latent heat with measurements of air temperature, humidity gradients, net radiation and soil heat flux. It is relatively inexpensive but relies on several assumptions such as an extensive fetch over a homogeneous surface (Barr *et al.*, 1994).

Stable isotopes have been used as tracers for identifying the sources of water uptake in ecosystems and for evaluating quantitatively the relationships among water, energy and isotopic budgets. For example, effects of drought on forest carbon balance can be detected by analyzing the isotopic budget of $\delta^{13}C$ and $\delta^{18}O$ (Lin *et al.*, 2019). The deuterium:hydrogen isotope ratios of continental runoff and ET have been used to determine the transpired fraction of ET as 56–74% (25th to 75th percentiles), with a median of 65% and mean of 64% (Good *et al.*, 2015). Furthermore, studies across an ecosystem gradient in the USA and Mexico provided evidence of ecohydrological separation, whereby different subsurface compartmentalized pools of water supply either plant transpiration fluxes or the combined fluxes of groundwater and streamflow (Evaristo *et al.*, 2015).

Satellite remote-sensing technology has been used to estimate landscape-scale ET since the 1980s (Zhang *et al.*, 2016), and recently in an urban environment (Qiu *et al.*, 2023). Coupling energy balance models with remotely sensed land-surface temperature retrieved from thermal infrared imagery provides proxy information of the surface moisture and vegetation cover growth status (Anderson *et al.*, 2021). Models such as the regional atmosphere–land exchange inverse (ALEXI) model and the associated flux disaggregation model (DisALEXI) are based on the two-source energy balance (TSEB) land-surface representations (Yang *et al.*, 2017). An application of these modeling systems in a lower coastal plain in North Carolina showed promise to map high-resolution ET (e.g.daily, 30 m) for a landscape with mixed land uses with natural wetland forests, drained pine forest with multiple stand ages, and croplands (Yang *et al.*, 2017). Large uncertainty remains among various remote-sensing ET products, and thus an OpenET platform has been developed to include an ensemble of multiple remote-sensing models to increase access to field-scale (30 m) ET data for the contiguous USA (Volk *et al.*, 2024).

Long-term and watershed-scale ET rates are estimated as the difference in measured precipitation and streamflow, assuming a negligible change in storage (Wilson *et al.*, 2001). Watershed-scale ET is dependent on its land use, vegetation cover and dominant soils, in addition to climate (Ukkola and Prentice, 2013; Amatya *et al.*, 2015).

A few ET method comparison studies at the watershed scale found that each approach had its own limitations (Wilson *et al.*, 2001; Ford *et al.*, 2007; Domec *et al.*, 2012b; Shimizu *et al.*, 2015; Tie *et al.*, 2018; Pluntke *et al.*, 2023). The eddy covariance method measures fluxes continuously, offering high temporal resolution data series, but data availability is limited by site topography, the cost of instrumentation, systematic errors and gap-filling issues. In addition, the eddy covariance method may underestimate ET by as much as 20% due to a lack of energy balance closure (Wilson *et al.*, 2002), especially on wet days, because the sonic anemometer and infrared gas analyzer must be dry to function properly (Fischer *et al.*, 2023).

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3.4 Indirect ET Estimates

3.4.1 PET-based methods

Due to the high cost of measuring ET at large scales, mathematical modeling has been widely used to estimate ET (McMahon *et al.*, 2013; Komatsu and Kume, 2020). ET models can be roughly divided into two groups: biophysical (theoretical) and empirical models. Many theoretical models have evolved around the famous Penman–Monteith model (Monteith, 1965), which represents the most advanced process-based ET model for a single canopy.

In practice, it is often rather difficult to parameterize the process-based ET models to estimate actual ET, which is influenced by many complex factors other than meteorology that can be routinely measured. To simplify calculations, the concept of potential ET (PET) was introduced in the 1940s and represents the potential maximum ecosystem water loss when the water supply is not limiting. Although the ambiguous concept of PET is increasingly challenged, it remains used by practitioners. Actual ET is scaled down from the hypothetical PET by limiting canopy conductance and soil moisture and correlates to pan evaporation (Fisher *et al.*, 2017). Such PET models are often embedded in hydrological models that can simulate the dynamics of soil moisture, a major control of soil evaporation and transpiration (Tian *et al.*, 2012).

Many PET models (>50) exist and can be classified into five groups (Lu *et al.*, 2005) based on the theories behind the algorithms: (i) water budget; (ii) mass-transfer; (iii) combination; (iv) radiation; and (v) temperature based. These models give inconsistent values due to their different assumptions and input data requirements, or because they were often developed for specific climatic regions (McMahon *et al.*, 2013).

Because of the large uncertainties of different PET methods (Amatya *et al.*, 1995), the agricultural ET community suggests not using the term PET (Xiang *et al.*, 2020), and efforts have been made to develop standardized methods to better estimate ET for different crops. One standard crop reference ET method has been adopted by the Food and Agriculture Organization of the United Nations (FAO), formally in the FAO Irrigation and Drainage Paper No. 56 (FAO-56; Allen *et al.*, 1998). ET_0 is defined as "the rate of evapotranspiration from a hypothetic crop with an assumed crop height (12 cm) and a fixed surface resistance (70 s/m) and albedo (0.23), which would closely resemble evapotranspiration from an extensive surface of green grass cover of uniform height, actively growing, completely shading the ground and not short of water.' ET_0 is calculated using the Penman–Monteith model with the specific parameters for a standard grass with a LAI of 4.8 (Sun *et al.*, 2011a):

$$ET_0 = \frac{0.408\Delta(R_n - G) + \gamma \frac{C}{T+273.16} U_2 (e_s - e_a)}{\Delta + \gamma(1 + 0.34U_2)} \quad (3.4)$$

where ET_0 is the daily grass reference ET (mm), Δ is the slope of the saturation water vapor pressure at air temperature T (kPa/°C), R_n is net radiation (MJ/m^2), G is soil heat flux (MJ/m^2), γ is the psychrometric constant (kPa/°C); e_s is saturation vapor pressure (kPa), e_a is actual vapor pressure (kPa), U_2 is mean wind speed (m/s) at 2m height and C is the unit conversion factor with a value of 900.

Once ET_0 is calculated, actual ET for a particular ecosystem type can be estimated by simply multiplying by a crop coefficient (K_c) developed for that crop using field-measured ET. The K_c method works well in irrigation agriculture for various croplands that have uniform phonology. However, for forests, this method can be problematic given the large variability of species composition of a forest, leaf biomass dynamics throughout the season, and the stand age, structure and density effects on tree biomass and hydraulic properties (e.g. canopy conductance, sapwood area). A casual use of ET_0 as the maximum ET in a hydrological model may result in underestimation of ET for a forest-dominated landscape (Amatya *et al.*, 1995; Amatya and Harrison, 2016), where the actual forest ET rates in a humid climate often exceed ET_0. A study based on global eddy covariance data suggests that K_c for any forest type may vary tremendously, and that latitude, precipitation and LAI are the best predictors of K_c (Liu *et al.*, 2017). Forests generally have higher K_c values than other ecosystem types (Fig. 3.6).

3.4.2 Empirical ET models

Empirical ET models are derived from direct ET measurements at the ecosystem scale and may be best used as a first-order approximation under mean climatic conditions. The following model was derived from field data collected at 13 sites using a variety of methods (Sun *et al.*, 2011b). The model estimates monthly ET for any land-cover types as a function of LAI, ET_0 (mm/month) and precipitation (P; mm/month):

$$ET = 11.94 + 4.76 \times \text{LAI} + ET_0(0.032 \times \text{LAI} + 0.0026 \times P + 0.15) \quad (3.5)$$

where ET_0 is the FAO-56 grass reference ET as discussed above.

Other forms of the ET model use Hamon's PET instead of the more data-demanding FAO reference ET method (Sun *et al.*, 2011a):

$$ET = 0.174 \times P + 0.502 \times PET + 5.31 \times \text{LAI} + 0.0222 \times PET \times \text{LAI} \quad (3.6)$$

Using a similar concept and a 250 FLUXNET synthesis data set, Fang *et al.* (2016) developed the following two types of monthly ET models requiring different input variables:

$$ET = 0.42 + 0.74 \times PET - 2.73 \times \text{VPD} + 0.10 \times R_n \quad (R^2 = 0.73, \text{RMSE} = 17.0\text{mm/month}) \quad (3.7)$$

where PET is monthly potential ET (mm) calculated by Hamon's method, VPD is vapor pressure deficit (hundreds of Pascals) that can be estimated from relative air humidity, R^2 is the coefficient of determination and RMSE is the root mean squared error. As R_n is rarely available at the regional scale, another model that uses commonly available weather data was developed:

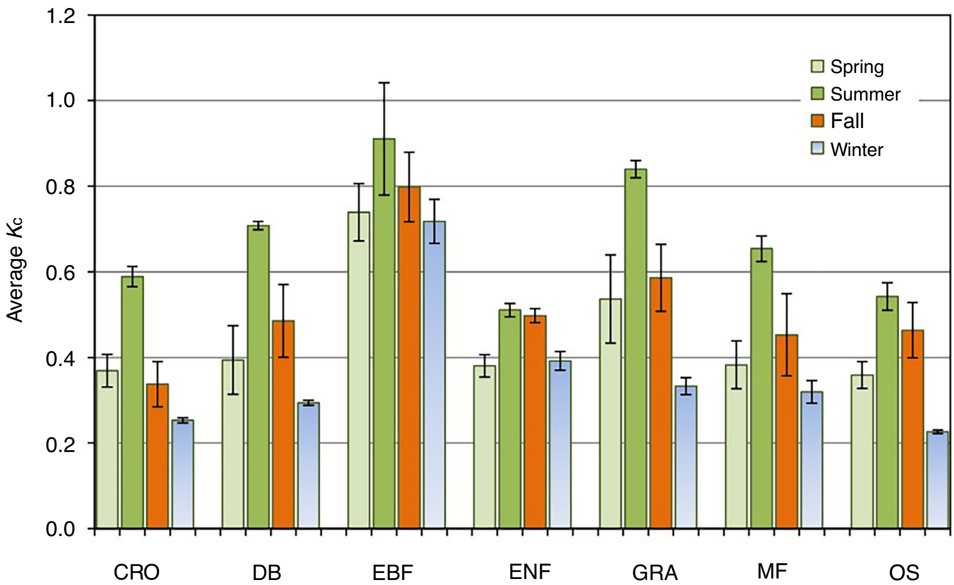

Fig. 3.6. A comparison of the seasonal mean crop coefficient (K_c) calculated from global eddy flux measurements for cropland (CRO), deciduous broad-leafed forest (DB), evergreen broad-leafed forest (EBF), evergreen needle-leaf forest (ENF), grassland (GRA), mixed forest (MF), and open shrubland (OS). K_c is estimated as measured ET divided by the grass reference ET (ET_o) calculated by the standard FAO-56 method (Allen *et al*., 1998). Error bars represent standard deviation.

Table 3.2. Empirical evapotranspiration (ET) models by land-cover type developed using three commonly measured biophysical variables.

Land-cover type	Model	RMSE	R^2	*n*
Shrubland	$ET = -3.11 + 0.39 \times \text{PET} + 0.09 \times P + 11.127 \times \text{LAI}$	12.5	0.80	193
Cropland	$ET = -8.15 + 0.86 \times \text{PET} + 0.01 \times P + 9.54 \times \text{LAI}$	20.9	0.70	653
Grassland	$ET = -1.36 + 0.70 \times \text{PET} + 0.04 \times P + 6.56 \times \text{LAI}$	16.8	0.66	803
Deciduous forest	$ET = -14.82 + 0.98 \times \text{PET} + 2.72 \times \text{LAI}$	23.7	0.74	754
Evergreen needle leaf forest	$ET = 0.10 + 0.64 \times PET + 0.04 \times P + 3.53 \times \text{LAI}$	17.8	0.68	1382
Evergreen broad leaf forest	$ET = 7.71 + 0.74 \times PET + 1.85 \times \text{LAI}$	16.8	0.76	233
Mixed forest	$ET = -8.763 + 0.95 \times PET$	13.1	0.79	259
Savannas	$ET = -5.66 + 0.18 \times \text{PET} + 0.10 \times P + 44.63 \times \text{LAI}$	11.1	0.68	36

ET and *P* are measured in mm/month; *PET* is estimated by Hamon's method (mm/month)
LAI, leaf area index (m^2/m^2);R^2, coefficient of determination;RMSE, root mean square error;*n*, sample size;

$$ET = -4.79 + 0.75 \times PET + 3.92 \times \text{LAI} + 0.04 \times P (R^2 = 0.68, \text{RMSE} = 18.1\text{mm/month}) \quad (3.8)$$

A series of ecosystem-specific monthly scale ET models were also developed using the global eddy flux data (Table 3.2) (Fang *et al.*, 2016). An empirical annual ET model was developed by combining a water balance method with a climate and land-cover regression equation to estimate mean annual ET across the conterminous USA (Sanford and Selnick, 2013). The climate variables included mean annual daily, maximum daily and minimum daily temperatures, and mean annual precipitation. The land-cover types included developed forest, shrubland, grassland, agriculture and marsh.

The long-term mean ET in a region is controlled mainly by water availability (precipitation) and atmosphere demand (PET), and this relationship is well described in the Budyko framework (Budyko *et al.*, 1962; Zhang *et al.*, 2004; Gan *et al.*, 2021). Using the same concept, Zhang *et al.* (2001) analyzed watershed balance data for over 250 catchments worldwide and developed a simple two-parameter ET model. The model offers a practical tool that can readily be used for assessing the long-term average effect of vegetation changes on catchment evapotranspiration:

$$ET = P \times \frac{1 + w\frac{PET}{P}}{1 + w\frac{PET}{P} + \frac{P}{PET}} \quad (3.9)$$

where w is the plant-available water coefficient representing the relative difference in plant water use for transpiration and P is annual precipitation. PET can be estimated by the Priestley and Taylor (1972) model. The best-fitted values for forest and grassland are 2.0 and 0.5, respectively, when PET is estimated using the Priestley and Taylor (1972) model (Zhang *et al.*, 2001).

The Budyko framework has been widely used to explain the mean spatial patterns of ET under land-cover change (Zhou *et al.*, 2015; Gan *et al.*, 2021) and climate change (Li and Quiring, 2021). The model has been also been extended to finer temporal scales such as monthly to fully capture the dynamics of ET over time (Zhang *et al.*, 2008).

3.4.3 Emerging ET estimation methods

Emerging novel ET methods based on the maximum entropy production (MEP) theory, offer new ways to estimate ET with limited meteorological data (Wang and Bras, 2011). For example, the MEP model provides simultaneous solution of latent, sensible and surface medium heat fluxes using only three input variables: net radiation, surface temperature and specific humidity, without the need for surface conductance parameters used in the traditional Penman–Monteith equation.

Two inexpensive micrometeorological methods, flux variance method and surface renewal analysis, are available as an alternative to estimate ET. Both methods estimate sensible heat flux derived from high frequency (~10 Hz) air temperature measurement, using a fine-wire thermocouple (Shapland *et al.*, 2014; Gray *et al.*, 2022; Fisher *et al.*, 2023) and require net radiation and soil heat flux to estimate ET.

A new generation of ecohydrological models that combine the effects of CO_2 on ET processes and couple the physical and biological processes such as soil moisture redistribution, hydraulic distribution, photosynthesis, canopy conductance and tree growth is available to fully understand the atmosphere–vegetation–soil processes mechanistically (Cheng *et al.*, 2017). Such models can provide climate models with better ET information for quantifying the feedback of forest cover change to regional and global climate systems (Fisher *et al.*, 2017).

3.5 Conclusions

ET has been increasingly recognized as an important measure in many academic disciplines (Yi *et al.*, 2024) and resource management concerned with tree species, density, stand age, prescribed burning, fertilization and thinning under a changing climate (Sun *et al.*, 2023). Much progress has been made in the past three decades toward measuring forest ET ‘everywhere all the time’ (Baldocchi and Ryu, 2011; Jung *et al.*, 2019). However, there still are large data gaps in many parts of the world in applying existing ET models, resulting in difficulty in answering critical questions such as how reforestation and global greening up affect water supply and low flows (Yang *et al.*, 2023). Climate change and rising demands for forest water services require better models to reliably account for the role of forest management in regulating ET and streamflow and other ecosystem services (e.g.carbon sequestration). Regional land-surface models should be rigorously validated with field measurements of ET at multiple scales to be creditable for quantifying the benefits of forests in climate mitigation and adaptation (Sun *et al.*, 2024).

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