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Key Points:

- Longleaf pine forests (LLP) exhibit lower total evapotranspiration than loblolly pine (LOP) forests based on eddy flux and remote sensing data
- Significantly lower leaf area, and higher albedo and land surface temperature found in LLP than LOP forests
- Restoring LLP forests in the southeastern United States could potentially augment water yield compared to LOP forests

Supporting Information:

Supporting Information may be found in the online version of this article.

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Potential for Augmenting Water Yield by Restoring Longleaf Pine (*Pinus palustris*) Forests in the Southeastern United States

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Abstract Over 95% of original longleaf pine (*Pinus palustris*) (LLP) forests have been converted to other land uses, including loblolly pine (*Pinus taeda L*) (LOP), croplands, urban uses during the past two centuries in the southeastern United States (U.S.) for socioeconomic developments. Restoring the LLP forests represents a contemporary forest management objective to improve wildlife habitat, water yield, and overall ecosystem services and resilience to a changing climate. Given the importance of understanding ecohydrological processes for guiding restoration efforts, this study compared evapotranspiration (ET) measurements at eight eddy covariance flux sites dominated by LLP or LOP forests in the southeastern U.S. In addition, we developed a "paired stands" approach to compare remote sensing based ET estimates and associated site biophysical properties for approximately 1,600 LLP-LOP pairs. We found significant differences in ET, ET/Precipitation ratio, and water yield/precipitation ratio between the two types of pine forests, and these differences are explained by surface properties and management histories. Compared to LOP, the LLP forests generally had lower ET due to their significantly ($p < 0.05$) lower leaf area index but higher land surface temperature and albedo. Regionally, forest ET differences increased with the increase in atmospheric dryness index (reference ET/precipitation ratio). Therefore, we conclude that large-scale restoration of LLP forests has the potential to reduce ET and augment water yield in the long run, especially in relatively drier watersheds. Maintaining low stand tree density and understory leaf area characteristic of natural LLP ecosystems through active forest management is critical for enhancing forest water supply. Our study provides the scientific basis for large scale restoration of a diminishing ecosystem for benefiting water resources in the southeastern U.S.

Plain Language Summary Almost all the virgin longleaf pine forests have been converted to croplands, commercial plantation forests, urban uses during the past two centuries in the southeastern United States (U.S.) Restoring these fire-dependent, open longleaf pine forests from existing dense fire-prone loblolly pine forests is expected to improve habitats for endangered and rare plant and wildlife species and to reduce forest water use thus to increase water supply for humans and aquatic ecosystems downstream. This study aims to provide the sciences that support the large-scale longleaf pine restoration by directly comparing water use patterns of longleaf and loblolly pine forests. Advanced field monitoring, satellite data, and modeling techniques are used to contrast water use patterns between the two types of forests. We conclude that forest structure and management matter to forest water budget and longleaf pine restoration has the potential to enhance water supply when properly implemented at the regional scale. Our study results have important implications to use forest management as a "Nature based Solutions" strategy to help tackle emerging water shortage issues under a changing climate and increasing human water demand in the southeastern U.S.

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1. Introduction

The heavily forested (>60% land area) southeastern United States (U.S.) is known as the world's "wood basket" (Fox et al., 2007), with rich biodiversity and abundant water resources (Wear & Greis, 2012) thanks to an ideal climate. However, the region is not immune to water shortages due to increased human demands, climatic variability, and dynamic land use change (Sun et al., 2008, 2013). Changes in water demand have been driven by population growth, reduced water supplies from periodic drought (McNulty et al., 2019) and declined water quality (Caldwell et al., 2023), and increased water consumption following the large-scale establishment of pine plantations for fiber productions (i.e., loblolly pine (*Pinus taeda* L.) (Pisarello et al., 2022). Forest mesophication and elevated water use by forests over the past decades amid climate change also contributed to the rising water shortage concerns (Caldwell et al., 2016; McLaughlin et al., 2013; Younger et al., 2023). The connections between forests and water supply are increasingly recognized by the global forest hydrology communities (Creed et al., 2019; FAO et al., 2021; Meli et al., 2024). Forest management and land restoration programs have been considered as one of the important strategies in climate change mitigation and adaptation in the southeastern region (Vose et al., 2016) and globally (Douville et al., 2024; Filoso et al., 2017; Sun et al., 2024).

In the southeastern U.S., loblolly pines and slash pines (*Pinus elliottii*) are two preferred species and widely planted for timber production during the past century due to their rapid growth and adaptability to the local climate (Oswalt et al., 2014). The United States Department of Agriculture (1988) reported loblolly pine as the most planted conifer in the U.S., occupying 13.4 million ha in 1997 (Schultz, 1997). Planted pine occupied 15.8 million ha in the Southeastern US in 2012, an area that is projected to increase in the future (Huggett et al., 2013).

In 2017, the loblolly-shortleaf pine, covering 1.4 million hectares, was the primary planted forest-type group on southern timberland, comprising 71% of all the South's planted forests (Oswalt et al., 2019). Loblolly pine plantations, typically managed for high-density timber production, possess a high basal area and leaf area index (LAI), leading to elevated rates of water consumption than natural forests (Bracho et al., 2018). While forest biomass management strategies such as thinning offer potential mitigation for reducing water loss (Del Campo et al., 2022; McLaughlin et al., 2013; Pisarello et al., 2022), changing climate patterns and environmental stresses, including fire and drought, are likely to change growing conditions of those loblolly pine plantations (Matallana-Ramirez et al., 2021). The large-scale expansion of plantation forests in the southeastern U.S. and land conversion for agriculture and urban development during the past two centuries have resulted in a huge loss of native longleaf pine forests (Mitchell et al., 2014). Longleaf pine ecosystems covered approximately 60 million hectares during pre-European settlement (Frost, 2007). However, by 2017, less than 2 million hectares of longleaf pine remained, representing only 3%–5% of their original extent (Oswalt et al., 2019). The loss of this longleaf pine habitant has severely reduced plant and wildlife biodiversity depending on this ecosystem.

In recent years, there has been a notable shift toward restoring and conserving longleaf pine forests on public lands (Hanberry et al., 2023; McIntyre et al., 2018). These efforts are motivated by enhancing the diverse array of ecosystem services that longleaf pine forests provide. These include improved wildlife habitats for the gopher tortoise, Louisiana pine snake, and red-cockaded woodpecker, enhanced carbon sequestration (Johnsen, 2021), and potentially lowered water consumption, thus elevating water yield and resilience to environmental stressors of periodic droughts and wildfires common in the southeastern U.S. (Brantley et al., 2017; Kirkman & Jack, 2018; Oluoch et al., 2021). Longleaf pine forests are generally characterized as having low tree density and prescribed fires are often used to maintain grassy ground covers. However, significant knowledge gaps exist about how specific forest management and land restoration options can improve regional water supply (Acharya et al., 2022; Domec et al., 2015; McLaughlin et al., 2013). Although the concept of using forest management for harvesting water is not new in the southeastern U.S. (Reinhart et al., 1963) and general principles about how forest restoration may affect hydrology have been established (Jones et al., 2022), uncertainty remains due to the large variability of climate, local watershed conditions, and management regimes (Brantley et al., 2024).

Forest hydrology research is plentiful in the southeastern region (Jackson et al., 2004) and small watershed scale studies suggest that tree species matter to water use and water yield (Swank & Douglass, 1974). However, studies on longleaf pine hydrology are limited and have a short history (Brantley et al., 2024; Qi et al., 2022; Younger et al., 2023). Existing studies suggest that longleaf stands consume less water than loblolly pine for several reasons (Ford, Laseter et al., 2011; Gonzalez-Benecke & Martin, 2010; Samuelson et al., 2001). The water budget characteristics of longleaf pine and loblolly pine are fundamentally different largely due to management practices (Ford, Laseter et al., 2011; Gonzalez-Benecke & Martin, 2010). Loblolly pine stands, typically managed for

Table 1
A List of Spatial Remote Sensing Data for Estimating Evapotranspiration and Surface Property Variables

Data name	Resolution	Time period	References
DisALEXI evapotranspiration (ET_RS)	30 m	2016–2021	(Y. Yang et al., 2017, 2021)
Land surface temperature (LST)	30 m	2016–2021	(Ermida et al., 2020)
Tree height	30 m	2022	(Rollins, 2009) https://landfire.gov/evh.php
LANDSAT reflectance	30 m	2016–2021	(Moreno-Martínez et al., 2020)
Leaf area index (LAI)	30 m	2016–2021	(Martínez-Ferrer et al., 2022)
Albedo	30 m	2016–2021	(Liang et al., 1999)
Annual precipitation	~4 km	2016–2021	(https://www.climatologylab.org/gridmet.html) (Abatzoglou, 2013)
Air temperature	~4 km	2016–2021	(Abatzoglou, 2013)
Alfalfa-reference evapotranspiration (PET)	~4 km	2016–2021	(Abatzoglou, 2013)

timber production, generally have a high stocking density. In contrast, longleaf pine stands, usually managed for open canopy conditions with frequent prescribed fires, were shown to have a significantly lower stocking density (Brockway et al., 2005; Kirkman & Jack, 2018). As a result, longleaf pine stands exhibit a lower LAI and higher albedo compared to loblolly stands (Sun et al., 2010), which may lead to reduced water loss through evapotranspiration (ET). The conversion of current loblolly pine plantations to native longleaf pine ecosystems is expected to increase water yield in the southeastern U.S. due to the lower ET (Brantley et al., 2017; Lockaby et al., 2013; Qi et al., 2022). However, most existing studies were based on modeling or conducted at stand (Ford, Laseter, et al., 2011; Gonzalez-Benecke & Martin, 2010) or relatively small (<400 km^2) watershed (Younger et al., 2023) scales with limited regional coverage. A recent study showed that longleaf pine management with prescribed fire had variable effects on total forest stand ET due to complex response of understory vegetation water use to fire exclusions under different soil water conditions (Brantley et al., 2024).

This study is designed to conduct a regional, comprehensive, and quantitative assessment to illustrate the benefits of longleaf pine restoration on water yield by examining the differences of water consumption between longleaf pine and loblolly pine stands across a climatic gradient in the southeastern U.S. We hypothesize that longleaf pine forests have lower gross ET and, thus, higher water yield than loblolly pine forests at the ecosystem level that includes understory vegetation and soils.

We integrate measured data from multiple sources and consider the wide range of environmental factors and site characteristics that influence water consumption in pine forests. We use a combination of high-resolution remote sensing data, eddy flux measurements, and physically based modeling to quantify the differences in water consumption (ET) and associated surface properties between longleaf pine and loblolly pine-dominated sites. Additionally, we investigate the contributing factors behind these distinctions, including climate, elevation, fire frequency, soil hydrology, and site characteristics. The outcomes of this study provide valuable insights into the potential benefits of longleaf pine restoration on forest hydrology and regional water resources in the southeastern U.S.

2. Methods

The eddy covariance (EC) flux measurement method is considered the "gold standard" for quantifying ecosystem level water exchange with the atmosphere (i.e., ET) (Aguilos et al., 2021; Sun et al., 2010; Volk et al., 2024) although recent literature (Fischer et al., 2023) suggests that eddy covariance may underestimate portions of wet canopy evaporation in forests due to general underestimation of turbulent fluxes and large data gaps for most flux sites. We acquired all available long-term eddy covariance ET (ET_EC) flux data at individual pine forest sites in the study region so we could directly evaluate the ET differences among forest types with consideration of climatic differences in precipitation and potential ET (PET). In lieu of side-by-side direct comparisons between the two types of forest ecosystems at these flux sites, we developed a remote sensing based "paired stands" method to directly compare ET and associated forest structure and biophysical characteristics (e.g., tree height, LAI, and albedo) (Table 1). Statistical methods were applied to each paired site and across sites to detect differences in ET

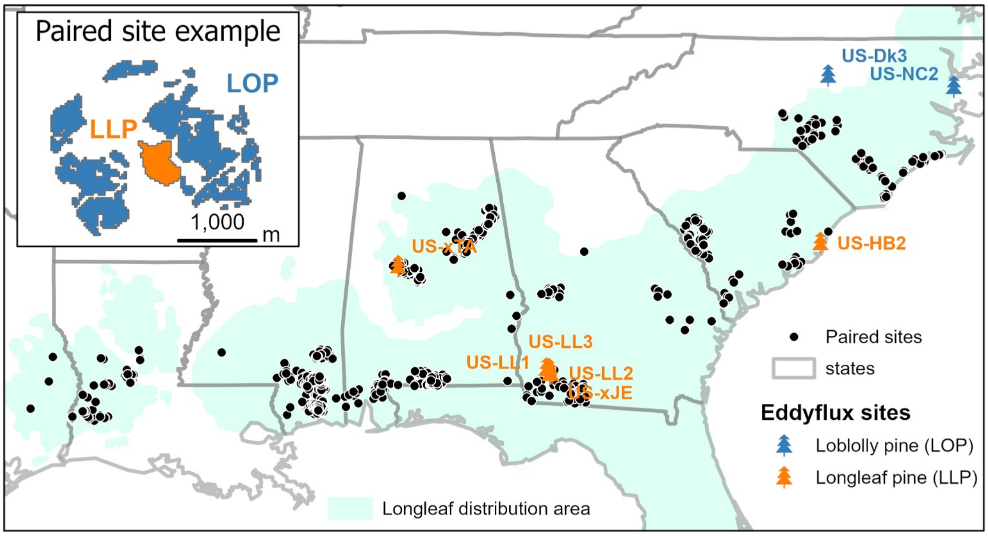

Figure 1. Locations of the longleaf pine (LLP) and loblolly pine (LOP) paired stand sites identified from the Forest Inventory and Analysis (FIA) database. Labels indicate the eight eddy covariance flux measurement sites, which span a broad climatic gradient in the southeastern U.S. (for details see Table S1 in Supporting Information S1). The insert map shows a 2-km buffer used to select paired loblolly stands around a longleaf pine block.

and other surface properties between longleaf and loblolly pine, and to identify the factors influencing these differences.

2.1. Eddy Covariance Flux Measurements

Eight permanent eddy flux sites within the AmeriFlux network in the southeastern U.S., including two loblolly and six longleaf pine sites, were selected in this study (Figure 1). The selection criteria for these eight sites included: (a) the prevalence of either loblolly or longleaf pine as the dominant tree species, (b) mature forest stands with a close canopy, and (c) a minimum of 2 years of measurements without disturbances. Detailed information on the eddy covariance flux sites is summarized in Table S1 in Supporting Information S1, and the original data can be accessed online (http://ameriflux.lbl.gov/). To calculate monthly ET, we took the average daytime ET values (shortwave radiation >20 W m^{-2}) from days with more than 90% valid 30-min latent heat flux measurements. The Bowen Ratio is calculated as the ratio of sensible (H) to latent heat flux (LE). Energy balance ratios (EBR) ((LE + H)/Net radiation) were calculated for each eddy covariance site by excluding ground heat flux, with higher EBR values (closer to 1) at the two loblolly pine sites (0.92 and 0.94), indicating a more accurate estimation of ET, while other sites yielded lower EBR values (ranging from 0.67 to 0.83) (Table S1 in Supporting Information S1).

2.2. Longleaf Pine—Loblolly Pine "Paired Stands" Sites

We identified 1,753 longleaf-loblolly pine stand pairs to directly compare estimated ET and associated surface properties, including LAI, albedo, land surface temperature (LST), and canopy height. These paired sites (Figure 1) were carefully selected using longleaf pine distribution data obtained from the Southeast Longleaf Pine Ecosystem Occurrences Geodatabase (LEO GDB v1.2) (FNAI, 2022) and their corresponding paired loblolly pine sites from the United States Department of Agriculture (USDA) 2018 Forest Inventory and Analyses Program (30 m × 30 m) (USFS FIA, 2021). The LEO GDB v1.2 contains 2.06 million acres (83,337 km^2) of longleaf pine sites located outside of Florida, with approximately 79% identified as longleaf dominant or codominant. Most of the existing data sets were found primarily from federal and state lands. Over 496,000 acres (2,007 km^2) were from rapid assessment field surveys on private lands (FNAI, 2022). Additionally, the 2018 forest type group data were developed using data from over 213,000 national forest inventory plots from the USDA Forest Service Forest Inventory and Analysis (FIA) program (Bechtold et al., 2005), in conjunction with auxiliary information, such as Landsat 8 Operational Land Imager scenes, climatic data, and topographic raster data (Wilson et al., 2018).

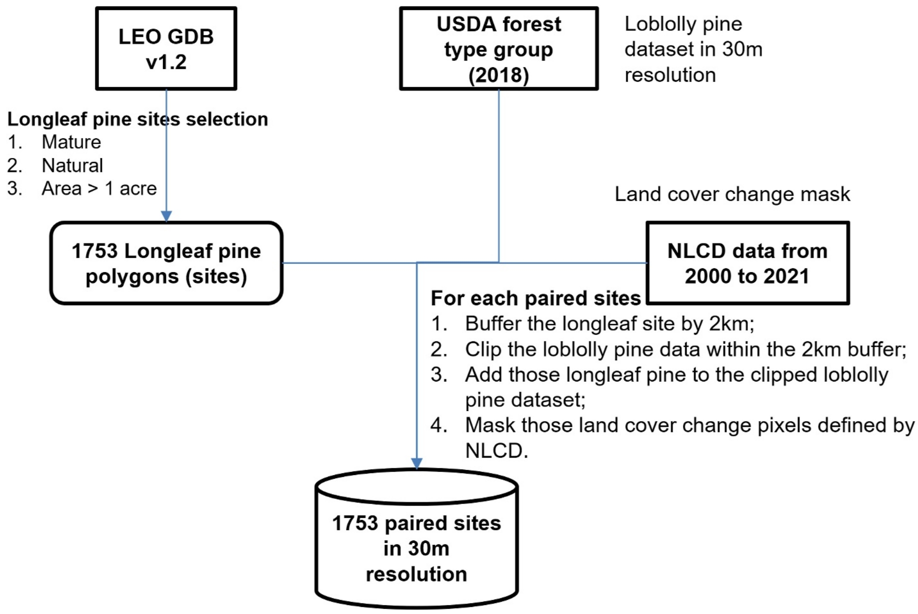

Figure 2. Workflow for creating the "paired stands" longleaf and loblolly pine sites in the southeastern U.S.

Several steps were used to narrow down the 1,753 "paired stands" sites (Figure 2). First, the majority of trees in the stands reached reproductive status (i.e., over 20 years old) that have a natural origin dominated by longleaf pine with an area larger than 1 acer (~4,000 m^2). We used the LEO GDB v1.2 data set with a stand area ranging from 6 (0.024 km^2) to 3,758 acres (15.2 km^2). Second, for each longleaf pine polygon block (or site), a 2-km buffer was used to select the loblolly pine stands (Figure 1 insert). Finally, areas with land cover change between 2000 and 2021 were excluded from the analysis. The land cover change was determined using the National Land Cover Database (NLCD) land cover change data set (L. Yang et al., 2018). In addition, any plot with areas smaller than 100 m × 100 m was eliminated to avoid the influence of edge effects.

Site characteristics from the LEO GDB v1.2 data set were also included in the analysis when available, to examine their effects on ET and other surface properties across different sites. These characteristics included fire evidence (Table S3 in Supporting Information S1), longleaf total basal area (Table S4 in Supporting Information S1), soil hydrology (Table S4 in Supporting Information S1), hardwood canopy basal area (Table S6 in Supporting Information S1), and various understory vegetation coverages, such as midstory cover (Table S7 in Supporting Information S1), midstory fire-tolerant hardwood cover (Table S8 in Supporting Information S1), tall shrub cover (Table S9 in Supporting Information S1), short shrub cover (Table S10 in Supporting Information S1), native herbaceous cover (Table S11 in Supporting Information S1), and native pyrogenic graminoid cover (Table S12 in Supporting Information S1). A total of 304 sites were found to have site characteristic information.

2.3. Remote Sensing Based ET (ET_RS) Estimates and Associated Surface Biophysical Property Data Sets

We used the Disaggregation of Atmosphere-Land Exchange Inverse model (DisALEXI) algorithm (Anderson et al., 2007; Y. Yang et al., 2022) implemented in Google Earth Engine (GEE) under the OpenET platform (Melton et al., 2022) to estimate the actual ET at 30-m resolution. This algorithm was based on the Two Source Energy Balance (TSEB) model (Kustas & Norman, 1997), which incorporates LST retrieved from satellite thermal observations and vegetation index data to calculate actual ET. In the DisALEXI model, LST is used to estimate the surface energy balance, while LAI informs canopy transpiration. The accuracy of the DisALEXI model for estimating ET has been validated across various regions in the U.S., demonstrating strong agreement with ground-based observations and flux tower measurements (Volk et al., 2024; Yang et al., 2017, 2020, 2021). The original DisALEXI ET (ET_RS) over Landsat overpass days were interpolated into daily ET based on the reference ET and then aggregated to monthly scale to be consistent with the other data sets. More details about the GEE-DisALEXI and the interpolation can be found in Yang et al. (2022) and Melton et al. (2022).

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The tree height information of longleaf and loblolly pine sites was extracted from the 2022 LANDFIRE's Existing Vegetation Height product (https://landfire.gov/evh.php), which provides the average height of the dominant vegetation in a 30-m × 30-m resolution. The vegetation height was estimated based on decision tree models that utilized field reference data, lidar, Landsat, and ancillary information (Rollins, 2009).

LST data were obtained from Landsat collection 2 level 2 product (Malakar et al., 2018). LAI and albedo values were calculated from high-resolution (30-m × 30-m) monthly gap-filled surface reflectance data derived from the fusion of Landsat and MODIS with the highly scalable temporal adaptive reflectance fusion model algorithm (Moreno-Martínez et al., 2020). Specifically, shortwave broadband albedo was calculated from the blue (0.45–0.49 μm), red (0.63–0.69 μm), near-Infrared (NIR, 0.77–0.90 μm), short-wave infrared (SWIR) 1 (1.55–1.75 μm), and SWIR 2 (2.08–2.35 μm) bands using weight coefficients for Landsat bands developed by Liang et al. (1999). LAI was calculated from the fused surface reflectance based on a trained artificial neural network (Martínez-Ferrer et al., 2022).

The mean annual precipitation (P), air temperature, and PET (alfalfa-reference evapotranspiration) were extracted from the daily Gridded Surface Meteorological Data set (Abatzoglou, 2013). Dryness index (PET/P, DI) and evaporative index (ET/P) for each site were also calculated as ratio of PET to P and the ET_RS to P, respectively.

For each paired site, remote sensing-based variables were initially calculated at a daily scale and then averaged into monthly time series for the period between 2016 and 2021. To ensure comparability, only months with a complete set of variables were included in the analysis. Additionally, only paired sites with more than 24 months of data within this period were selected. For seasonal comparison, the monthly data were further aggregated into peak (May-September) and non-peak growing seasons (January–April and October–December) for each year. This approach allowed for consistent comparisons between paired sites based on corresponding calendar months, ensuring that temporal differences did not affect the analysis. Ultimately, 1,619 paired sites met these criteria, with each site having a median of 33 months of data. The duration of data collection across these sites ranged from 25 to 59 months. This method ensures that the comparisons are valid and consistent across different sites, regardless of the varying durations of data collection.

The seasonal relative difference in ET and other surface properties between loblolly pine and longleaf pine for each paired site was calculated in three steps: First, we grouped the paired monthly data by month and species (longleaf vs. loblolly pine) and calculated the long-term monthly averages for each species to minimize duration effects. Then, we aggregated these monthly averages into seasonal means, distinguishing between the peak and non-peak growing seasons. Finally, for each season, we calculated the relative difference by subtracting the longleaf pine's seasonal means from these of loblolly pine, which are further divided by the longleaf pine's means and multiplied by 100. This approach provided a standardized metric for comparing the two forest types, effectively accounting for seasonal variations.

2.4. Statistical Analyses

2.4.1. Testing Differences Between Longleaf and Loblolly Pine Paired Sites

We conducted a Wilcoxon Signed Rank test, a non-parametric method, to assess significant differences in the monthly time series mean data for ET and other surface properties (LAI, LST, and albedo) for each of the 1,619 paired sites individually, spanning the period from 2016 to 2021 (Figure S1 in Supporting Information S1). The significance level was set at 0.05 (Hollander et al., 2013). Given the seasonal variation and the presence of missing values, we employed the paired option in the Wilcoxon test to ensure that comparisons were made only between matched data points from corresponding months for each paired site. However, we did not perform separate tests for each month due to the potential lack of sufficient measurements across some paired sites. For tree height comparisons, we applied the Wilcoxon Signed Rank test at the pixel scale (30-m × 30-m) within each pair site (Figure 1 insert).

We employed a mixed-effects model followed by a likelihood-ratio test (LRT) to detect ET differences between the pairs and to explore causes of the differences in relation to forest surface properties. This analysis was performed with monthly or seasonal time series mean data from both the complete set of 1,619 sites and a subset of 304 sites with detailed site characteristic data, as well as on the eight eddy flux sites.

The likelihood-ratio test was used to compare the two models, with the χ^2 statistic and corresponding p-value reported to determine whether the inclusion of species as a predictor significantly improved the model's fit. The two nested models represent two conditions, with or without species as an influence factor. The models consider the combination of variable ~ month/season + species + (1 | site), where the variable could be ET, LAI, albedo, or height (for height, the month was not included). The "species" term represents the comparison between longleaf and loblolly pine, while "month/season" accounts for seasonal variation. Random effects were included to capture site-specific variability.

Additionally, the mixed-effects model provided estimated coefficients (estimate), standard errors (SE), and t-values for each fixed effect, enabling us to assess both the magnitude and statistical significance of the species effect on each surface property variable. The estimated coefficient represents the average effect of a predictor (such as species) on the response variable (such as ET), after accounting for other variables and random effects in the model. The t-values were computed by dividing the estimated coefficients by their respective standard errors, providing a measure of how many standard errors the estimate is from zero. The analysis was conducted using the mixed function from the *afex* package in R version 4.3.2 (Singmann et al., 2024). This combined approach enabled us to comprehensively quantify the differences in ET and other surface properties between longleaf and loblolly pine sites.

2.4.2. Factors Affecting the Relative Difference in ET and Surface Property Variables Between Longleaf and Loblolly Pine

We performed separate comparative analyses on temporal ET dynamics for the peak and non-peak growing seasons. Two complementary approaches were utilized: Spearman rank correlation analysis for all sites (n = 1,619) and linear mixed-effects modeling for a subset of sites with available site-specific information (n = 304).

The non-parametric Spearman rank correlation analysis was employed to assess the relationships between long-term seasonal relative differences in ET and surface property variables and site-specific factors such as elevation and dryness index. Correlation coefficients (r) and p-values were calculated for each pairwise comparison, with distinct analyses conducted for the peak and non-peak growing seasons to capture seasonal variability.

For the 304 sites with detailed site characteristics, we applied a linear mixed-effects model to further explore the impact of seasonal variations, fire frequency, soil hydrology, and other site-specific characteristics (e.g., longleaf pine total basal area) on ET and surface property variables. The models were specified as: "Variable ~ Season + Fire evidence + Soil hydrology + Longleaf total basal area + ⋯ + (1|Site)," where "Variable" represents ET or any other surface property being analyzed, and the fixed effects include "Season," "Fire evidence," "Soil hydrology," "longleaf total basal area" and others. The random effect "(1 | Site)" accounts for variability specific to each site. The model fitting was carried out using the *lmer* function from the *lme4* package in R (Bates et al., 2015), with optimization managed by the "*bobyqa*" algorithm to ensure robust convergence.

This comprehensive approach integrates correlation analysis with mixed-effects modeling, allowing unraveling the complex interactions between surface property variables and site characteristics. By considering both environmental factors and management practices, our analysis provides a detailed and nuanced understanding of the drivers behind the relative differences detected between longleaf and loblolly pine stands.

3. Results

3.1. ET Differences Between Longleaf and Loblolly Pine

3.1.1. Eddy Covariance Flux Measurements of ET

Overall, longleaf pine stands exhibited lower monthly mean ET_EC rates compared to loblolly pine with varying magnitude by season (Figure 3a). During the non-peak growing season, the ET_EC of longleaf pine was only slightly lower than that of loblolly pine by −0.14 mm/day (SE = 0.25, t = −0.57). However, the differences were more pronounced during the peak growing season, with longleaf pine showing −0.94 mm/day lower ET_EC than loblolly pine (SE = 0.29, t = −2.7) (Figure 3a). Conversely, the Bowen ratio (Sensible heat/Laten heat) for longleaf pine was higher than that of loblolly pine by an average of 0.27 (SE = 0.08, t = 3.3), with a higher difference in the non-peak growing season (Figure 3b). During the peak growing season, the Bowen ratio for both

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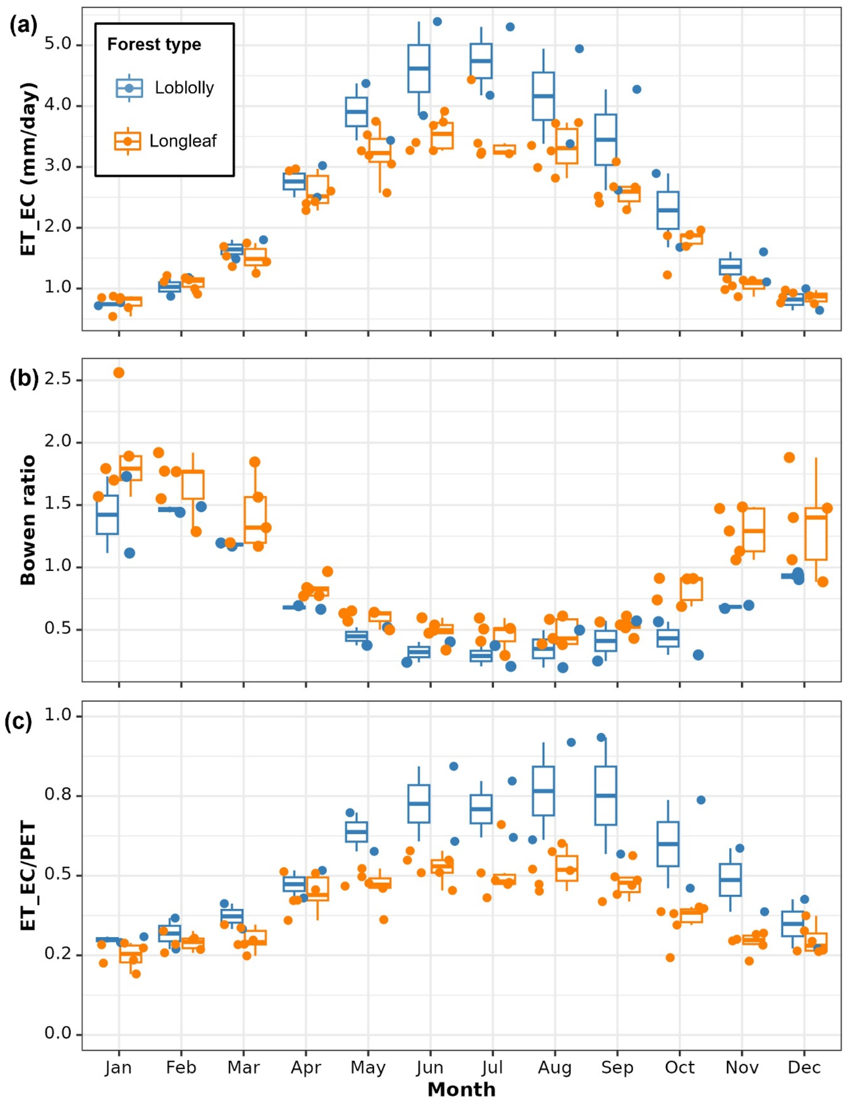

Figure 3. Comparison of monthly (a) eddy covariance evapotranspiration (ET_EC), (b) Bowen ratio, and (c) the ratio of ET_EC to PET (alfalfa reference ET between longleaf and loblolly pine sites based on eddy covariance flux tower data. Boxplots display the median and interquartile range, representing where the middle 50% of data points lie. Overlaid points represent individual data values.

species was approximately 0.5 while this ratio increased to over one in the non-peak season when the longleaf pine sites nearly reached 2.0. Additionally, the ratios of ET_EC to PET that normalized background energy availability for loblolly pine stands exceeded those of longleaf pine by an average of 0.15 (SE = 0.04, $t = 3.3$), even during the non-peak growing season (Figure 3c).

3.1.2. Remote-Sensing Based ET Estimates

Among the 1,619 paired sites in our database, we observed significantly higher ($p < 0.05$, Wilcoxon Signed Rank test) ET_RS in loblolly pine stands compared to longleaf pine stands at 1,052 sites (65%) (Table 2 and Figure 4). Only 150 sites (9%) showed a significantly higher ET_RS in longleaf pine stands. Among the 1,052 paired sites with significantly higher loblolly pine ET_RS, approximately 45% (473 sites) showed more than 10% higher ET_RS than their paired longleaf pine sites. Notably, 136 loblolly pine sites exhibited more than 20% higher ET_RS than their paired longleaf pine sites, with the majority located in Georgia, South Carolina, and North Carolina.

Table 2
Summary of the Number (and Percentage) of Paired Sites Showing Differences in Magnitudes of Remote Sensing Evapotranspiration (ET_RS) and Surface Properties Between Longleaf Pine (LLP) and Loblolly Pine Across 1,619 Paired Sites in the Southeastern U.S.

Variable	LLP significantly lower	LLP lower (not significant)	LLP higher (not significant)	LLP significantly higher
ET_RS (mm/day)	1,052 (65%)	227 (14%)	190 (12%)	150 (9%)
Land surface temperature (LST, °C)	163 (10%)	127 (8%)	136 (8%)	1,193 (74%)
Albedo	397 (25%)	188 (12%)	153 (9%)	881 (54%)
Leaf area index (LAI, m^2 m^{-2})	805 (50%)	233 (14%)	191 (12%)	390 (24%)
Height, m	785 (48%)	317 (20%)	235 (15%)	414 (26%)

Note. The Wilcoxon Signed Rank test was used to assess whether there is a significant difference ($p < 0.05$) between longleaf pine (LLP) and loblolly pine for all variables.

The mixed-effects model analysis further confirmed that longleaf pine stands consistently exhibit lower ET_RS than loblolly pine stands, even after accounting for site variations (Table 3). A likelihood-ratio test demonstrated that including species as a predictor significantly improved the model fit ($\chi^2(1) = 1,119$, $p < 0.01$), highlighting the significant difference in ET_RS between longleaf and loblolly pine. Across all 1,619 sites, the mixed-effects model estimated that longleaf pine stands have an ET_RS rate that is, on average, 0.20 mm/day (SE = 0.007,

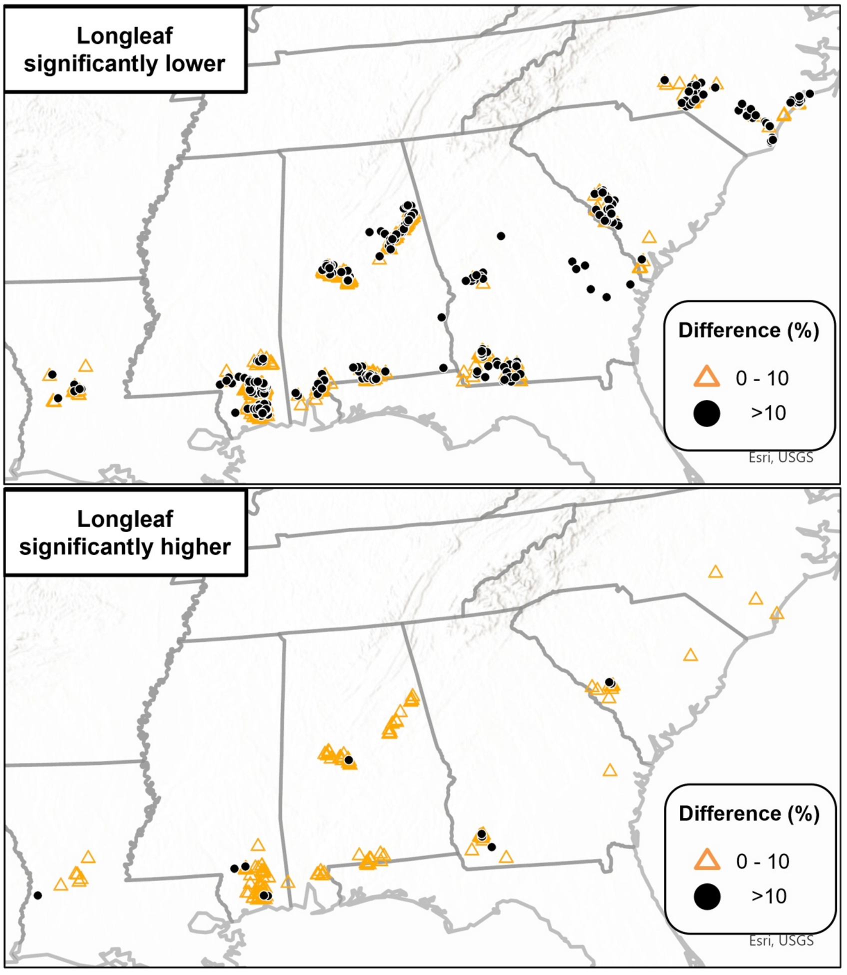

Figure 4. Remote sensing evapotranspiration (ET_RS) difference between loblolly and longleaf pine stands across those 1,619 paired sites. The Wilcoxon Signed Rank test was used to assess whether there is a significant difference ($p < 0.05$) between longleaf pine and loblolly pine.

Table 3
Summary of Differences in Remote Sensing Evapotranspiration (ET_RS) and Surface Properties Variables Between Longleaf Pine and Loblolly Pine Sites Across all Sites and for the Subset of Sites With Additional Site-Specific Information

	All sites (n = 1,619)			With site information (n = 304)		
Variable	Estimate	SE	t	Estimate	SE	t
ET_RS (mm/day)	−0.20	0.007	−27.5	−0.36	0.017	−20.9
LAI	−0.10	0.003	−33.8	−0.22	0.007	−33.0
LST (°C)	0.69	0.030	23.2	1.15	0.079	14.5
Albedo	0.002	<0.001	26.1	0.004	<0.001	22.4
Height (m)	−0.34	0.005	−65.4	−0.84	0.010	−80.2

Note. The estimated coefficient (estimate) represents the average difference in the variable between longleaf pine sites and loblolly pine sites, with positive values indicating higher values for longleaf pine and negative values indicating higher values for loblolly pine. SE is the standard error of the estimate, and the t-value indicates the significance of this difference within the model.

$t = -27.5$) lower than loblolly pine stands. This difference was even more pronounced within the subset of 304 sites with additional site characteristic information, such as longleaf total basal area, soil hydrology, fire evidence, and understory coverage, where longleaf pine stands had an ET_RS rate 0.36 mm/day (SE = 0.017, $t = -20.9$) lower than loblolly pine stands. These findings consistently indicate that longleaf pine has lower ET_RS than loblolly pine, both across the entire data set and within sites that consider detailed management and site characteristics.

3.2. Surface Property Differences Between Longleaf and Loblolly Pine Stands

The Wilcoxon Signed Rank test and mixed-effects model analysis revealed significant differences in surface properties between longleaf and loblolly pine stands (Tables 2 and 3 and Figure S2 in Supporting Information S1). Likelihood-ratio tests confirmed that including species as a predictor significantly improved model fit for each surface property, with χ^2 values of 2,626 ($p < 0.01$) for LAI, 460 ($p < 0.01$) for LST, 2,626 ($p < 0.01$) for albedo, and 6,378 ($p < 0.01$) for canopy height.

Longleaf pine sites exhibited significantly higher LST compared to loblolly pine sites. On average, LST was 0.69°C (SE = 0.030, $t = 23.2$) higher in longleaf pine stands, with this difference increasing to 1.15°C (SE = 0.079, $t = 14.5$) in the subset of 304 sites with detailed site information Table 3). In 74% of pairs (1,193 sites), longleaf pine had significantly higher LST ($p < 0.05$), with 26% (425 sites) showing a difference greater than 1°C).

In contrast, longleaf pine sites had significantly lower LAI and canopy height than loblolly pine sites. Across all sites, longleaf pine stands exhibited an average LAI that was 0.10 lower (SE = 0.003, $t = -33.8$) and a canopy height that was 0.34 m shorter (SE = 0.005, $t = -65.4$) (Table 3). These differences were even more pronounced in sites with additional data, where the LAI of longleaf pine sites was 0.22 lower (SE = 0.007, $t = -33.0$) and height was 0.84 m shorter (SE = 0.010, $t = -80.2$) that the loblolly pine sites. There are 50% of paired sites (805 sites) that had significantly lower LAI in longleaf pine stands, with 17% (269 sites) showing more than a 10% difference (Figure S2 in Supporting Information S1). Similarly, longleaf pine was shorter in 48% of sites (785 sites), with 24% (387 sites) exhibiting a height difference of more than 10%.

Regarding albedo, longleaf pine stands generally exhibited higher values across most sites. The model estimated that albedo was, on average, 0.002 higher for longleaf pine compared to loblolly pine (SE = <0.001, $t = 26.1$), increasing to 0.004 (SE = <0.001, $t = 22.4$) at sites with detailed site characteristic information. In approximately 54% of paired sites (881 sites) (Figure S2 in Supporting Information S1), longleaf pine had significantly higher albedo values, though this difference was less pronounced compared to LAI and height, with fewer than 100 sites showing more than a 10% difference in albedo.

3.3. Correlation and Attribution Analysis

The Spearman correlation analysis revealed significant relationships between the relative differences in surface property variables (ET, LAI, LST, albedo, and height) between longleaf and loblolly pine sites across both peak and non-peak growing seasons (Figure 5). The relative difference in ET exhibited a strong negative correlation with the relative difference in LST during both the peak ($r = -0.71$, $p < 0.001$) and non-peak ($r = -0.72$, $p < 0.001$) seasons. A positive correlation was observed between the relative differences in ET and LAI, with a stronger relationship in the peak growing season ($r = 0.53$, $p < 0.001$) compared to the non-peak season ($r = 0.35$, $p < 0.001$). The correlation between ET and albedo relative differences was more pronounced during the non-peak growing season ($r = -0.50$, $p < 0.001$) than during the peak growing season ($r = -0.31$, $p < 0.001$). Moderate positive correlations were identified between ET relative differences and both height relative differences and the site average DI, with slightly stronger correlations during the peak growing season ($r \approx 0.2$, $p < 0.001$). A marginal correlation was observed between ET relative differences and site average elevation (Figure 5) and climate variables (P, PET) (Figure S3 in Supporting Information S1).

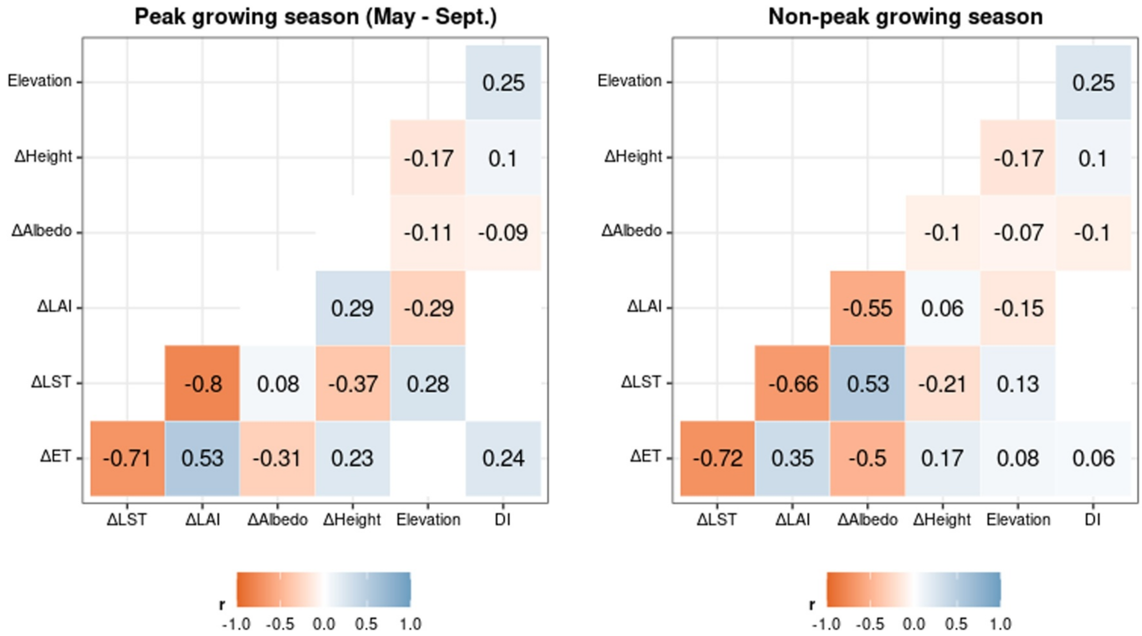

Figure 5. Spearman correlation matrix of variable relative differences between loblolly and longleaf pine sites across different seasons. The figure displays only significant correlation coefficients ($p < 0.05$). Dryness index (DI) was defined as the ratio of Alfalfa-reference evapotranspiration (PET) to precipitation.

Additionally, a robust negative correlation was found between the relative differences in LST and LAI in both the peak ($r = -0.78$, $p < 0.001$) and non-peak ($r = -0.66$, $p < 0.001$) growing seasons (Figure 5). The relative difference in albedo exhibited stronger correlations with the relative differences in LST and LAI during the non-peak growing season, highlighting seasonal variability in surface property interactions. Height relative differences were positively correlated with LAI relative differences and negatively correlated with LST relative differences, particularly during the peak growing season, while elevation displayed opposite correlations with LST and LAI relative differences compared to height.

The linear mixed-effects model provided a detailed understanding of how seasonality and site characteristics influence the relative differences in ET and surface properties between longleaf and loblolly pine sites (Table 4). Longleaf pine stands generally exhibited lower ET_RS and LAI compared to loblolly pine stands, while showing higher LST and albedo. During the peak growing season, the relative differences between the two species were more pronounced, with longleaf pine having about 4% lower ET_RS (SE = 0.7, $t = 5.5$) and LAI (SE = 0.4, $t = 11.5$) compared to loblolly pine, relative to the non-peak season. In contrast, the relative difference in albedo between the species decreased by about 2% during the peak growing season (SE = 0.1, $t = 29.3$). Total basal area and midstory cover of longleaf pine were significant factors influencing the relative differences in ET and other surface properties. Generally, sites with higher basal areas or midstory cover showed reduced relative differences in ET_RS and surface properties. For example, in sites with a basal area of ≥80 sq. ft/ac, the relative differences in ET_RS and LAI were 17.6% (SE = 3.6, $t = -4.9$) and 24.7% (SE = 6.3, $t = -3.9$) smaller, respectively, compared to sites with a basal area <50 sq. ft/ac (Table 4).

Soil hydrological characteristics and fire management also significantly impacted ET relative differences discussed above. Sub-mesic soils led to about 10% smaller relative differences in ET_RS (SE = 2.0, $t = -4.9$) and LAI (SE = 3.5, $t = -2.9$) between longleaf and loblolly pine sites compared to xeric soils. Fire frequency moderately influenced these relative differences. Specifically, frequent fires led to a 5% smaller relative difference in ET_RS (SE = 2.5, $t = -2.0$), a 10% smaller relative difference in LAI (SE = 4.4, $t = -2.3$), and a 1.3% smaller relative difference in LST (SE = 0.6, $t = 2.0$) compared to sites with no fire.

3.4. Factors Affecting the Runoff Coefficient Differences Between Paired Longleaf and Loblolly Pine Sites

Following the analysis of ET, we also conducted Spearman correlation and linear mixed-effects modeling to investigate the relative differences in water yield, as indicated by the runoff coefficient (1-ET_RS/P), assuming

Table 4
Effects of Season and Sites Characteristic on the Relative Difference Between Loblolly and Longleaf Pine Sites of ET and Surface Properties

		ΔET_RS (%)			ΔLAI (%)			ΔLST (%)			ΔAlbedo (%)			ΔHeight (%)		
Effect (reference category)	Categories	Estimate	SE	*t*	Estimate	SE	*t*	Estimate	SE	*t*	Estimate	SE	*t*	Estimate	SE	*t*
Intercept		34.2	2.8	12.2	40.2	4.9	8.2	−10.3	0.7	−14.1	−9.1	1.0	−8.7	25.8	4.2	6.1
Season (non-peak)	Peak growing	3.6	0.7	5.5	4.0	0.4	11.5	0.5	0.1	4.6	2.3	0.1	29.3			
Fire evidence (no fire)	Frequent fire	−4.9	2.5	−2.0	−9.9	4.4	−2.3	1.3	0.6	2.0	3.0	0.9	3.2	−9.4	5.1	−1.8
	Infrequent fire	−0.3	2.6	−0.1	−8.4	4.6	−1.8	0.7	0.7	0.9	1.5	1.0	1.5	−5.5	5.2	−1.1
Longleaf total basal area (<50)	50	−11.3	2.6	−4.4	−14.0	4.5	−3.1	2.7	0.7	4.0	2.3	1.0	2.4	−6.0	2.6	−2.3
	60	−12.9	2.9	−4.4	−17.7	5.1	−3.5	3.4	0.8	4.4	2.5	1.1	2.3	−7.3	3.0	−2.4
	70	−13.7	3.3	−4.2	−20.4	5.8	−3.5	3.6	0.9	4.2	4.5	1.2	3.6	−3.4	3.4	−1.0
	80	−17.0	4.4	−3.9	−22.8	7.7	−2.9	4.7	1.1	4.1	5.3	1.7	3.2	−4.5	4.5	−1.0
	>80	−17.6	3.6	−4.9	−24.7	6.3	−3.9	5.4	0.9	5.7	4.7	1.4	3.5	−3.8	3.7	−1.0
Soil hydrology (xeric)	sub_mesic	−9.9	2.0	−4.9	−10.4	3.5	−2.9	2.5	0.5	4.7	1.6	0.8	2.1	−6.7	2.1	−3.3
	mesic	−5.8	4.3	−1.4	1.5	7.5	0.2	0.6	1.1	0.5	0.5	1.6	0.3	−4.2	4.4	−1.0
Midstory cover (<5%)	6%–25%	−4.5	2.3	−1.9	2.8	4.1	0.7	0.8	0.6	1.3	−0.4	0.9	−0.4	−2.1	2.4	−0.9
	26%–55%	−12.2	3.0	−4.1	−12.9	5.3	−2.4	3.3	0.8	4.2	1.6	1.1	1.4	−5.5	3.1	−1.8
	56%–100%	−14.8	3.9	−3.8	−18.6	6.9	−2.7	4.6	1.0	4.5	2.6	1.5	1.8	−11.8	4.0	−2.9

Note. The intercept estimate represents the baseline relative difference (%) between loblolly and longleaf pine sites for each variable when all categorical effects are set to their reference category. The positive value indicates that loblolly pine is higher than longleaf pine. The reference category for each effect is indicated in parentheses. The estimated coefficients (estimate) provided for each category show the difference compared to the reference category. SE is the standard error of the estimate, and the *t*-value indicates the significance of this difference within the model.

runoff = (P − ET_RS) with no other losses, between loblolly and longleaf pine stands. The Spearman correlation across all 1,619 sites revealed that the runoff coefficient difference was positively correlated with the dryness index ($r = 0.20$, $p < 0.001$) and elevation ($r = 0.08$, $p < 0.001$), while it was negatively correlated with precipitation ($r = -0.21$, $p < 0.001$). This relationship is consistent with the Budyko framework (Figure 6), which suggests that as the climate becomes drier (higher DI), the ET/P ratio increases for both loblolly and longleaf pine. Notably, the gap in ET/P between the two species becomes more pronounced in regions with a higher PET/P (>1.2), where loblolly pine shows significantly higher ET_RS compared to longleaf pine.

For the subset of 304 sites with detailed site characteristics, the linear mixed-effects model indicated that factors including longleaf pine basal area, midstory cover, fire frequency, and soil hydrology significantly affect the difference in the runoff coefficient between loblolly and longleaf pine sites (Table S2 in Supporting Information S1). Specifically, higher longleaf pine basal area and increased midstory cover also led to notable decreases in the runoff coefficient difference, with reductions reaching up to −0.08 (SE = 0.02, $t = -4.8$) in sites where the basal area exceeded 80 sq. ft/ac, compared to sites with a basal area below 50 sq. ft/ac. Frequent fire was associated with a −0.02 reduction (SE = 0.01, $t = -2.0$) in the runoff coefficient difference relative to sites with no fire. Additionally, sub-mesic soil conditions resulted in a significant −0.06 reduction (SE = 0.01, $t = -5.9$) in the runoff coefficient difference compared to xeric soils.

4. Discussion

4.1. Implications of Forest Management to Water and Energy Balances in the Context of Climate Change Mitigation and Adaptation

Our study represents the first region-wide comparison in ET, the water loss by forests to the atmosphere, and associated surface properties and site characteristics between loblolly pine versus longleaf pine forests in the southeastern U.S. The results based on two different data sources, eddy covariance flux and remote sensing-based, converge and offer compelling evidence that loblolly pine forests use more water than longleaf pine in general. The detected lower ET and higher runoff coefficient in longleaf pine stands due to unique biophysical surface conditions (e.g., lower LAI, higher albedo) compared to longleaf pine, particularly during the peak

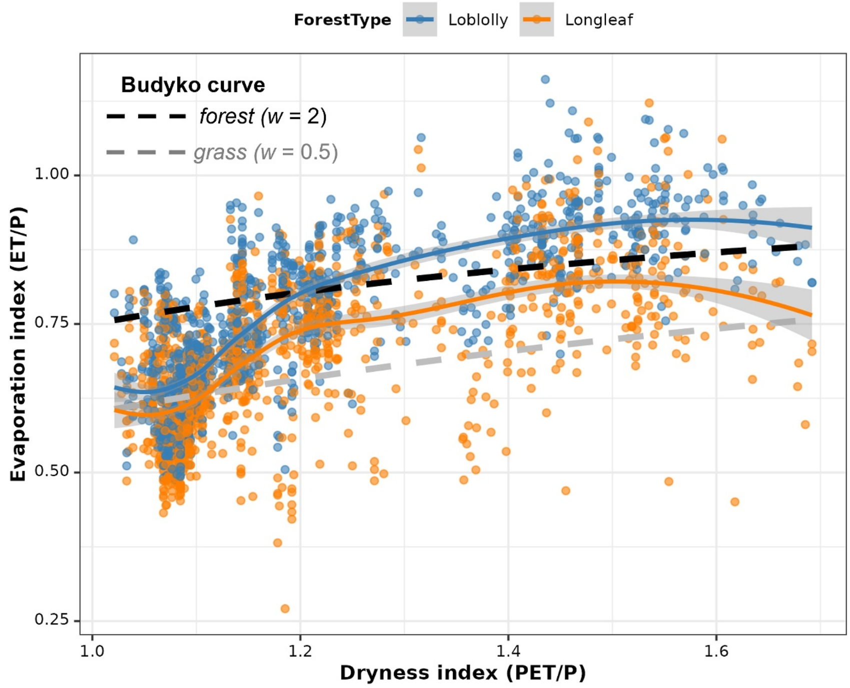

Figure 6. The relationships between evaporative index (ET/P) and dryness index (PET/P) for those paired sites showing difference in evapotranspiration between longleaf and loblolly pine stands. The dashed lines are based on Budyko curve (Budyko, 1974) using a model by Zhang et al. (2001) for forest ($w = 2$, black) and grass ($w = 0.5$, gray). The shaded gray area surrounding the loess curve represents the confidence interval (0.95).

growing season, are consistent with previous watershed scale studies in the region (Qi et al., 2022; Younger et al., 2023). Findings from this study have important implications to the water and energy balances and forest management.

The results of runoff coefficient analysis suggests that there is a potential to reduce water use and augment water yield by restoring longleaf pine forest stands with low tree density and leaf biomass through prescribed burning, especially in xeric sites. As climate change is expected to increase the frequency and intensity of droughts in the southeast of U.S. (McNulty et al., 2013), the lower water consumption of restored longleaf pine ecosystems could potentially help mitigate the impacts of droughts on aquatic ecosystems (Pisarello et al., 2022; Qi et al., 2022). Moreover, this reduced water use can contribute to regional biodiversity stability and resilience, reinforcing the ecological benefits of longleaf pine restoration (Hanberry et al., 2023). This is particularly important given the increasing demand for water due to population growth (Brown et al., 2019). Longleaf pine is known for its drought tolerance, which may be attributed to its higher leaf water potential and hydraulic architecture (Samuelson et al., 2012). This strategy of the longleaf pine could be more beneficial in drier environments (Figure 6), potentially helping conserve water resources during drought periods. On the other hand, loblolly pine plantations, particularly those under intensive management (i.e., fertilization), exhibit a greater sensitivity to drought conditions compared to natural forests (Domec et al., 2015). Furthermore, middle rotation loblolly pine forests (10–15 years old) reach their peak in water use and are known to be more susceptible to drought conditions than their mature counterparts (Aguilos et al., 2021). Therefore, forest restoration is likely most effective for younger and productive stands that have a relatively high ET rate. In addition, stand thinning can be an effective forest management option to reduce water use by loblolly pine plantations (Amatya & Skaggs, 2008).

The effects of land use and land cover changes on atmospheric cooling and wetting depended on water and energy balances that are coupled through the ET processes (Hao et al., 2023). The observed differences in ET between longleaf and loblolly pine stands are strongly correlated with variations in LST and LAI that are key factors for estimating ET by the DisALEXI model (Anderson et al., 2007; Yang et al., 2022). The positive relationship between ET and LAI suggests that higher leaf area contributes to increased ET rates in longleaf pine stands. Conversely, the strong negative correlation between ET and LST indicates that higher surface temperatures are associated with reduced ET, which may be linked to the lower LAI and higher albedo in longleaf pine compared to loblolly pine (Figure 5). This finding highlights the critical role of LAI in regulating transpiration, where denser canopies with higher LAI contribute to greater transpiration and, consequently, elevated ET levels. The correlation between ET and LAI is particularly notable, as it reinforces the importance of canopy stand density and structure in influencing water fluxes, consistent with previous studies that have identified LAI as a primary driver of ET variability across different forest types (Aguilos et al., 2024; L. Samuelson et al., 2001; Sun et al., 2011). Site-specific factors such as fire frequency, basal area, and soil hydrology also significantly impacted the observed differences in ET and other surface properties between longleaf and loblolly pine stands. Among these, the total basal area of longleaf pine, representing stand density, emerges as a key determinant. In sites with higher longleaf pine basal areas, the typically higher ET and LAI observed in loblolly pine stands are moderated, aligning their water use and canopy characteristics more closely with those of longleaf pine. This finding suggests that managing stand density through practices such as thinning can effectively manage hydrological dynamics (McLaughlin et al., 2013; Vose et al., 2011). Similar strategies could be applied to manage understory cover, further affecting ET and surface properties. Soil hydrology and fire frequency also play significant roles in modulating these differences. In sub-mesic soils, where moisture availability is higher, the gap in ET between longleaf and loblolly pine narrows. Longleaf pine, which shows lower water use efficiency under drier conditions, benefits from the increased soil moisture, thereby reducing its ET disparity with loblolly pine (Samuelson et al., 2012). The less pronounced difference in LAI between these two species under these more favorable soil conditions highlights the critical role of soil moisture in sustaining the growth and water use patterns of these species (Ford, Laseter et al., 2011).

The significantly higher LST, lower ET, and higher Bowen Ratio observed in longleaf pine forests (Figure 3) suggest that these forests may provide less cooling compared to loblolly pine (Bonan, 2008). The reduction in water consumption resulting from longleaf restoration might inadvertently contribute to increased sensible heat flux, potentially leading to regional warming, highlighting the need for careful consideration of the biophysical effects of restoration practices in energy balances (Prevedello et al., 2019). We also find that loblolly pine tends to use more water than longleaf pine under drier conditions (Figure 6). This finding suggests that ecosystems dominated by loblolly pine may be at an increased risk of water stress in the face of a potentially drier future. It underscores the need for strategic forest management that considers the water use characteristics of different tree species, particularly in response to climate change (Brown et al., 2019).

4.2. Uncertainty and Future Research Needs

While our study confirms the significant differences in ET and related surface properties between longleaf pine and loblolly pine with two independent data sources (e.g., eddy covariance and remote sensing), it is important to acknowledge the uncertainties and limitations associated with the findings. First, the large data sets used in our study are novel but are subject to inherent uncertainties. For instance, the estimates of ET, LST, LAI, and albedo are derived from remote sensing data and eddy covariance measurements, both involve multiple steps of data processing and modeling/scaling in space or time (Liang et al., 2003; Martínez-Ferrer et al., 2022; Yang et al., 2017). Errors in remote sensing data can arise from various sources, including sensor noise, atmospheric effects, and algorithmic inaccuracies in deriving the variables of interest (Verrelst et al., 2015). Previous case studies have affirmed the efficacy of DisALEXI ET in forested contexts (Volk et al., 2024; Yang et al., 2021, 2022), yet remote sensing-based ET models work less accurately for natural ecosystems and tend to overestimate ET in evergreen forests (Volk et al., 2024). LST, LAI, and Albedo are critical inputs in the DisALEXI model, as is the case with most energy balance-based models. These parameters interact in complex ways, and their relationships with ET are not simply linear. Our study has examined these parameters individually, providing a clearer understanding of the differences in LST, LAI, Albedo, and ET between longleaf and loblolly pine species.

Eddy covariance measurements, while providing direct and continuous measurements of ET, are subject to uncertainties related to footprint, measurement errors, data gaps, and the need for data processing and gap-filling (Mauder et al., 2013). Contrary to remote sensing-based ET estimates that tend to overestimate due to inadequate accounting for soil water content (Fischer et al., 2023; Fisher et al., 2008, 2020), ET_EC is inclined to underestimate total ET due to lack of energy balance closure (Wilson et al., 2002) and the underrepresentation of interception (Kool et al., 2014; Ringgaard et al., 2014). The higher LAI and density of loblolly pine suggests greater water loss via canopy interception, potentially widening the ET disparity with longleaf pine, as EC flux systems might underrepresent this in loblolly pine (Ringgaard et al., 2014). The energy balance closure ratio for the loblolly pine sites was much higher than for longleaf pine sites (Table S1 in Supporting Information S1). The discrepancy in evapotranspiration (ET_EC) observed between loblolly pine and longleaf pine could be marginally reduced following the application of the energy balance closure. The adjacent "paired stands" method is novel and essential for direct comparisons of two types of forest stands. However, we selected only naturally originating longleaf sites, the management history (e.g., natural vs. plantation) of paired loblolly sites was not explicitly considered. Longleaf pine forests are often managed for multiple ecosystem benefits and are frequently burnt. In contrast, loblolly pine is typically managed exclusively for timber production and mostly has an artificial origin. Thus, the divergence in surface properties (e.g., leaf area index and albedo) between longleaf and loblolly pine may partly reflect differences in management practices (Qi et al., 2022; Shephard et al., 2021), rather than being a direct result of their respective environmental adaptation strategies or even the genetics.

Despite these uncertainties, our study provides a valuable multi-sensor, muti-scale approach for understanding the differences in ET between two major pine ecosystems across a large physiographic gradient. ET is a major water loss in forested watersheds in the southeastern region, and its improved quantifications help us understand hydrologic response to tree species change. Future studies should incorporate more detailed forest management information, including the understory, ground cover, soil condition, and fire history information from both forest types (Brantley et al., 2024) for improved data analysis and interpretation. In addition, traditional "paired watershed experiment" studies are needed to directly measure the effects of longleaf pine restoration on water yield (Amatya et al., 2021; Trettin et al., 2019) and validate existing forest hydrological models (Amatya et al., 2020; Sun et al., 2023) for guiding large-scale forest restoration.

5. Conclusions

Our study provides a regional comparison of ET and multiple related surface properties (i.e., leaf area index, albedo, tree height, land surface temperature) between longleaf pine and loblolly pine forests across the southeastern United States. We confirm that loblolly pines generally exhibit higher ET, particularly during the peak growing season, while maintaining lower land surface temperature than longleaf pines. These ET variations can be attributed to the lower land surface temperature, higher LAI, but lower albedo in loblolly pine than longleaf pine forests. Moreover, both regional climate and site-specific characteristics contribute to these differences. Our runoff coefficient difference analysis, as well as the Budyko framework, confirms the significant influence of climatic regimes on water use across these two different forest types. The high ET of loblolly pine plantation forests suggests their potential vulnerability to water stress under future drier climatic conditions. Conversely, the lower ET of longleaf pine suggests that forest restoration efforts combined with thinning or prescribed fire management could contribute to water conservation, potentially increasing water yield and water availability for human and aquatic ecosystems in the Southeast.

Overall, this study represents an essential first step toward quantifying the regional differences in water consumption, thus water yield patterns between two dominant forest types in the southeastern U.S. where longleaf pine restoration is underway. Our new findings have important implications for this regional ecological restoration effort, particularly in the context of climate change adaptation through natural resource management. Managing forests for water is increasingly called for as a Nature-based Solutions (NbS) to emerging water shortage problems even in "water rich" regions. This research demonstrates that tree species, forest stand and structure, and forest management matter to water yield and our integrated study provides the much-needed hydrologic sciences to guide large scale ecological restoration actions in the southeastern U.S.

Data Availability Statement

Data sets used for this study were obtained from several published sources:

Database	References
DisALEXI evapotranspiration (ET_RS)	(Yang et al., 2017; Yang et al., 2021)
Land surface temperature (LST)	(Ermida et al., 2020)
Tree height	(Rollins, 2009) https://landfire.gov/evh.php
LANDSAT Reflectance	(Moreno-Martínez et al., 2020)

Continued

Database	References
Leaf area index (LAI)	(Martínez-Ferrer et al., 2022)
Albedo	(Liang et al., 1999)
Annual precipitation, air temperature, and Alfalfa-reference evapotranspiration (PET)	(Abatzoglou, 2013)

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