Evapotranspiration of Pine Forests: A Global Synthesis

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Abstract Pine (*Pinus* spp.) forests are found in many areas with a wide range of bioclimates, providing a myriad of ecosystem services. Pine trees have been widely planted for various purposes such as commercial timber production, soil erosion control and water quality improvement of source waters, urban forestry, wildlife habitat, and bioenergy for carbon sequestration. Quantifying these benefits requires a clear understanding of the hydrological cycle in pine forests, especially the evapotranspiration processes. This synthesis study aims at synthesizing published literature documenting the water balance components including evapotranspiration (ET), the sum of canopy/litter interception, tree transpiration, soil/understory evaporation, water yield as surface runoff and subsurface drainage, and soil water storage of pine

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forests, natural or managed, at stand or watershed levels. We conducted the analyses using the Budyko's water and energy balance framework to show how the aridity index, defined as potential evapotranspiration/precipitation ratio (PET/P), influences water use strategies and controls on evaporative efficiency (ET/P) of pine forests under different climatic regimes and management. We examine influences of tree and stand age, xylem anatomy, forest management such as thinning, species conversion (e.g., from loblolly pine to longleaf pine or deciduous to pine), and artificial drainage on pine forest ET and hydrology. We explain the large variability of forest ET and its components (i.e., canopy interception) and across a large global climatic gradient. We identify research gaps for fully accounting pine forest evapotranspiration such as water loss by understories and stress the importance of canopy interception and soil evaporation. Our review suggests that total ET rates of evergreen pine species generally are higher than native broadleaf deciduous forests under most climatic conditions. We demonstrate the success and challenges to use pine forests to meet multiple ecosystem services (soil erosion control, water supply, and timber yield) in a changing environment.

1 Introduction

Forests dominated by the genus *Pinus* are found over a large climatic and a nutrient gradient from the Arctic with a short growing season to the tropics with a year-round growing season and from nutrient-poor sandy soils to nutrient-rich organic soils (Knight et al. 1994; Richardson et al. 2007). For example, pines are naturally found in North America (the USA, Canada), Europe, and Asia, where that annual precipitation can vary from 300 to 1500 mm (e.g., Southern USA and China) with seasonal temperature extremes ranging from −40 to 20 °C (Adams et al. 2019). Pines are widely planted worldwide beyond their natural range because of their favorable long tracheids and wood properties for structural timber (Tor-ngern et al. 2017) and high growth rate (Fahey and Jackson 1997; Calder 2007) and bioenergy (Pisarello et al. 2022; Ruzol et al. 2022), often as monoculture in the past 50 years (Nichols et al. 2006). Because pines can survive in harsh environments (i.e., poor nutrients, drought, frequent burns), pines are widely used as pioneering trees for afforestation in soil erosion control or urban greening in China (Bao et al. 2004; Chen et al. 2007, 2023; Ma et al. 2018), rehabilitating degraded grass lands in Nepal (Ives 2006; Ghimire et al. 2013, 2014), and reforestation in India (Naudiyal and Schmerbeck 2017) and the Caribbean with a tropical climate (Francis et al. 2022). Pine forests vary greatly in leaf phenology, leaf morphology, canopy structure, and water use patterns, and their water balances can be rather complex (see review in Tor-ngern et al. 2017).

Pine plantations have greatly expanded since the nineteenth century, thanks to the advances of silviculture. For example, there were almost no pine plantations in the Southern USA in the 1950s, but planted pine, mostly loblolly pine (*Pinus taeda L*), increased from 8.5 million ha in 1985 to 13 million ha in 1999 with an estimated

increase to 20 million ha by 2040 (Weir and Greis 2002). The growth of many pine plantations in the Southern USA is limited by soil nutrient availability (nitrogen and phosphorus) which limits leaf area production and therefore growth efficiency and stand production (Fox et al. 2007). Therefore, intensive forest management such as fertilization and minor drainage has been used to increase productivity, causing concerns of stream water quality and wetland degradations. In China, pine trees, native (*P. tabuliformis*; *P. massoniana*) (Wei et al. 2005) or introduced species from the USA (*P. taeda* and *P. elliottii*), have been widely used for massive reforestation for timber production and soil erosion controls (Ma et al. 2014; Xu 2011). Throughout the Caribbean, exotic pine trees such as *Pinus caribaea* or *Pinus oocarpa* have been used to reforest many degraded landscapes for their fast growth and resilience to drought (Francis et al. 2022).

Due to their wide distribution and large areas, pine forests are important for local economies, and their ecological implications, both benefits and risks, have been increasingly scrutinized globally. For example, intensive pine forest management in Southeastern USA in the 1980s that involved fertilization and artificial drainage substantially increased productivity (Jokela et al. 2010) but also caused concerns about stream water supply (Shepard 1994). A global review suggests plantation forests use more water and have lower biodiversity than native forests (Hua et al. 2022). Some other studies argued that plantation forests could provide net benefits for conservation purposes, but it is context-specific and depends on multiple factors, including controlled management (Carnus et al. 2006; Vanclay 2009). Coniferous forests generally have higher evapotranspiration than hardwoods under similar precipitation conditions (Ford et al. 2011). A watershed-scale forest manipulation experiment in the humid southern Appalachians Mountains shows that converting negative deciduous forests to pine plantations decreases water yield by over 30% (Swank and Douglass 1974). Swank and Douglass (1974) predicted that converting piedmont hardwood forests of the Southeastern USA to loblolly pine could reduce annual streamflow by about 4 acre-inches (100 mm) for each acre converted. Converting Englemann spruce (*Picea engelmanni*) to aspen (*Populus tremuloides*) forests alters snow distribution and transpiration and may result in 185 mm net loss of moisture available for streamflow and a loss of 71 mm when fir forests (*Abies lasiocarpa*) cover the watershed in the Colorado River Basin (Hibbert 1979; LaMalfa 2007; Zou et al. 2010). Thus, a succession of aspen to conifers would cause a decline of water yields in the Western USA (Gifford et al. 1984). Conversion of mixed evergreen forest to pine plantation in the northwestern South Island initially resulted in an increase in low flow, peak flow, and total flow of 310–340 mm (61–68%), but planting the harvested areas with pines caused the hydrology (low flow, high flow, total flow) to return to re-harvesting levels within 8–10 years (Fahey and Jackson 1997). Another study suggests that converting tussock grasslands to pine plantations in southern New Zealand decreased flow by 230 mm or 27% by year 10 (Fahey and Jackson 1997). At a site in northern Uruguay, the water yield reduction over the 3 years after pine plantation of a grassland watershed was 15%, with 50% reduction in peak flow rates 2 years after planting and by 75% 4 years after planting (Chescheir et al. 2009). Ramirez et al. (2022) compared the water

balance of pine plantations and thorny forests in a Mediterranean landscape in Chile. They found that the ET rates of pines are 379 mm in the dry year and 616 mm in the wet year, while shrubland ET is 291 and 371 mm, respectively. Comparatively, pines in the dry year lost 88 mm more than shrubland on average and 245 mm more in the wet year. Similar studies in Japan (Komatsu et al. 2008) and West Virginia in the Eastern USA reported that total water loss from coniferous forests was higher than from deciduous forests due to higher canopy interception rates and total ET of conifer trees (Rau et al. 2022). It is generally believed that coniferous evergreen trees use more water than deciduous trees in Germany. For example, the mean annual canopy transpiration rate for Scots pine (*Pinus sylvestris*) is 320 mm, higher than that of European beech (*Fagus sylvatica L.*) forest (304 mm). A direct comparison of the neighboring pine/beech stands showed that the annual transpiration of pine was 30–80 mm higher than beech. Annual ET (transpiration + canopy interception) averaged 582 mm in the pine stands compared to 496 mm in the beech stands. The annual deep seepage ranged from 15 to 88 mm under the pine (mean 66 mm) and from 100 to 273 mm (mean 134 mm) under the beech, which equals 2–13% and 15–31% of annual precipitation, respectively (Leuschner et al. 2022). In Nepal, the hydrologic effects of afforestation with Chir pine (*Pinus roxburghii*) remain somewhat controversial. Local observations by farmers from the Jhikhu Khola region suggest that certain springs dried up after the afforestation program was implemented (Ives 2006). Limited forest hydrological studies in Nepal (Ghimire et al. 2013, 2014) do suggest higher water use of planted pines than degraded grass, but effects of tree planting on springs could be moderated by better forest and soil management or use native broadleaf trees promoting soil infiltration. In the tropics, exotic pine (*Pinus caribaea* or *Pinus oocarpa*) plantations also used more water than native secondary forests due to the higher canopy interception storage and the presence of understory in pines (Francis et al. 2022).

In addition to changes in water yield and carbon sequestration due to replacing hardwoods with pines, there are also concerns that pine planting may enhance climate warming and aridification due to changes in albedo in the north latitude. Based on measurements in paired pine and beech forests and the review of literature data, Leuschner et al. (2022) suggest that Scots pine (*Pinus sylvestris* L.) plantations in northern Germany had 4–6% lower albedo and 9% higher net radiation as well as higher canopy temperature and evapotranspiration in pine forests than beech forests. Consequently, Leuschner et al. (2022) conclude that large-scale planting of Scots pine is not climate-smart and environment friendly. However, little is known about how the albedo and net radiation contrasts translate to the effects on local air temperature and climate warming. There are arguments that forest with high leaf area and ET (i.e., latent heat) may have lower sensible heat transported to the boundary layer of the atmosphere, thus actually reducing global warming (Sun et al. 2010; Stoy 2018).

2 Objectives

This chapter aims to provide an overview of water balances (i.e., evapotranspiration, water yield) of pine forests at the stand-to-watershed scale by surveying published relevant literature. Such information is important for better forest management and meeting the needs of multiple ecosystem services from carbon sequestration to water supply.

The synthesis attempts to provide a summary of canopy interception, soil/understory evaporation, transpiration rate, and water yield. Data are put in the context of pine stand age and background climate using the Budyko framework that describes mean energy and water balances with respect to aridity index at a broad scale. We provide a summary of the effects of tree species conversions, such as from deciduous forests to pine, or from pine to hardwoods, or between pine species, such as from loblolly pine to longleaf pine on water balances.

3 Methods

We use the following water balance equation to guide our data compilation and synthesis at the stand or small watershed scale:

$$dS / dt = P(t) - \mathrm{ET}(t) - Q(t) \tag{1}$$

Equation (1) indicates that the change in soil water (unsaturated zone) and groundwater (saturated zone) storage (S) in a forest at any time t is a result of the balances of precipitation (P), evapotranspiration (ET), and total runoff or water yield (Q) or outflow or drainage in systems that are wet and subject to artificial drainage such as managed pine plantations (Amatya et al. 1996; Amatya and Skaggs 2011). The term Q includes deep seepage (DS) to groundwater on a watershed scale. ET is the sum of evaporation (E) from soil, litter, and understory (Es), canopy intercepted evaporation and litter interception (Ei), and plant transpiration (Et) (Tie et al. 2018).

$$\mathrm{ET}(t) = \mathrm{Es}(t) + \mathrm{Ei}(t) + \mathrm{Et}(t) \tag{2}$$

ET(t) is an important ecohydrological variable that links energy, water, and carbon fluxes (Sun et al. 2011; Fisher et al. 2017). Many variables affect Es, Ei, and Et; thus, ET is rather difficult to quantify accurately at a short timescale (Sun et al. 2016; Fisher et al. 2017). Meteorological variables, such as net solar radiation, air temperature, humidity, wind speed, atmospheric vapor pressure deficit, precipitation, and soil water availability, are dynamic and vary across time and space. Forest biophysical properties such as canopy structure, leaf area index (LAI), rooting depth, tree age and height, aerodynamic conductance, and leaf stomata conductance

are major controls on vegetation ET and vary greatly between species (Sun et al. 2011).

The magnitude of dS/dt can be large on daily and even on monthly scale (Dymond et al. 2014). At a longer temporal scale (multiple years), dS/dt is negligible, and $Q(t)$ can be expressed as follows:

$$Q = P - \mathrm{Es} - \mathrm{Ei} - \mathrm{Et} \tag{3}$$

We put the hydrological analyses in the Budyko water and energy balance framework (Budyko 1974; Chen and Sivapalan 2020) to show how the aridity index (potential evapotranspiration/precipitation) influences pine water use strategies and efficiency (ET/P) of pine forests in different climatic regions, demonstrating the role of climate in partitioning P into ET and water yield. There are many forms to describe ET/P (evaporative index) vs. PET/P (DI, dryness index) relationship. For example, based on global water balance data from 250 watersheds, Zhang et al. (2001) derive the following relationship to show that long-term mean forest ET is higher than grass ET.

$$\frac{ET}{P} = \frac{1 + w\dfrac{PET}{P}}{1 + w\dfrac{PET}{P} + \dfrac{P}{PET}} \tag{4}$$

For this model, w is found to be about 2.0 for forests and 0.5 for grasslands.

Other forms of the Budyko curve are available, including the widely used Fu model (Fu 1981; Zhang et al. 2004):

$$\frac{ET}{P} = 1 + \frac{PET}{P} - \left[1 + \left(\frac{PET}{P}\right)^{w}\right]^{1/w} \tag{5}$$

Using data from 470 watersheds, Zhang et al. (2004) found the w parameter value to be 2.84 to best fit data for forested and 2.55 for grass-dominated watersheds, respectively. These parameter values are close to 3.0 found by Amatya et al. (2002) for a managed pine forest site in coastal North Carolina in the USA.

In this study, PET was assumed to be equivalent to FAO grass reference ET (ETo), representing the local evaporation demand. To be consistent across sites, a global dataset ETo and P was used to calculate the mean dryness index, PET/P (Zomer et al. 2022).

We assume that annual forest ET rates estimated by Eqs. (4) and (5) represent the mean theoretical values for all forests in stable average climatic conditions. The two models provide differing ways of general approximations of ET rates and uncertainty of ET rates under different climatic regimes. So, any deviations from the

calculated values under the average conditions suggest local observed ET may be influenced by factors beyond mean climatic regimes. In many cases, pine forest ET or Et values are only reported for the growing season since ET is low and Et is negligible in the nongrowing season for cold regions. For this type of sites, we discuss forest total ET or transpiration in the context of mean annual climate (P and PET) or growing season only.

Patterns of water yield (Q) from forests are influenced by precipitation, PET, forest ET, and soil properties (Eq. 3) and deep seepage in some cases. Changes in forest compositions and structure due to forest management or other disturbances (i.e., climate change) affect water yield Q by directly or indirectly altering Es, Ei, and Et. For example, thinning forests may increase Es but decrease Ei and Et, resulting in an increase or insignificant change in ET or Q due to offsets in components. For example, wildland fires may kill understory and/or overstory vegetation and reduce soil infiltration capacity, thus decreasing Et and Ei and increasing Q at least in the short term. However, if the after wildland fire or tree mortality, the increase in Es can exceed the decrease in Et, Q may decrease (Goeking and Tarboton 2022). Drainage (ditching) that has been used in establishing pine plantations in the southeast may facilitate subsurface flow, lower groundwater levels, and increase outflow (Skaggs et al. 2016, 2020). In such a management scenario, forest ET may be reduced due to likely lower soil moisture (Amatya et al. 1996).

This study compiles published literature on pine forest hydrology with a focus on measured or modeled ET and its components at either the annual or growing seasons. Datasets cover a wide range of climatic zones and 17 major pine species. We recognized that pine forests are often managed for different purposes and ecosystem benefits from bioenergy to timber production to water yield augmentation. So, in this assessment study, we reviewed and compared results from studies on the ET and water yield differences under various management conditions such as species conversion and thinning.

4 Results and Discussion

As discussed, forest ET and components vary greatly due to local climate, water availability, species, tree size, age, and leaf area, and any single factor cannot explain the spatial variability reported in the literature. We first present a comparison among pine forest canopy interception rates for major pine species globally (Fig. 1). Then, we examine characteristics of pine transpiration with other tree species using a sap flow dataset (105 sites) available in the USA. We also report total pine forest ET rates measured by the eddy covariance methods and other methods (e.g., modeling and lysimeters). Finally, we compare growing season pine ET and annual ET in the context of forest ET estimated by the theoretical Budyko framework to demonstrate how pine ET may differ from the mean ET of other forest ecosystems.

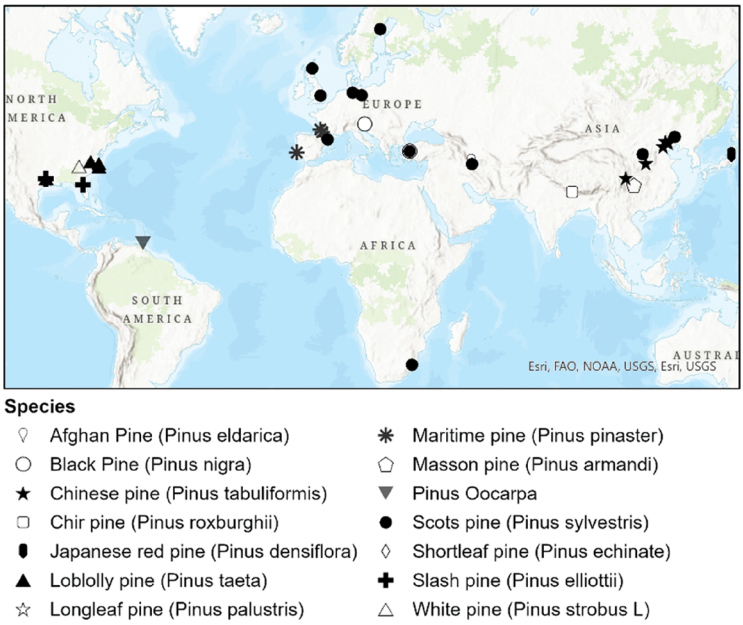

Fig. 1 Reported sites with studies on canopy interception for pine forests. (Data in Supplementary Table S1)

4.1 Interception by Pine Forests (Ei)

Forest interception (Ei), the sum of canopy (understory and overstory) and litter interception, represents intercepted precipitation, rainfall, or snow, evaporated from the surfaces of plant litter on forest floors, leaves, branches, and stems of forest during and after precipitation events. While transpiration dominates total ET (35–80% of ET), rainfall interception by plant canopy (10–50% of total precipitation) and litter of forest floor evaporation is (10–50% of throughfall) important as well. However, litter layer interception and soil surface evaporation have received relatively little attention in the literature (Domec et al. 2012; Gerrits et al. 2007; Sun et al. 2015). Because of the large surface of pine needles (Vose et al. 1994) and relatively high leaf area (up to all-sided LAI of 32 m^2/m^2 in *P. radiata* stand in New Zealand) (Grace 1987) and litterfall of pine stands, Ei can be a large component of the total ET and thus the water budgets for a watershed dominated by pine trees (Komatsu et al. 2008; Llorens and Domingo 2007; Sun et al. 2015). Ei can be even more important for water cycles in a dry climate with light rainfall intensity (Attarod et al. 2015). For example, an interception study on Afghan pine (*Pinus eldarica*) plantation shows that pine forest stand intercepted as high as 66% (36–88%) of rainfall on a storm basis and 44% on an annual accumulative basis in the arid region (mean annual precipitation = 1270 mm, PET = 2619 mm) in Iran (Attarod et al.

2015). Interception of understory along can be as long as 29% of precipitation in the pine plantations in the Caribbean (Francis et al. 2022).

Unique to forest hydrology, the large amounts of plant litter (including the O_i + O_e horizons) are important for preventing soil erosion and water evaporative loss, storing water temporarily, and supplying soil nutrients and organic matter. Meanwhile, litter can intercept significant throughfall to reduce recharge to soils. For example, a study in South Africa (Bulcock and Jewitt 2012) documents that canopy interception by *E. grandis*, *A. mearnsii*, and *P. patula* was 14.9%, 27.7%, and 21.4% of gross precipitation, respectively, while litter interception was 8.5%, 6.6%, and 12.1% of gross precipitation, respectively, resulting in a decrease in recharge to soils. A litter removal experiment at the University of Tokyo Forests, Japan, shows that removing litters decreased litter layer interception in a watershed dominated by *Pinus densiflora* and *Quercus serrata*, increasing total flow (27 mm/year) and peak flow rates (1.4–1.5 times higher than control), particularly during relatively large flood runoff events. A study in the Southeastern USA on litterfall interception in a *P. elliottii* stand suggests that rainfall interception was 2–32% of rainfall and biomass materials related to phenological activity and meteorological disturbances affected the temporal variability of litter composition and litter interception processes. Litter interception is determined by both amounts of litter on the ground and its drying rate influenced by local climate. Hardwood forests in the humid southern Appalachians intercept about 2–6% of annual rainfall (Helvey and Patric 1965; Brantley et al. 2019). A summary of interception studies in North America indicates that conifer forest litters could lose 2–27% of gross precipitation (Helvey 1971).

Quantitative studies on forest canopy interception have a long history (Helvey 1971; Waring et al. 1981; Amatya et al. 1996; Sun et al. 2016; Qian et al. 2022), and mathematical models (e.g., Gash model) have been developed (Muzylo et al. 2009). Helvey (1971) provided the summary of early canopy and littler interception studies for conifer forests in the USA. A global review of canopy interception modeling studies in the tropics and extra-tropics is found in Wang et al. (2007). This study focuses on the literature on *Pinus* canopy interception to show its large variability due to differences in canopy characteristics that reflect species, age, stand structure, crown properties (roughness, density, leaf hydrophobicity), leaf size, and amount (leaf area index) and background climate as represented by precipitation and ET (Appendix Table 1).

In general, canopy interception rates increase with the stand age and leaf area (Brantley et al. 2019). For example, Ei for Chinese pine (*Pinus tabuliformis* Carr.) accounts for 20.4%, 24.8%, and 32.8% of gross rainfall in 40-, 50-, and 60-year-old, respectively (Dong et al. 2020), while 35-year-old Mongolian pine (*Pinus sylvestris* var. *mongolica*, MP) stand intercepts 29.5% of rainfall (Liu et al. 2016). Similarly, Brantley et al. (2019) found that the stand canopy interception as a percentage of precipitation (P) increased from 7.7% at age 2 to 26.4% at old growth (Age > 200) in a chronosequence study in the southern Appalachian Mountains in Southeastern USA. Conifers generally have higher canopy interception rates (Ei/P) than hardwoods that exhibit seasonal differences, but less than spruce-fir-hemlock forest type

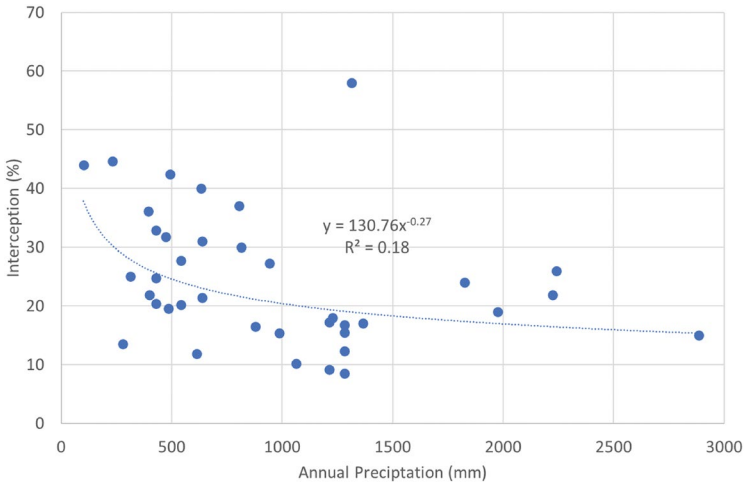

Fig. 2 There is a large variability in canopy interception rates among pine hydrology research sites. In general, annual accumulative pine forest interception rates decrease with an increase in precipitation. Each dot represents one global study site

(Waring et al. 1981). The interception rate decreases with an increase in storm size in the form of Log(Ei) = $a + b \log(P)$ (Gavazzi et al. 2016) (a, b are parameters). Similarly, at the annual scale, cumulative interception rates are generally higher in arid regions than in humid regions (Fig. 2). This is especially true for arid regions with light and infrequent rains (Attarod et al. 2015). Reported annual mean interception rates can be as high as 72% in black pine (*Pinus nigra*) forests found in urban Slovenia (Zabret et al. 2018). This contrasts with a 28-site 1-year study on North American biomes that have interception rates as 10–25% (Allen et al. 2019).

Also, canopy interception rates vary seasonally due to tree leaf area dynamics and precipitation characteristics (Gavazzi et al. 2016). Reducing basal area and subsequent leaf area through thinning decreases canopy interception (McCarthy et al. 1991; Sun et al. 2015). Komatsu et al. (2008) summarize 12 studies on an interception from coniferous plantation forests in Japan and derive a positive correlation between stem density and interception ratio as Ei (%) = 0.00498 × (stem density in stems/ha) + 12.0.

Differences in canopy interception often explain the water yield change due to species conversion from deciduous forests to evergreen coniferous forests. For example, a species conversion study demonstrates that converting native deciduous forests with planted white pine (*Pinus strobus* L.) could reduce water yield by over 20% in the Appalachians Mountains. In this case, canopy interception by white pine can be as high as 585 mm/year or 26% of annual precipitation, representing 40–45% of total watershed ET (1291 mm) which is significantly higher than the ET from a deciduous forest (Ford et al. 2007). Another comparative study in Japan with succession from Japanese red pine (*Pinus densiflora*) to evergreen oak showed that the canopy interception reduced from 208 to 115 mm or from 17

to 9% of the annual gross rainfall due to reduced rainfall storage on tree surface (Iida et al. 2006).

4.2 Tree Transpiration (Sap Flow)

Water use by individual trees or transpiration (Et) is the dominant ET components of forest ecosystems. Previously reported global mean Et/(ET) from multiple independent sources, including satellite-based estimations, reanalysis, land surface models, and isotopic measurements, varies substantially from 24% to 90% (Wei et al. 2017). Combining global ET estimates and relationships between LAI and Et/ET for different vegetation types, Wei et al. (2017) show that Et accounts for about 57.2% (with standard deviation ± 6.8%) of global terrestrial ET. Another global study estimates Et/ET as 56–74% (median = 65%, mean = 64%), and most (65 ± 26%) of evaporation is from soils (Good et al. 2015). Et/ET varies among different types of vegetation, and generally, it increases with LAI (Hu et al. 2018). The average Et/ET in temperate coniferous forests is 55 ± 15%, while it is ca. 65 ± 18% for boreal forests (Schlesinger and Jasechko 2014). A global meta-analysis of arid ecosystems suggests Et/ET is about 50% (Sun et al. 2019) but variable depending on leaf area dynamics.

Transpiration from trees has been widely measured (Poyatos et al. 2016, 2021) globally through the SAPFLUXNET, thanks to the invention of sap flow methods that estimate either total sap flow through a tree's stem or sap flux density or the flow rate per unit sapwood area (Vandegehuchte and Steppe 2013; Granier 1987). Sap flow measurements provide insights into water use patterns at the species level and an understanding of environmental and ecological controls on water demand in extreme climates such as drought and heatwaves (Ahongshangbam et al. 2023). Sap flow measurements at the tree level are also helpful to answer bigger hydrological questions, such as managing forests for water supply under climate change (Caldwell et al. 2016) when the tree species level data are scaled up from hillslope to watershed and landscape scales (Boggs et al. 2015, 2021).

4.2.1 Transpiration Affected by Tree Age, Sapwood Area, and Height

Water use by trees increases with the increase in tree size as measured by tree diameter measured at the breast height (DBH) (Fig. 3). The amount of water transported through the sapwood area of a tree stem increases as the leaf area index (LAI) and sapwood area increase over time (Domec et al. 2012).

Tree water use increases with age initially from the seedling and young to mid-rotation and mature stage (Aguilos et al. 2021a), but transpiration rates may decrease as trees get older. Tree transpiration rates decrease as trees grow taller because it takes more energy to move water from roots to the top of the canopy in taller (older) trees with longer hydraulic pathways and lower whole-tree conductance trees.

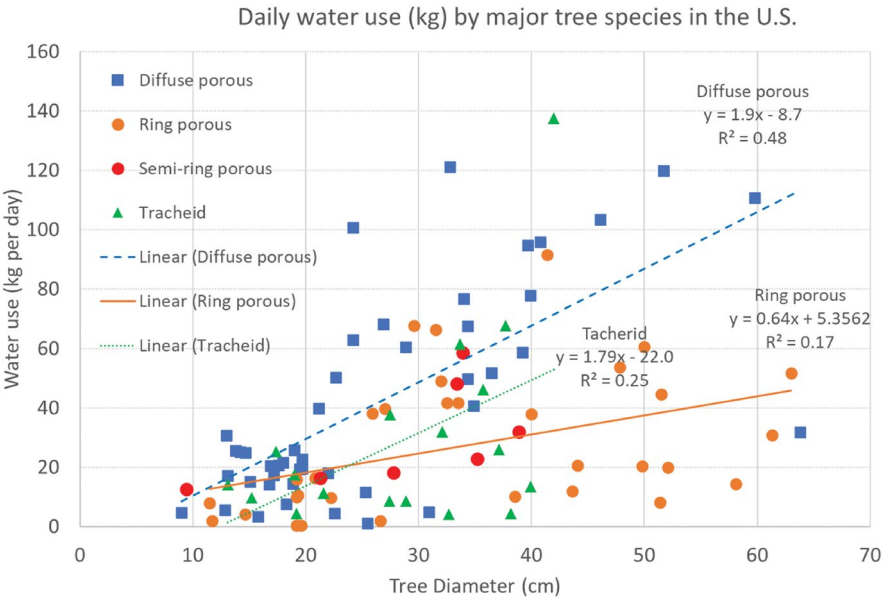

Fig. 3 Measured growing season daily mean sap flow rates (transpiration) grouped by xylem anatomy and tree diameter at breast height (DBH) for major species in the USA. *Diffuse-porous species* include red maple (*Acer rubrum*), sugar maple (*Acer saccharum*), birch (Betula spp.), hackberry (*Celtis laevigata*), dogwood (*Cornus florida*), American beech (*Fagus grandifolia*), European beech (*Fagus sylvatica*), sweetgum (*Liquidambar styraciflua*), tulip-poplar (*Liriodendron tulipifera*), black gum (*Nyssa sylvatica*), hop hornbeam (*Ostrya virginiana*), sycamore (*Platanus occidentalis*), American basswood (*Tilia americana*), catalpa (*Catalpa speciosa*). *Ring porous species* include green ash (*Fraxinus pennsylvanica*), oak (*Quercus* spp.). *Semi-porous species* include hickory (*Carya* spp.), aspen (*Populus* spp.), cherry (*Prunus serotina*). *Tracheid species* include fir (*Abies balsamea*), juniper (*Juniperus monosperma*), white spruce (*Picea glauca*), pine (*Pinus* spp.), northern white cedar (*Thuja occidentalis*), and Easter hemlock (*Tsuga canadensis*)

These patterns were found in ponderosa pine (*Pinus ponderosa*) forests (Ryan et al. 2000) and redwood (*Sequoia sempervirens*) (Ambrose et al. 2010) in Western USA. Measured tree sap flow rates (transpiration) for ~40-year-old 12-m-tall ponderosa pine trees were reported to be 45% higher than that for the ~290 years old 36-m-tall pines during a peak growing season (June–August) in an arid site (precipitation = 360 mm/year) in Oregon (Ryan et al. 2000). Similarly, Delzon and Loustau (2005) studied changes in water use of four even-aged maritime pine (*Pinus pinaster* Ait.) stands (10, 32, 54, and 91 years old) under similar environmental conditions in southwestern France. The highest transpiration rates were 3.8, 2.3, and 1.1 mm/day for 10-, 32-, and 54-year-old stands, respectively. Transpiration in the 91-year-old stand was similar to the 54-year-old stand, about 125 mm a year (or 16.4% of precipitation). The largest difference was observed between the 10- and 54-year-old stand. Annual total overstory stand transpiration declined with age from 508 mm/year (or 63% of precipitation) for the 10-year-old stand to 144 mm/year for the 54-year-old stand.

4.2.2 Transpiration and Xylem Anatomy

The xylem structure of tree stem and branches characterizes hydraulic conductivity and area of sapwood and drives transpiration rates (Ford et al. 2011). Tree species level transpiration studies in the Southeastern USA show that transpiration rates of diffuse-porous species like maples (*Acer* spp.) and tulip-poplars (*Liriodendron tulipifera*) are up to four times higher than similarly sized ring-porous species like oaks (*Quercus* spp.) (Ford et al. 2011) (Fig. 3). These differential xylem properties reflect tree water use strategies and how trees respond to drought (McQuillan et al. 2022).

Pine trees are characterized as having a tracheid xylem structure with relatively lower water use than the diffuse-porous group but are comparable to ring-porous or semi-ring-porous groups (Fig. 3). For example, under a similar climate in the humid Appalachian Mountains in western North Carolina, Eastern USA, a tulip-poplar tree (*Liriodendron tulipifera*) with a diameter of 40 cm transpires about 100 kg/day, while white pine (*Pinus strobus*) transpires only 13 kg with similar DBH. This contrasts with chestnut oak (*Quercus prinus*) (DBH = 52 cm) which belongs to the ring-porous group and transpires only 20 kg/day.

4.2.3 Transpiration Rates Influenced by Climate Regime

The large variability of mean daily water use at the tree level presented in Fig. 3 is unsurprising. Tree transpiration is known to be controlled by both soil water variability and atmospheric demand capacity that can be quantified by atmospheric vapor pressure deficit (VPD) (Shuttleworth and Wallace 1985; Novick et al. 2016) and a more complete climatic variable, potential evapotranspiration (PET), that integrates all meteorological factors often including net radiation and VPD (Whitehead and Kelliher 1991; Lu et al. 2005; Sun et al. 2011). We use regional PET/P (dryness index, DI) to represent the local climate regime and examine how background climate influences normalized water use by dividing daily mean water use per tree by its basal area (BA) (Fig. 4).

It appears that pine forest distributions in the USA have a large range in terms of climate with PET/P ranging from 0.75 (humid) to 1.25 (arid). Normalized water use rates generally increase with an increase in DI for the 0.75–1.1 dryness range, especially for deciduous trees characterized by a diffuse-porous xylem structure. However, water use rates for all forest types decrease when the climate gets drier (DI > 1.2). A sharp decrease in water use is found for diffuse-porous species, while water use is stabilized or moderately decreased. These patterns might suggest that trees growing in relatively dry regions (DI = 1.2–1.5) have lower transpiration and water stress. Transpiration rates are found to be the highest where DI is about 1.1 for most tree species including pines (Fig. 4). The extremely high value of water use of 180 g/day/cm^2 is for young quaking aspen (*Populus tremuloides*) (DBH = 9.4 cm).

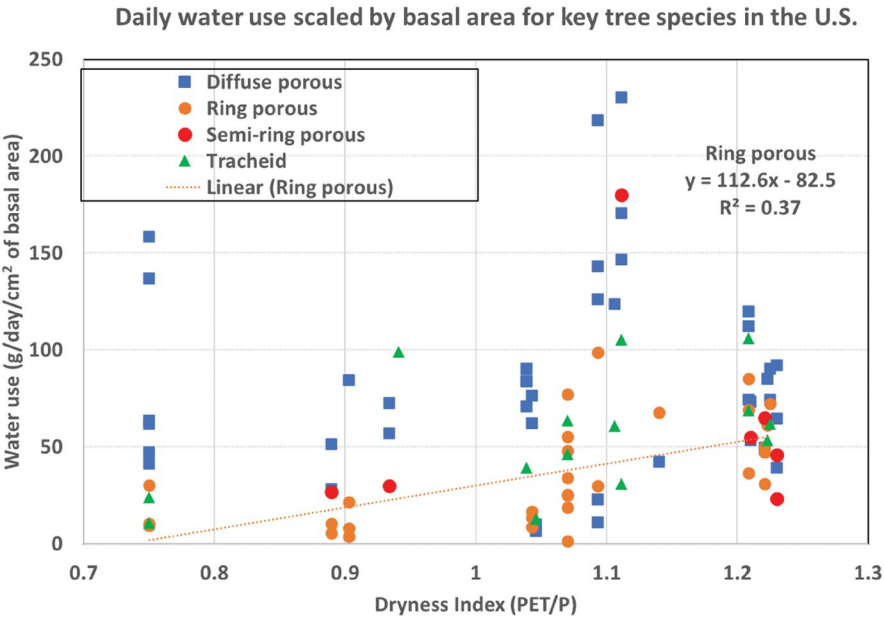

Fig. 4 Normalized water use (g/day/basal area cm^2) and climate dryness index (PET/P) for major tree species group by xylem structures in the USA

4.3 Total Evapotranspiration (ET)

As the sum of transpiration (Et), canopy and litter interception (Ei), and soil water evaporation (Es), total ET is affected by meteorological (e.g., net radiation, wind speed, VPD), and biological processes (e.g., tree hydraulics (root distribution and depth, LAI, and stomata conductance) and soils (soil water content or matric potential)). These processes may compensate, cancel, or enhance the ET rates contributed by each of the ET component. For example, an increase in LAI as trees mature generally increases stand transpiration and canopy interception, but it can also decrease soil and understory vegetation evaporation because of canopy shading resulting in reduced radiation and lower wind speed on forest floor. Thinning may reduce overstory transpiration and canopy interception, but it may increase transpiration from the understory or the remaining trees (Boggs et al. 2015), resulting in complex ET and water yield responses (del Campo et al. 2022). Studies suggest that forest ET is a conservative process (Roberts 1983)—tree transpiration rates tend to be stable in response to periodic climatic variability in precipitation (Oishi et al. 2010, 2018). Meteorological droughts and minor thinning do not necessarily result in a dramatic decline in forest total ET (Liu et al. 2018). Forest ET demand can also be met by variable soil water stores at deeper layers or rock fractures, the Earth's Critical Zone (Stocker et al. 2023).

Published pine forest ET data discussed below come from three primary sources, measurements by the eddy covariance method, gaged small watersheds, and simulated water balances, including annual or seasonal ET. In cold temperate or boreal regions, annual ET is dominated by the growing season, and ET measurements are often only available for the growing seasons. In such cases, we examine ET for the growing season in the context of the mean aridity index calculated at the annual scale to represent the local climatic regime and to be consistent with Budyko's analytic framework that characterizes mean conditions.

4.3.1 Climate and Pine Species Effects on Annual ET

The assembled datasets cover a large climatic gradient from the moist tropical Fiji (*P. caribaea*, $P = 2021$ mm, ETo = 1500 mm, aridity index ETo/$P = 0.76$) to extreme arid regions such as Iran ($P = 203$ mm, ETo = 2075 mm, ETo/$P = 10.2$) (Figs. 5 and 6). Some pine species are found in a large climatic range from arid to humid regimes. For example, Aleppo pine (*Pinus halepensis*) is found in Spain and Israel with a large annual precipitation range from less than 260 mm to more than 1500 mm. Pine trees can survive under a climate with low precipitation and cold temperature (ETo < 300 mm, *P. strobus* in Canada) or dry and hot environments (ETo > 2000 mm, *P. halepensis* and *P. eldarica*, in Israel and Iran, respectively).

Pine forest ET rates vary tremendously from less than 300 mm/year (*P. banksiana*) to more than 1800 mm/year (*P. caribaea*) (Fig. 7). Overall, annual ET increases with precipitation (Fig. 8). On average, pine forests lose about 66 ± 23% of annual precipitation through ET. The mean value is similar to those reported by Ford et al. (2011) ($ET = 0.72P - 10.48$) but is much higher than reported value (53.7%) for global forest lands (Oki and Kanae 2006). Due to climatic variability, pine forest

Fig. 5 A distribution of pine forest evapotranspiration research sites (total 158 sites). Numbers next to each color-coded symbol by pine species are aridity index values (ETo/P). Details of each study site are reported in Supplementary (Table S2)

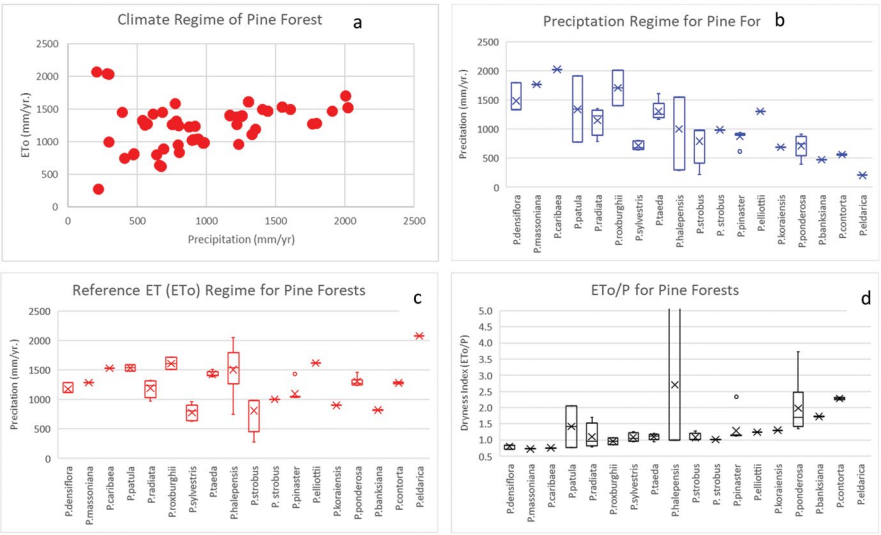

Fig. 6 Climate regimes of 18 pine forests. (**a**) Annual precipitation and reference ET (Eto), (**b**) precipitation by species, (**c**) ETo by pine species, and (**d**) dryness index (Eto/*P*) by pine species. ETo/*P* = 10.2 for *Pinus eldarica* not shown

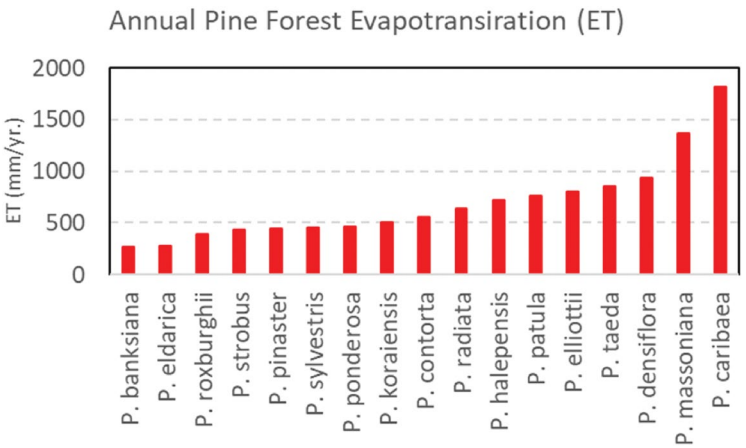

Fig. 7 A summary of reported values for annual evapotranspiration for 17 *Pinus* species

ET/*P* values vary tremendously from less than 40% in the cold areas (*P. strobus*) in Canada or wet regions (*P. radiata*) in Chile to more than 137% (*P. eldarica*) in an arid region. For the latter case, the *P. eldarica* stand likely used up all annual precipitation in the measurement year and accessed soil water storage.

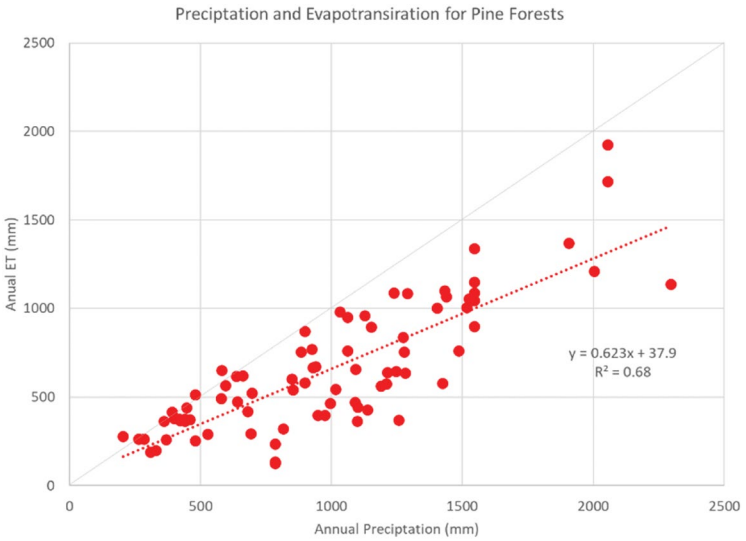

Fig. 8 Annual evapotranspiration increases with annual precipitation for 17 *Pinus* species

4.3.2 Stand Age Effects

In addition to the climatic regime (*P* and ETo) and species controls on ET rates, stand age also affects total forest ET. Forest ET rates increase with age as trees mature and leaf areas and sapwood areas increase. For example, long-term eddy flux measurements on loblolly pine (*P. taeda*) plantation forests on the coastal plain of North Carolina across an age chronosequence show that ET rates increase rapidly from 0 to 10 years and become stabilized around year 15 at the middle rotation stage (Fig. 9) (Aguilos et al. 2021b). However, age effects on ET can be masked by climatic variability. Changes in LAI and canopy structure over stand age may not necessarily cause a large change in annual ET in rather wet humid conditions such as forested wetlands. For example, annual ET estimates by the eddy covariance method in north central Florida averaged 959, 951, and 1110 mm along a chronosequence of slash pine (*P. elliottii*) for clear-cut, mid-rotation, full-rotation plantation stands, respectively (Gholz and Clark 2002). In such a case, total annual ET is more sensitive to environmental fluctuations than to stand age or management activities that affect both soil evaporation and transpiration. The role of vegetation in influencing shallow groundwater table and ET is most pronounced during the dry period (years) (Amatya et al. 1997; Sun et al. 2000; Skaggs et al. 2011; Riley et al. 2023).

Müller and Bolte (2009) quantified ET rates of Scots pine (*P. sylvestris*) trees using large lysimeters and found that the water consumption first increased with age and then decreased, reaching a peak around year 30 (Fig. 10). At age 30, Scots pine trees used up all water input from precipitation, resulting in no deep seepage from the rooting zone (Fig. 10).

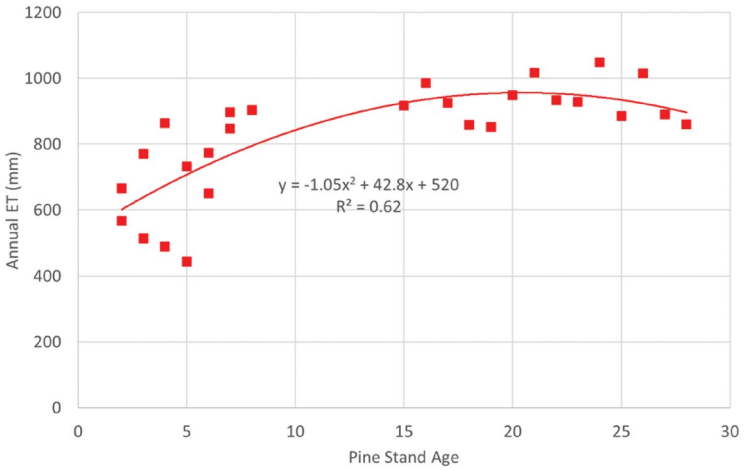

Fig. 9 Evapotranspiration rates of loblolly pine (*P. taeda*) plantations increase with stand, especially from seedlings to 15 years old. The ET data (2005–2018) are collected using an eddy flux method for stands with multiple ages at the lower coastal plain of North Carolina in the Southeastern USA (Sun et al. 2010; Domec et al. 2012; Aguilos et al. 2021a, 2021b)

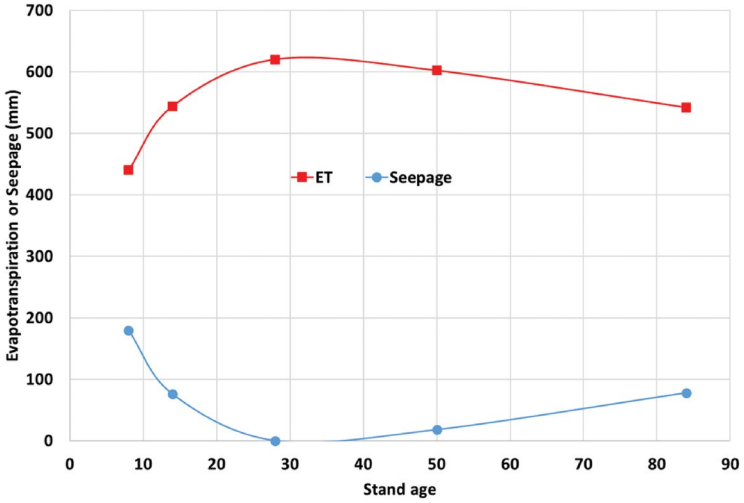

Fig. 10 Influences of Scots pine (*P. sylvestris*) growth stages on the water balances measured in lysimeters in Germany (annual precipitation = 620 mm) (Müller and Bolte 2009)

4.3.3 Effects of Management (Ditching and Prescribed Fires)

Globally, since the mid-eighteenth century, drainage has been used to increase timber yields on poorly drained peatlands and mineral soils in Northern Europe, Canada, and the Southern USA (Skaggs et al. 2016). In the Southeastern USA, large

acreage of loblolly pine (*Pinus taeda* L.) and slash pine (*Pinus elliottii*) plantations have been established on pine flatwoods or formerly forested wetlands on the coastal plains. Silviculture practices often involve water management, such as free or controlled drainage (Amatya et al. 1996), to lower soil wetness and benefiting forest productivity. Studies document that tree growth is higher by 80%–1300% and as much as ten times greater wood production on drained compared to undrained loblolly pine plots (Skaggs et al. 2020). Amatya et al. (1996) report that controlled drainage using weirs reduced both drainage volumes (15–30%) and daily peak outflow rates and increased ET by 10–20%. However, a remote sensing study in North Carolina suggests that drained mature loblolly pine plantations have similar annual ET to adjacent natural forests without artificial drainage but have a much higher ET rate than young plantation forests (Yang et al. 2017).

Prescribed burning is also used in the Southern USA to control understory competition and improve nutrient and water availability and wildlife habitats (McLaughlin et al. 2013). These practices have important effects on water yield and groundwater recharge by reducing forest water use (ET). LAI is the dominant forest structural factor influencing both soil evaporation and interception rates; thus, it has been widely used as a major indicator for forest management to augment water yield (Acharya et al. 2022; Pisarello et al. 2022) and ET modeling (Sun et al. 2011; Malone et al. 2015).

4.3.4 Effects of Pine Species Conversions: The Case of Longleaf Pine Forest Restoration

Historically, longleaf pine (*Pinus palustris* Mill.) dominated much of the coastal plain and portions of the piedmont in the Southeastern USA (Peet et al. 2018). However, over the past century, management that favored fast-rotation wood production and fire suppression led to a drastic reduction in longleaf pine in favor of loblolly pine (*Pinus taeda* L.) plantations for timber production. Concerns about climate change and the rise of demand for multiple ecosystem services promoted large-scale efforts throughout the region to restore longleaf pine ecosystems that are believed to be more resilient to climate change (Franklin 2009; Brantley et al. 2018). One of the recognized ecological benefits of longleaf pine restoration is an increase in water yield. Compared to productive loblolly pine plantations, longleaf pine forests have lower ET because of their lower tree density, open canopies with C4 grass as an understory, lower total leaf areas, and leaf stomata conductance (Brantley et al. 2018; Qi et al. 2022). A remote sensing study across the southeastern region using a "paired stand" approach suggests that most longleaf pine stands have lower ET than the paired loblolly pine stands (Fig. 11). This contrast is explained by lower LAI and tree height but higher land surface temperature (LST) and albedo for longleaf pine stands than adjacent loblolly pine stands (Liu et al. 2025, Unpublished data). A synthesis study on eddy flux measurements of pine forests for the region also indicates that longleaf pine stands have lower ET and ET/P ratios (Liu et al. 2025; Aguilos et al. 2024).

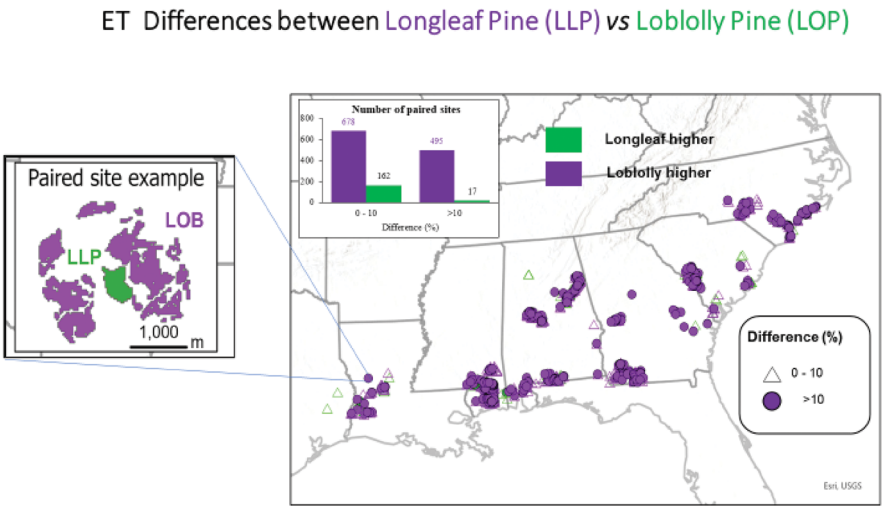

Fig. 11 A comparison of annual evapotranspiration (ET) between longleaf pine (LLP) stands and their adjacent loblolly pine (LOP) stands within a 2-km radius. Only sites with significant differences ($p < 0.05$ by paired-t test) are shown. ET is estimated using ECOSTRESS surface temperature data and an energy balance simulation model at a 30 m by 30 m resolution (https://lpdaac.usgs.gov/news/release-ecostress-usda-et-and-esi-products/) (Hook and Anderson 2019)

4.3.5 Global Pine Forest ET Under the Budyko's Framework

According to Budyko's water and energy balance theory, as quantitatively described in Eqs. (3) and (4), the evaporative index ET/P nonlinearly increases with the aridity index PET/*P*. Equations (3) and (4) have different forms, but they provide similar curves for PET/*P* vs. ET/*P* relationships of forest lands, especially under dryer conditions (PET/*P* > 1.0) or water-limited climatic regimes. Although the measured ET/*P* values follow the general trend as expected (Fig. 12), observed ET/*P* values at many sites deviate from ET/*P* values estimated by the theoretical two equations that represent the long-term means over a large spatial sale. Among the 84 pine forest sites examined, 35 sites (or 42%) exhibited higher annual ET/*P* values than predicted by the Budyko relationship, and 49 sites have lower ET/*P* values. These deviations from "the norm" offer insights into understanding how pine forest water uses respond to local climate (Creed et al. 2014) and other environmental factors such as soil and topography (Zhou et al. 2015).

We discuss these ET/*P* deviations in five major groups to illustrate the likely reasons causing the discrepancies.

Group 1 Growing season ET exceeds precipitation. These sites are dominated by maritime pine (*P. pinaster*) in France (Moreaux et al. 2011) with PET/*P* around 1.0 and annual precipitation of 900–1400 mm. These sites receive little precipitation (e.g., 20–35% of total annual) in the growing season when PET and ET are high. This type of climate also is common in the Pacific Northwest of the USA where

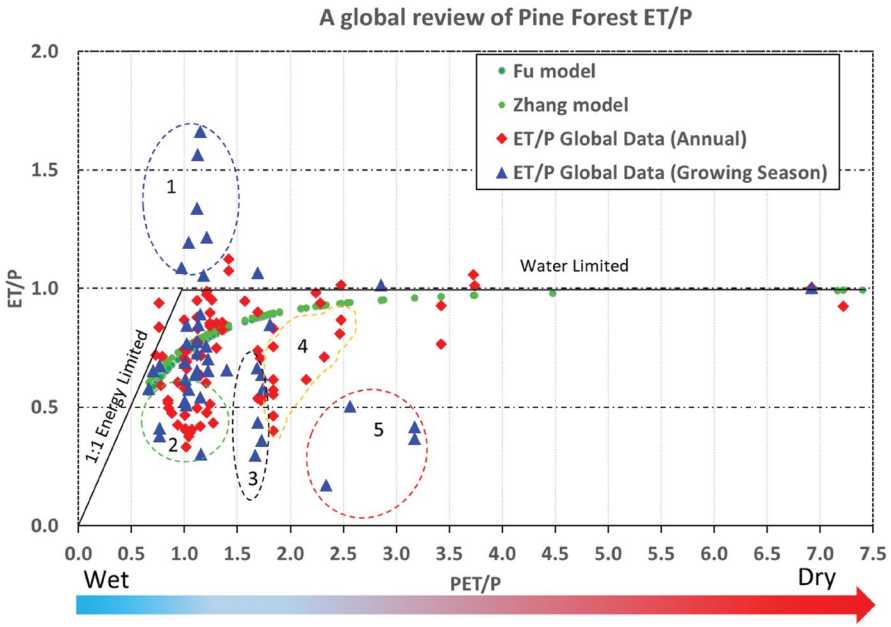

Fig. 12 A comparison between measured annual or growing season evaporative index (ET/*P*) values of pine forests and predicted by two theoretical models. ET/*P* rates are influenced by regional climate patterns and local environmental conditions and forest management (see Supplementary Table S2). The five circles represent large deviations from predicted ET/*P*

most of the precipitation falls in the winter (Segura et al. 2020). For these sites, nongrowing season precipitation and soil water storage are important for tree water use and growth in the summer months when the low flows present.

Group 2 Annual ET/P values for this group are much lower (<0.5) than expected (0.75), suggesting forest disturbances or soil water stress for tree growth. These are boreal forest sites with a short growing season. The Canadian sites (Tang et al. 2017) dominated by white pine (*P. strobus*) even-aged plantations including young, intermediate, and mature trees have warm summers and cold winters. The *P. sylvestri* stands in Finland (Ilvesniemi et al. 2010) had a boreal climate receiving precipitation dominated by winter snows.

Group 3 Lower ET in the growing season (May–September) than expected. These forests are found in Saskatchewan, Canada, that are dominated by jack pine (*P. banksiana*) under a cool climate (PET < 700 mm/year) with low precipitation (<500 mm/year) mostly in the growing season. The low growing season ET (117–313 mm) also reflects the impacts of wildfire and harvest disturbances (Mkhabela et al. 2009).

Group 4 Lower annual (ET/*P* < 0.8) than expected (0.93) in a dry climate (PET/*P* = 2.0–2.5). These sites are found in Orgon (Tang et al. 2015) dominated by ponderosa pine (*P. ponderosa*) and Lodgepole pine (*P. contorta*) in Wyoming (Biederman et al. 2014) (a wetter site with *P* = 840 mm compared to regional *P* of 560 mm dominated by winter snow). The modeled ET/*P* values for Aleppo pine (*Pinus halepensis*) stands in Spain were 0.4–0.61 much lower than expected (0.96) under a dry climate (PET/*P* = 1.84) (González-Sanchis et al. 2015) and semiarid regions (Bellot and Chirino 2013) (PET/*P* = 3.4). The simulated low ET rates found by González-Sanchis et al. (2015) demonstrate the hydrologic effects of "adaptive forest management" (AFM) that alter forest structure and density and reduced ET.

Group 5 Lower growing season (ET/*P* < 0.6) than expected (1.0) in a dry climate (PET/*P* = 2.3–2.5). These two of the four sites are in France (Delzon and Loustau 2005) where only sap flow measurements were reported and pine trees experienced substantial water stresses and loss of needles during drought. The other two sites dominated by *P. tabulaeformis* and *P. sylvestris* are in a city park with only growing season sap flow measurements available in Inner Mongolia northern (Chen et al. 2023).

It should be stressed that measured ET/P at the stand scale or even a watershed level is not likely to match the predicted by the two theoretical models due to the local conditions (i.e., climate, topography, and disturbances). Also, there is uncertainty in the empirical parameters derived from long-term water balance for many types of forests and watershed characteristics (Zhang et al. 2001, 2004).

5 Summary and Implications

Pine forests are found in all climatic zones on Earth and constantly impacted for global change (Richardson et al. 2007). Pine trees are increasingly planted for many purposes from urban greening and soil erosion control (e.g., in northern China and other dry regions) to commercial timber production (e.g., in Southern USA, southern China, tropics, and other humid regions). Pines as evergreen species may have lower albedo, higher leaf area, and longer growing seasons and thus often have higher canopy interception rates when compared to deciduous broadleaf forests.

Forest canopies (both overstory and understory) can intercept significant amount of precipitation influencing the precipitation partitioning and water yield from forests. Forest management practices, such as thinning and prescribed burning that reduce tree density and total stand leaf area index, can decrease total ET loss and increase water yield and groundwater recharge, thus having the potential to enhance forest resilience to drought. Stand age, height, structure, and plant species compositions affect canopy interception, litter interception, transpiration, and total ET from pine forests. As pine trees mature and get taller, ET may decrease. Growing season ET of pine forests can

greatly exceed precipitation in the growing season; thus, nongrowing season precipitation is vital to meet water demand for ecological functions. The total annual ET of pine forests can be lower or higher than predicted from the Budyko type of general models, suggesting the complex effects of local climate, disturbance, and management on forest ET. Few studies have examined ET from understories in forests, hindering accurately modeling effects of forest management on total ET and water yield.

Our global review demonstrates a large variability of water use by pine trees and forests across a large climatic gradient, a combination of precipitation and potential ET. Pine forest water balances can be altered by changing tree density through thinning and prescribed burning, tree species conversion, artificial drainage, and climate change and variability. Tree planting with pines must consider their differential water demand to maximize ecosystem service goals (e.g., carbon, water, biodiversity, soil erosion control). This is especially important given the large uncertainty in projected future climate change, which is likely to exacerbate extreme events such as droughts that threaten forest sustainability in many parts of the globe.

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Appendix

Table 1 A comparison of canopy interception rates among key *Pinus* trees around the globe

Location	Species	Climate (annual *P* and ET) (mm)	Interception rate (I/P) (%)	References
USA 35°48′ N, 76°40′ W	Loblolly pine (*Pinus taeda*) (age, 13–23)	Humid (10 years, mean *P* = 1227)	14–23 (biweekly)	Gavazzi et al. (2016)
USA 34°50′ N, 76°39′ W	Loblolly pine (*Pinus taeda*) (age, 15)	Humid *P* = 2885 (storm events)	5–35 (un-thinned)	McCarthy et al. (1991)
USA 34°50′ N, 76°39′ W	Loblolly pine (*Pinus taeda*) (age, 15)	Humid *P* = 2885 (storm events)	5–25 (thinned)	McCarthy et al. (1991)
USA 36°20′ N, 79°28′ W	Loblolly pine (*Pinus taeda*) (age, 35–37)	*P* = 2224 (3 years)	21.9 (annual)	Tor-ngern et al. (2018)
USA	Longleaf pine (*Pinus palustris* Mill.)	Humid	20	Helvey (1971)

(continued)

Table 1 (continued)

Location	Species	Climate (annual *P* and ET) (mm)	Interception rate (I/P) (%)	References
USA 29°44′ N, 82°9′30″ W	Slash pine (mid-rotation age) *Pinus elliottii*	*P* = 1062, ET = 1057	10.2 (annual)	Gholz and Clark (2002)
USA 29°44′ N, 82°9′30″ W	Slash pine (rotation age) *Pinus elliottii*	*P* = 1288 ET = 1194	8.4 (annual)	Gholz and Clark (2002)
USA 35.07° N, 83.43° W	White pine (*Pinus strobus* L.) (age, 48–49 plantation)	*P* = 2240 ET = 1291	26 (annual)	Ford et al. (2007)
USA 31.498° N, 94.756° W	Longleaf pine (*Pinus palustris* Mill.) (age, 21)	*P* = 1282 (44 storms) 1 year	12.3	Roth II and Chang (1981)
USA 31.498° N, 94.756° W	Shortleaf pine (*Pinus echinata*) (age, 21)	*P* = 1282 44 storms 1 year	8.5	Roth II and Chang (1981)
USA 31.498° N, 94.756° W	Loblolly pine (*Pinus taeda*) (age, 19)	*P* = 1282 44 storms 1 year	15.5	Roth II and Chang (1981)
USA 31.498° N, 94.756° W	Slash pine (*Pinus elliottii*) (age, 21)	*P* = 1282 44 storms 1 year	16.8	Roth II and Chang (1981)
USA	Red pine (*Pinus resinosa* Ait.)	N/A	15.0 (annual)	Helvey (1971)
USA	Ponderosa pine (*Pinus ponderosa* Dougl. ex Laws.)	N/A	14.0 (annual)	Helvey (1971)
Northern China (40°23′ N, 116°50′ E)	Chinese pine (*Pinus tabulaeformis*) (age, 33 plantation)	*P* = 1419 (3 years, 61 storms)	31.7 (storm)	Xiao et al. (2007)
Northern China (40°49′ N, 111°41′ E)	Chinese pine (*Pinus tabuliformis*)	May–September *P* = 240 ET = 393	23–48 (monthly scale)	Wang et al. (2022)
Northern China (41.7° N, 117.5° E)	Chinese pine (*Pinus tabuliformis*) (age, 28 plantation)	June–October *P* = 313 (1 year, 50 storms)	19.6–31.3	Dong et al. (1987)
Northern China (41.3° N, 118.52° E)	Chinese pine (*Pinus tabuliformis*)	429	20.4	Dong et al. (2020)
Northern China (41.3° N, 118.52° E)	(*Pinus tabuliformis*)	429	24.8	Dong et al. (2020)
Northern China (41.3° N, 118.52° E)	(*Pinus tabuliformis*)	429	32.8	Dong et al. (2020)

(continued)

Table 1 (continued)

Location	Species	Climate (annual *P* and ET) (mm)	Interception rate (I/P) (%)	References
Southwestern China (31°41′07″ N, 103°53′58″ E)	Chinese pine (*Pinus tabuliformis*) (age, 23 plantation)	*P* = 806 (136 storms)	37	Bao et al. (2004)
Southwestern China (29°38′ N, 106°41′ E)	Masson pine (*Pinus armandii*) (age, 50–70 plantation)	*P* = 1972 (2 years, 84 storms)	15.4	Wang et al. (2021)
Southwestern China 30°54′ N, 103°35′ E	Mixed *Pinus tabulaeformis* and *Pinus armandii*	*P* = 167 (24 storms)	51	Chang et al. (2006)
Northwestern China 35°52′ N, 110°45′ E	Chinese pine (*Pinus tabulaeformis*) (age, 25 plantation)	*P* = 486 (1 year, 5 storms)	19.6	Liu et al. (1991)
Northwestern China 38°20′11″ N, 109°42′54″ E	Mongolia Scots pine (*Pinus sylvestris* var. *mongolic*a)	*P* = 395 (28 storms)	36.1 (modeled)	Deng (2020)
Northern China 120°43′ E, 42°55′ N	Mongolia Scots pine (*Pinus sylvestris* var. *mongolica*) (age, 27 plantation)	*P* = 279.4 (42 storms) 1 year	13.5	Sun et al. (2021)
Nepal 27°34′ N, 85°33′ E	Chir pine or longleaf Indian pine (*Pinus roxburghii*) (age, 25 plantation)	*P* = 878 1 year	16.5	Ghimire et al. (2012, 2013)
Spain 42.2° N, 1.8176° E	Scots pine (*Pinus sylvestris*)	*P* = 1825 30 months (152 storms)	24.0	Llorens et al. (1997)
Sweden 64°10′ N, 19°45′ E	Scots pine (*Pinus sylvestris*)	Growing season 3 years, mean *P* = 400	21.9	Tor-ngern et al. (2017)
Japan 36°07′ N, 140°06′ E	Japanese *red pine* (*Pinus densiflora*)	*P* = 1213 1 year (un-thinned)	17.2	Iida et al. (2005)
Japan 36°07′ N, 140°06′ E	Japanese *red pine* (*Pinus densiflora*)	*P* = 1245 (thinned)	9.2	Iida et al. (2005)
44°05′ N, 0°05′ W	Maritime pine (*Pinus pinaster*)	*P* = 613 1 year	11.9	Gash et al. (1995)
Portugal 38°50′ N, 8°51′ W	Maritime pine (*Pinus pinaster*) (age 60)	*P* = 1366.2 31 months	17.1	Valente et al. (1997)

(continued)

Table 1 (continued)

Location	Species	Climate (annual *P* and ET) (mm)	Interception rate (I/P) (%)	References
France 44°42′ N, 0°46′ W	Maritime pine (*Pinus pinaster*)	Total *P* = 1976 3 years	14–22	Loustau et al. (1992)
52°20′ N, 0°42′ W	Scots pine (*Pinus sylvestris*) (age 18)	Total *P* = 942.4 2 years	27.3	Gash (1979)
UK 57°41′ N, 3°29′ W	Scots pine (*Pinus sylvestris*)	*P* = 493 1 year	42.4	Gash et al. (1980)
Germany 52°26′34.55″ N, 13°26′1.97″ E	Scots pine (*Pinus sylvestris*)	*P* = 633, ET = 623 (8 years simulated)	40.0	Müller (2009)
Germany 52°58′ N, 10°19′ E	Scots pine (*Pinus sylvestris*)	*P* = 638 mm, ET = 588 (1991)	31.0	Leuschner et al. (2022)
Germany 52°58′ N, 10°19′ E	Scots pine (*Pinus sylvestris*)	*P* = 815 mm, ET = 738 (1992)	30.0	Leuschner et al. (2022)
Iran 36°25′ N, 50°55′ E	Afghan pine (*Pinus eldarica*)	*P* = 101	44.0 (46–80 by storms)	Attarod et al. (2015)
Iran 35°42′ N, 51°08′ E	Afghan pine (*Pinus eldarica*)	*P* = 232.5	44.6	Sadeghi et al. (2014)
Slovenia 46.04° N, 14.49° E	Black pine (*Pinus nigra*)	*P* = 1380	72	Zabret et al. (2018)
Turkey 39.155° N, 29.816° E	Black pine (*Pinus nigra*)	*P* = 542	27.7	Aydın et al. (2018)
Turkey 39.155° N, 29.816° E	Scots pine (*Pinus sylvestris*)	*P* = 542	20.2	Aydın et al. (2018)
South Africa 29°11′ S, 30°39′ E	Patula pine (*Pinus sylvestris*)	*P* = 692	21.4	Bulcock and Jewitt (2012)
Trinidad and Tobago 10°41′45.3″ N, 61°29′23.0″ W	*Pinus oocarpa*	*P* = 1314	58.0	Francis et al. (2022)

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