# Changes in soil moisture availability and water yield in response to longleaf pine restoration in southeast Texas

Brett L Lawrence [A][B] *, +1-936-581-6833, brett@ravenenvironmental.com; Matthew McBroom [A]

[A] Stephen F. Austin State University, 1936 North St, Nacogdoches, Texas 75962, USA

[B] Raven Environmental Services, Inc., 6 Oak Bend Drive, Huntsville, Texas 77340, USA

*Corresponding author

## Abstract

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Our study, based in Trinity County, Texas, focused on whether strategic management of longleaf pine forest could promote a less water-intensive land cover type. We modeled soil evapotranspiration (ET) by measuring vertically stratified soil moisture (15-120 cm) across five forest monitoring sites, four of which received restoration treatments, and one served as a control. Forest attributes, including leaf-area-index (LAI) and traditional forest inventory metrics were measured intermittently across each monitoring stand. Modeled ET was used to create measures of pretreatment and post-treatment water yield and determine whether certain forest attributes were associated with increased water availability. Following forest management activities, cumulative soil moisture entering and exiting treatments were higher compared to our control. Where LAI decreased, we observed increases in modeled total soil moisture (TSM) and matric potential at greater depths (75-120 cm), and increases in subsurface flow, suggesting increases in water availability are best detected at greater soil depths. LAI served as a significant and non-linear predictor of annual water yield during both plot-level ($R^2$ = 0.62) and stand-level ($R^2$ = 0.52) analysis, with an estimated 29.35 cm yr$^{-1}$ increase in water yield in scenarios where forest thinning reduced LAI by 1.7 units (2.65 → 0.95). The same analysis of wetting and drying periods indicated that most of that increase is attributable to warmer periods where ET is higher. These results support the assertion that strategic forest management can benefit water resources in limited scenarios, especially where forest thinning is applied and an open pine structure is maintained using prescribed fire or other invasive species control. Continued, long-term monitoring of clearcut conversions to open longleaf pine forests, and away from dense, intensively managed loblolly pine, show potential for creating water yield increases.

**Keywords:** water yield, longleaf pine, forest restoration, leaf-area-index

# Introduction

Forested land cover provides a host of important ecosystem services that humans benefit from, including carbon sequestration (Sundquist et al., 2008; Samuelson et al., 2014), filtering high-quality water to downstream municipal users (Shah et al., 2022; Caldwell et al., 2023), and housing complex plant and animal biodiversity (Walker, 1993; Noss, 1999). The conservation and restoration of forests are an important consideration in the context of global environmental issues like climate change and biodiversity loss (Hill et al., 2019). Amongst these, water security is an increasingly sensitive environmental issue, with future water resources anticipated to be strained by population growth and climate change (Vörösmarty et al., 2000; Vörösmarty et al., 2010).

Landscapes can vary widely in how their respective water budgets are characterized. A complex matrix of variables plays a role, such as annual precipitation, vegetation type, soils, and typography (Huxman et al., 2005). These systems are in constant flux, responding to short-term pulses and inputs, along with long-term climatic changes and anthropogenic influences on the landscape. These includes post-colonization deforestation and land-use conversion for agricultural purposes (Bonan, 1999; Hung et al., 2016). Also important to consider are human alterations of historic fire regimes, which traditionally shaped vegetation composition and structure (Bowman et al., 2020). For our study's region, these changes have contributed to woody plant encroachment (WPE), or thicketization, as described by work in nearby regions of Texas (Wilcox et al., 2022). Thicketization is characterized by a shift away from herbaceous, grass-type groundcover, towards woody brush understory conditions that are a relatively unfavorable fuel-type for carrying low-intensity fire. The latter is more susceptible to intense fire behavior that can damage overstory trees and cause relatively severe disturbances. These changes also have implications for the water cycle, and specifically, water yield.

Fire suppressed landscapes also undergo species composition shifts that can result in decreased water availability. Mesophication, or a shift towards more water dependent hardwood species in Southeastern US forest, can be brought on by changes in disturbance regimes and climatic conditions (Caldwell et al., 2016; Hanberry et al., 2018). Combined factors such as mesophication and thicketization fundamentally change the water cycle in forested systems and have implications for components of the water budget, such as evapotranspiration (ET) and water yield.

The longleaf pine ecosystem has become a major conservation objective in the context of these changing climatic conditions and altered disturbance regimes (America's Longleaf, 2014). Longleaf pine is one of four southern yellow pine species native to the Southeast US, but its range has dramatically reduced as species like loblolly pine have become the primary crop tree for growing and yielding wood products (Oswalt et al., 2012; McIntyre et al., 2017; Holland et al., 2019). While loblolly pine is a native species, these industrial forests are characterized by a monoculture of dense, uniform overstory trees, and unmanaged understory conditions that are dramatically different than their pre-settlement counterpart. Native, historical longleaf pine, on the other hand, is defined by a relatively open structure of trees with a diverse composition of understory forbs and grasses (Brockway and Lewis, 1997). When managed effectively, multi-aged stand structures can be created that add to this complexity while also providing more sustainable silvicultural practices (Mitchell et al., 2006; Barlow et al., 2011). These combined features support a critical component of the longleaf pine ecosystem, which has a structure resilient to, and reliant on, intermittent and low-intensity fire (Stambaugh et al., 2011). The reintroduction of prescribed fire into our study area was a significant objective of the project, and a barometer for its success.

Culminating evidence suggests that relatively open longleaf pine forests are associated with increased water resources benefits. For example, the relatively open structure of natural longleaf pine stands can result in less intercepted water that is made available for soil infiltration (Trettin et al., 2018). Previous study also demonstrated that areas managed for open longleaf pine generate lower ET and increased streamflow (Brantley, 2013; Qi et al., 2022; Younger et al., 2023; Liu et al. 2025). However, evidence of other southern pine species managed toward an open, fire-maintained structure were also beneficial to water yield (McLaughlin et al. 2013; English et al., 2024). Other work has suggested more general forest characters, such as LAI (Acharya et al., 2022), ecohydrological setting (Filoso et al., 2017), and stand age were more consequential to the water budget (Brown et al., 2005). Given longleaf pine's relative drought and fire tolerance (Samuelson et al., 2012), it could serve as a relatively climate resilient option when managing forests and water resources in the southern US. The overall conclusion is, to promote increases in water yield within southern pine forests, one must manage towards openness between trees, and groundcover characterized mostly by grass and forb species. This is in contrast to industrial pine forest, where objectives are focused primarily on short rotation yield and clearcut regeneration (Dickens and Li, 2023). The former scenario requires routine intervals of prescribed fire, an active management tool that is important for supporting herbaceous groundcover (Brockway and Lewis, 1997; Stambaugh et al., 2011). This can result in a cost-prohibitive approach for some landowners. However, ecosystem services association with restored longleaf pine areas, such as water yield benefits, have gained traction as a potential economic incentive for supporting restoration efforts (Susaeta and Gong 2019).

Our study investigates whether a period of active management away from woody encroachment, and towards this a more open longleaf pine structure, reduces evapotranspiration and increases potential water yield. To achieve this, we conducted a period of pretreatment soil moisture and water potential monitoring in 30- to 60-year-old longleaf pine forest in Trinity County, Texas, and followed with continued monitoring through a period of active management over 2 years. Five different monitoring sites were established: 4 different treatments and 1 control. In addition to soil moisture and water potential monitoring, we sampled stand-level forest attributes such as LAI, BA, and vegetation cover during pretreatment and post-treatment periods. We hypothesized that soil moisture properties would be notably different in treatment areas versus the control area. We followed with an analysis of whether modeled ET at our weather station could validate modeled values of soil evapotranspiration at monitoring sites; and finally, we performed a regression analysis of forest attributes versus daily values of modeled water yield. Our analysis primarily focused on identifying some connection between treatments and water yield, with changing forest attributes providing a source of predictor variables.

# Methods

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## *2.1 Study Area and Workflow*

The Brushy Creek management area is in Trinity County, Texas, USA, approximately six miles north of Onalaska, Texas, USA. The total treatment area was 807 ha, and within that area, 121 ha was designated as monitoring areas. Brushy Creek falls within the Lake Livingston and Kickapoo Creek watersheds, both of which have stream systems that terminate in nearby Lake Livingston to the south (Figure 1).

Existing forest types ranged from longleaf pine dominant areas (approximately 200 ha), mixed southern yellow pine, and loblolly pine (*Pinus taeda*) plantation. All these forest types were characterized by significant woody understory encroachment, were densely stocked, and considered to be degraded conditions relative to the historical longleaf pine ecosystem. Understory brush species included yaupon holly (*Ilex vomitoria*), wax myrtle (*Myrica cerifera*), American beautyberry (*Callicarpa americana*), and American sweetgum (*Liquidambar styraciflua*). The latter, while a tree species, had become a highly present and invasive shrub-like component of the understory vegetation in select areas.

Outside of longleaf pine areas, dominant forest overstory was a combination of southern yellow pine species with small amounts of mature hardwood. Typically, loblolly pine would be the dominant species, followed by longleaf pine, and limited amounts of shortleaf pine (*Pinus echinata*) and slash pine (*Pinus elliottii*). The west side of Brushy Creek consisted of approximately 121 ha of industrial, loblolly pine forest that was uniform in structure and species composition. Examples of scattered mature hardwood species included post oak (*Quercus stelatta*), southern red oak (*Quercus falcata*), American sweetgum, winged elm (*Ulmus alata*), and white ash (*Fraxinus americana*).

The major soil type found on Brushy Creek was Colita fine sandy loam (52% of total area) at 0 to 3 percent slopes (NRCS, 2024). Where that major soil type occurred, 90% was comprised of Colita or similar soils, with the remaining 10% made up of Laska and Rayburn minor components. Ecologically, these soils were characterized as a seasonally wet upland with fine to very fine sandy loams across the A, E/B, and Btg/E soil profiles (0-100 cm). Soil depths greater than 100 cm were made up of sandy clay loam and bedrock (NRCS, 2024).

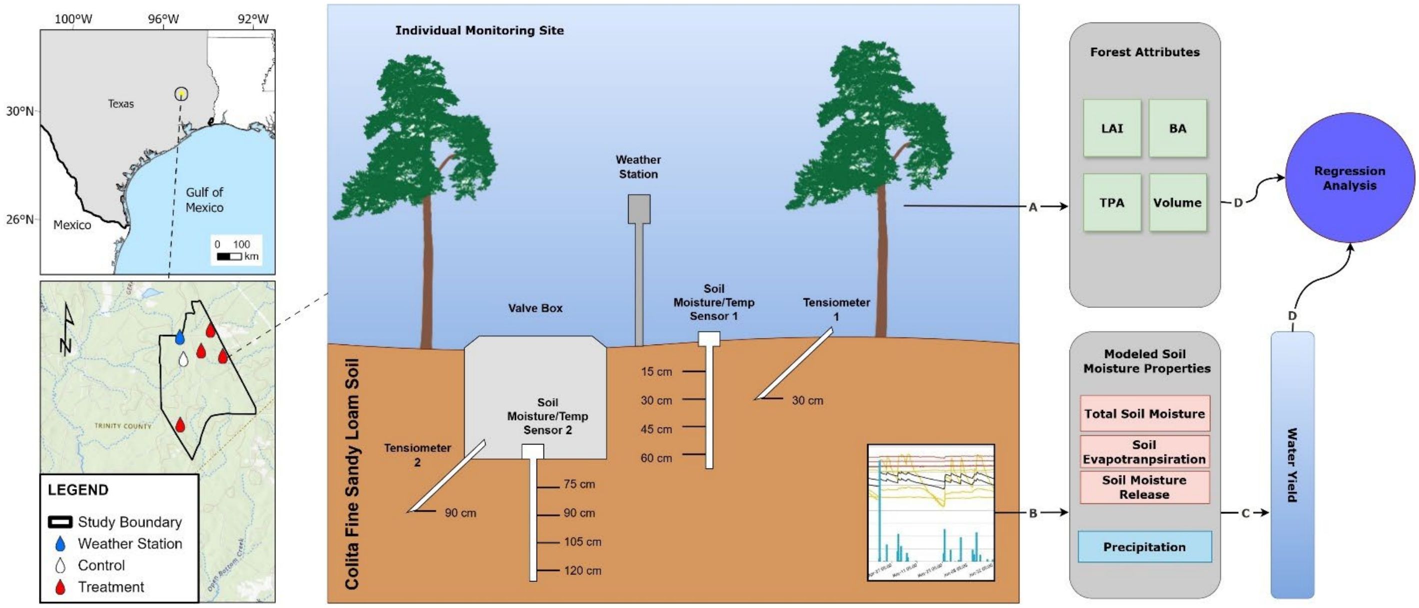

**Fig 1**. The location of Brushy Creek, layout of monitoring sites, and a flowchart of the data types collected and how they were analyzed. (A) Forest attributes were collected at inventory plots, and (B) soil moisture and water potential were collected at five different monitoring sites. (C) Soil moisture data was used to model soil ET and generate daily

values of water yield. (D) Daily water yield was compared to pretreatment and post-treatment forest attributes to identify significant relationships.

## *2.2 Water Monitoring Sites, Forest Attributes, and Forest Practices*

### *2.2.1 Water Monitoring*

Five water monitoring sites were installed, including one control ("Co") and four treatment areas receiving management practices aimed towards restoring open-canopy longleaf pine conditions. These included mature longleaf pine ("ML"), relatively young longleaf pine ("YL"), a mature mixed pine area that included slash pine ("SL"), and a clearcut area that was regenerated with longleaf pine ("CC").

A monitoring site was made up of two TEROS 54 soil moisture probes, two TEROS 32 tensiometers, and a ZL6 data logger (METER Group, Pullman, WA, USA). Soil moisture probes measured volumetric water content (VWC, $m^3/m^3$) and soil temperature (°C) at 15, 30, 45, and 60 cm depths at one sensor. One probe was installed at the soil surface level, and the second installed at a 60 cm soil depth by excavating and installing two stacked valve boxes. This created a vertically stratified profile of soil moisture and temperature readings from 15-120 cm and provide readings down to, and below, the root layer. Valve boxes were backfilled, sealed with tape internally, and covered with a small piece of tarp weighted with nearby debris. This simulated a water sealed environment that prevented false soil moisture increases from rain or box flooding.

Two tensiometers measured matric potential (kPa) at each monitoring site. A tensiometer was installed adjacent to a corresponding soil moisture probe at the normal soil surface level and inside the excavated gage boxes. Sensor length was 45 cm and installed at a 60° angle relative to the soil surface. This provided water potential readings at 30 and 90 cm depths, or approximately half the depth of their corresponding soil moisture probe. Tensiometers were filled with deionized water at installation and intermittently refilled when the ceramic cups emptied from exceptionally dry conditions. All sensors collected soil moisture, soil temperature and water potential data at 5-minute intervals.

A METER Group ATMOS 41W weather station was installed at 2 m in height using a 4.12 cm diameter pole fixed to a t-post. Efforts were made to locate the weather station centrally to soil moisture monitoring sites. The 11 parameters collected by the weather station include: solar radiation ($W/m^2$), precipitation (mm), electrical conductivity (mS/cm), vapor pressure (kPa), relative humidity (%), barometric pressure (kPa),air temperature (min, max, and average in °C), horizontal wind speed (m/s), wind gust (m/s), wind direction (0-360°), and tilt (0-180°). Like soil moisture monitoring equipment, data points were collected at 5-minute intervals at the weather station. All the data collected on Brushy Creek was uploaded to METER Group's proprietary ZENTRA Cloud environment, where it was exported and backed up for analysis later.

### *2.2.2 Forest Inventory and Sample Design*

An unbiased systematic sampling method was used when generating an initial distribution of inventory plots in monitoring areas. Following the U.S. Forest Service's FSVeg Common Stand Exam (CSE) guidelines for relatively homogenous stands, a minimum of one plot per 4 ha was used to determine the number of plots needed and computing plot spacing (FSVeg, 2015). The formula for spacing was as follows:

$$\text{Plot Spacing (ft)} = \sqrt{\frac{Stand\ Acreage \times 43{,}560\ ft^2/acre}{Number\ of\ Plots}}$$

When generating the plot grid, the location of each soil moisture monitoring site (5 total) was used to anchor the remaining grid at fixed X and Y distances.

The CSE guidelines also provided an established cruise method that we used for our forest inventory on Brushy Creek. For data collection, the TimberPro forest inventory program was used on an iPad tablet (New Hampshire, US). The TimberPro inventory program generated an accuracy report in the field, and more plots were added if sampling error was too high. A 90% confidence interval was used when calculating the sampling error of monitoring stand inventories, with a target percent error of less than 20%. After completing our pretreatment inventory in March 2024, we established 38 total inventory plots: 11 in 38.5 ha ML area, 10 in 33.2 ha YL area, 6 in 20.8 ha Sl area, 8 in 26.4 ha CC area, and 3 in 2.9 ha Co area. These were resampled in October 2025 following treatments.

Inventory plots consisted of a 10 basal area factor (BAF), variable radius plot and one fixed-radius vegetation subplot (40.04 $m^2$). A 10 BAF prism was used to identify “in” and “out” trees when conducting the variable radius plot, and all trees ≥12.7 cm diameter at DBH were tallied. A DBH tape was used to measure tree diameters, and measure distances to plot center when determining whether boundary trees are in or out. A clinometer was used to measure total and merchantable height of trees.

The vegetation subplot measured the percentage of coverage for three categories: yaupon holly, all remaining woody vegetation, and grass or herbaceous groundcover. Any remaining cover, such as needle duff or distributed soils, was not factored into the total percentage. The 40.4 $m^2$ plot was measured out to a 3.59 m radius and assessed in quadrants. Yaupon holly was emphasized because it is a common invasive species in the region and made up a significant amount of the understory vegetation on Brushy Creek following years of fire suppression.

### *2.2.3 LAI Measurements*

Pretreatment leaf area index (LAI) was collected using a LAI-2200C plant canopy analyzer (LI-COR, Lincoln, Nebraska). Above canopy readings or A readings were made with a wand sensor in an open area using a 90-degree viewing cap, and the sensor facing true North. LAI data was gathered during optimal conditions that included evenly lit, clear, and blue skies. Automatic logging of A readings was made every 30 seconds while below canopy readings or B readings were collected at plot sites. This ensured that an A and B reading collected relatively close in time were available when calculating LAI later. Match files for both wands equipped with 90-degree viewing cap were created, and scattering correction files or K records created just before each plot's B readings were gathered.

LAI collection sites were structured in a similar manner to the methods used on FIA plots by Law et al., 2008 where B readings were collected along the radius of 40.4 $m^2$ and 404 $m^2$ plots. Four readings per plot, or eight in total, were collected at cardinal directions from plot center by measuring radial distances of 3.59 m and 11.34 m (Figure 2). Readings were collected at DBH or 1.37 m. DBH was used because it is widely referenced height for measuring tree diameter when conducting forest inventories. It also serves as an appropriate vertical reference point that captured dense understory vegetation into the LAI readings.

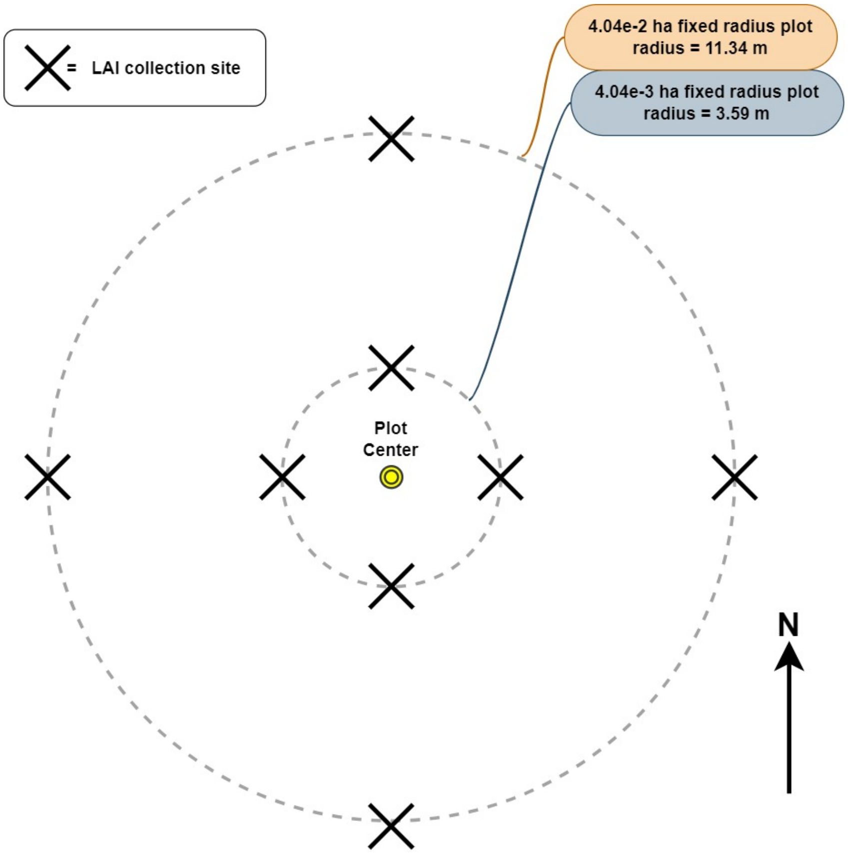

**Fig 2.** The locations of eight different B readings captured at 38 different inventory plots on Brushy Creek.

### *2.2.3 Forest Management Practices*

Forest management practices were implemented across all four treatment monitoring areas between August 2024 and August 2025. Generally, they aimed to promote an increase in longleaf pine species composition, a reduction in understory brush, and increase in herbaceous groundcover. The first treatments implemented were thinning timber harvest in ML and YL, and clearcut timber harvest in CC (8/8/2024 to 8/28/2024). During timber harvest in ML and YL monitoring sites, we worked closely with loggers to also remove or “mow” understory brush with the sawhead feller (Lawrence et al., 2025). Stands were thinned to a target BA of 13.77 $m^2$ $ha^{-1}$ and loggers were instructed to leave large, well-formed and healthy longleaf pine as often as possible (Figure 3).

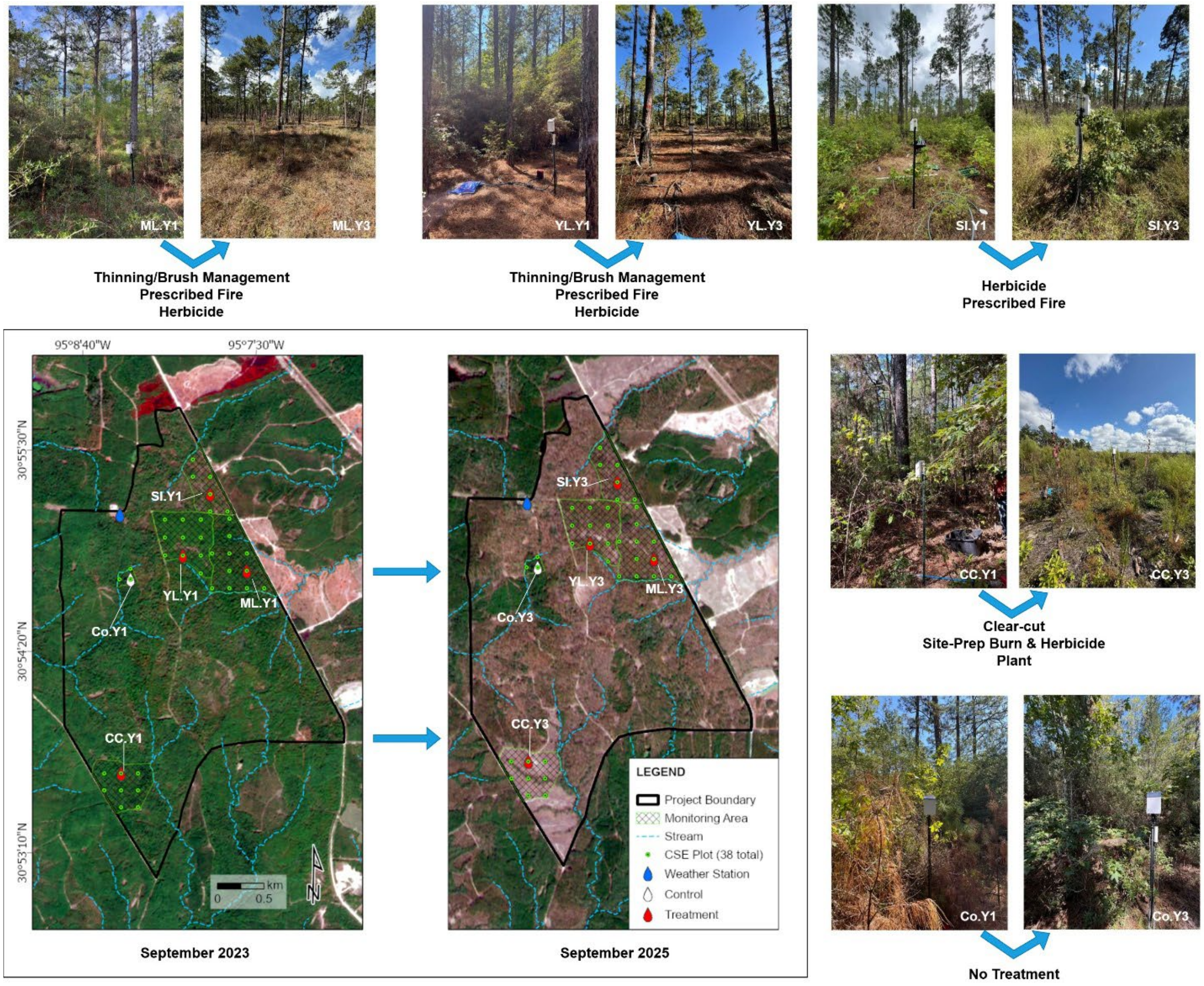

**Fig 3.** A summary of pretreatment and post-treatment outcomes at monitoring sites on Brushy Creek. This includes four areas receiving longleaf pine restoration treatments (ML, YL, Sl and CC), and our control (Co). Aerial imagery demonstrates the large-scale impact of our restoration treatments.

The CC area was sprayed with site-prep herbicide to control invasive competition from 9/23/2024 to 9/25/2024, and a site-prep prescribed burn was conducted on 11/21/2024. Containerized longleaf pine seedlings were planted at 2.1 x 3.0 m spacing (1,537 trees per hectare) in the CC area from 12/15/2024 to 1/1/2026. The Sl monitoring area was treated with understory herbicide on 8/21/2024 and prescribed burned on 11/14/2024. The ML and YL monitoring areas were prescribed burned on 3/2/2025 and treated with understory herbicide on 8/4/2025. Summaries of the pretreatment (March

2024) and post-treatment (October 2025) inventories quantified changes to forest attributes at both the stand and plot levels (Table 1).

**Table 1**. Table of all plot-level and stand-level (ex. Plot / Stand) forest attributes by monitoring area. Pretreatment data was collected in March 2024 and post-treatment was collected in October 2025.

| **Unit Name** | **Age** | **BA** | **TPA** | **Volume/Acre (Tons)** | **LAI** | **Woody (%)** | **Grass (%)** | **Longleaf (%)** | **Loblolly (%)** |
|---|---|---|---|---|---|---|---|---|---|
| *Year 1 – Pretreatment* | | | | | | | | | |
| ML | 54 | 120 / 109 | 66 / 92 | 166 / 142 | 1.26 / 2.24 | 80 / 79 | 10 / 8.6 | 50 / 46 | 17 / 45 |
| YL | 29 | 120 / 121 | 249 / 195 | 115 / 142 | 2.72 / 3.06 | 40 / 69 | 0 / 0 | 92 / 88 | 0 / 8 |
| Sl | 54 | 60 / 45 | 65 / 45 | 78 / 55 | 0.43 / 0.78 | 45 / 59 | 45 / 25 | 0 / 3 | 100 / 74 |
| CC | 35 | 130 / 116 | 188 / 179 | 120 / 116 | 3.58 / 3.35 | 90 / 78 | 0 / 1 | 0 / 0 | 100 / 93 |
| Ct | 77 | 50 / 53 | 19 / 51 | 95 / 75 | 2.9 / 3.71 | 80 / 79 | 0 / 5 | 0 / 12 | 100 / 84 |
| *Year 2 – Post-treatment* | | | | | | | | | |
| ML | 55 | 80 / 69 | 42 / 46 | 113 / 93 | 0.90 / 1.28 | 10 / 13 | 85 / 63 | 75 / 51 | 13 / 39 |
| YL | 30 | 60 / 54 | 91 / 75 | 55 / 55 | 0.46 / 0.63 | 10 / 23 | 55 / 31 | 100 / 92 | 0 / 2 |
| Sl | 55 | 60 / 45 | 65 / 45 | 78 / 55 | 0.64 / 0.86 | 35 / 28 | 60 / 46 | 0 / 3 | 100 / 74 |
| CC | 0 | 0 / 6.3 | 0 / 8.5 | 0 / 5 | 0.01 / 0.47 | 40 / 27 | 30 / 38 | 0 / 98 | 0 / 2 |
| Ct | 78 | 50 / 53.3 | 19 / 51 | 95 / 75 | 4.64 / 4.81 | 85 / 75 | 0 / 15 | 0 / 12 | 100 / 84 |

## *2.3 Modeling*

### *2.3.1 Weather Station ET*

Evapotranspiration was modeled using several direct measurements of environmental variables at our ATMOS41W weather station. These daily estimates of evapotranspiration were later used to validate daily soil evapotranspiration using linear regression. Weather station ET was calculated using the Penman-Monteith method:

$$ET_o = \frac{0.408\Delta(R_n - G) + \gamma \frac{900}{T + 273} u_2 (e_s - e_a)}{\Delta + \gamma(1 + 0.34u_2)} \tag{1}$$

Where $ET_0$ is the reference evapotranspiration (mm day$^{-1}$), $R_n$ is the net radiation at the vegetation surface, $G$ is the soil heat flux density, $T$ is the mean daily air temperature at 2 m height, $u_2$ is wind speed at 2 m height, $e_s$ is saturation vapor pressure, $e_a$ is actual vapor pressure, $e_s$- $e_a$ is saturation vapor pressure deficit, Δ is slope vapor pressure curve, and γ is the psychrometric constant.

### *2.3.2 Soil ET and Water Yield*

Previous examples of soil moisture measurements being used to generate measures of soil evapotranspiration are not uncommon (Fares and Alva, 2000; Nachabe et al., 2005; Acharya et al., 2022). Total soil moisture was calculated for non-rainy days using soil moisture content measured at 15, 30, 45, 60, 75, 90, 105, and 120 cm depths:

$$TSM = \sum_{i=1}^{7} \frac{1}{2}(z_i - z_{i+1})\ x\ (\theta_{i+1} + \theta) + z_1\ x\ \theta_1 \qquad (2)$$

Where $\theta_i$ is soil moisture content and z are depth at the *i*th sensor location. Soil moisture from the ground surface to the first sensor was calculated by adding $z_1\ x\ \theta_1$. Total soil moisture was calculated for all sensors ($z_{1\text{-}8}$), upper total soil moisture ($z_{1\text{-}4}$) and lower total soil moisture ($z_{5\text{-}8}$). For lower total soil moisture, our equation excluded the calculation of soil moisture starting at the surface and was as follows:

$$TSM_{lower} = \sum_{i=1}^{7} \frac{1}{2}(z_i - z_{i+1})\ x\ (\theta_{i+1} + \theta) \qquad (2)$$

Soil ET was analyzed at 5-minute collection intervals to determine Q, or lateral subsurface flow and $ET_{soil}$ for each monitoring site. Lateral subsurface flow was calculated using:

$$Q = \frac{TSM_{0400hr} - TSM_{midnight}}{4} \qquad (3)$$

Where TSM from midnight to 4:00am is negligible, and provides a means for calculating the constant Q, or water that is leaving or entering the soil column via lateral subsurface flow (Nachabe et al. 2005). Finally, $ET_{soil}$ was determined using:

$$ET_{soil} = TSM_j - TSM_{j+1} + 24\ x\ Q \tag{4}$$

Where $TSM_j$ is total soil moisture at midnight, and $TSM_{j+1}$ is total soil moisture of at midnight the following day. To account for lateral discharge or recharge, 24 hours of lateral subsurface flow (Q) was added to provide daily ET values.

Water yield was calculated using established methods in the Coastal Plain region where mean average precipitation (MAP) is estimated to be 1300 mm per year (McLaughlin et al., 2013; English et al., 2024). Water yield was calculated using:

$$Water\ Yield\ = (1 - \frac{ET}{PPT}) \times MAP \tag{3}$$

Where ET/PPT is the amount of daily soil ET divided by measured precipitation from the same period.

### *2.3.3 Statistical Analysis*

Our analysis included quantification of cumulative soil moisture change (gain and loss) for each monitoring site and comparing values before and after treatments. This provided a means of assessing whether our treatments had notably different amounts of soil moisture entering and exiting the soil column compared to our control. To further compare our treatments versus control, we calculated soil moisture release (SMR) for each site using polynomial regression of matric potential and TSM, both at upper and lower soil levels. Pretreatment and post-treatment SMR, average MP, and average TSM were compared on Brushy to provide further insights into how treatments were impacting soil moisture availability compared to our control. Polynomial regression analysis was performed using the "ggplot" package in RStudio, version 2024.04.2 Build 764.

When modeling relationships between forest attributes and soil moisture properties (i.e. MP, TSM, lateral subsurface flow, soil ET, and water yield), we used both linear and logarithmic regression in RStudio. For most of our analysis, we focused on LAI as a predictor variable because of its predictive strength in our study and other similar studies.

When analyzing data using regression, the "rempsyc" package in R was used to conduct a comprehensive assumptions test on datasets. For each dataset, a p-value was generated for Shapiro-Wilk (normality)[1], Brush-Pagan (heteroscasdicity)[2], and Durbin-Watson (autocorrelation)[3] tests. In instances of p-values < 0.05, a violation was noted and included in our results. Both assumptions tests and regression analysis were performed at a $\alpha = 0.05$ significance level ($p > 0.05$).

# Results

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### *3.1 Cumulative Soil Moisture Change: Before and After Treatments*

The Y1 to Y2 change in cumulative soil moisture gain and loss was greatest in treatment areas compared to our control (Figure 4). All treatment sites experienced an increase in the amount of cumulative soil moisture entering the soil column (X = 4.61 $m^3\ m^{-3}$) from Y1 to Y2, whereas the control experienced a decrease (-1.23 $m^3\ m^{-3}$). The average change in loss of cumulative soil moisture from Y1 to Y2 for treatments was -5.91 $m^3\ m^{-3}$, compared to -0.98 $m^3\ m^{-3}$ at the control site. This would indicate that following treatments, more water was both entering and exiting the soil column where treatments occurred. This is despite significant more rainfall in Y1 (2,224 mm) compared to Y2 (1,506 mm).

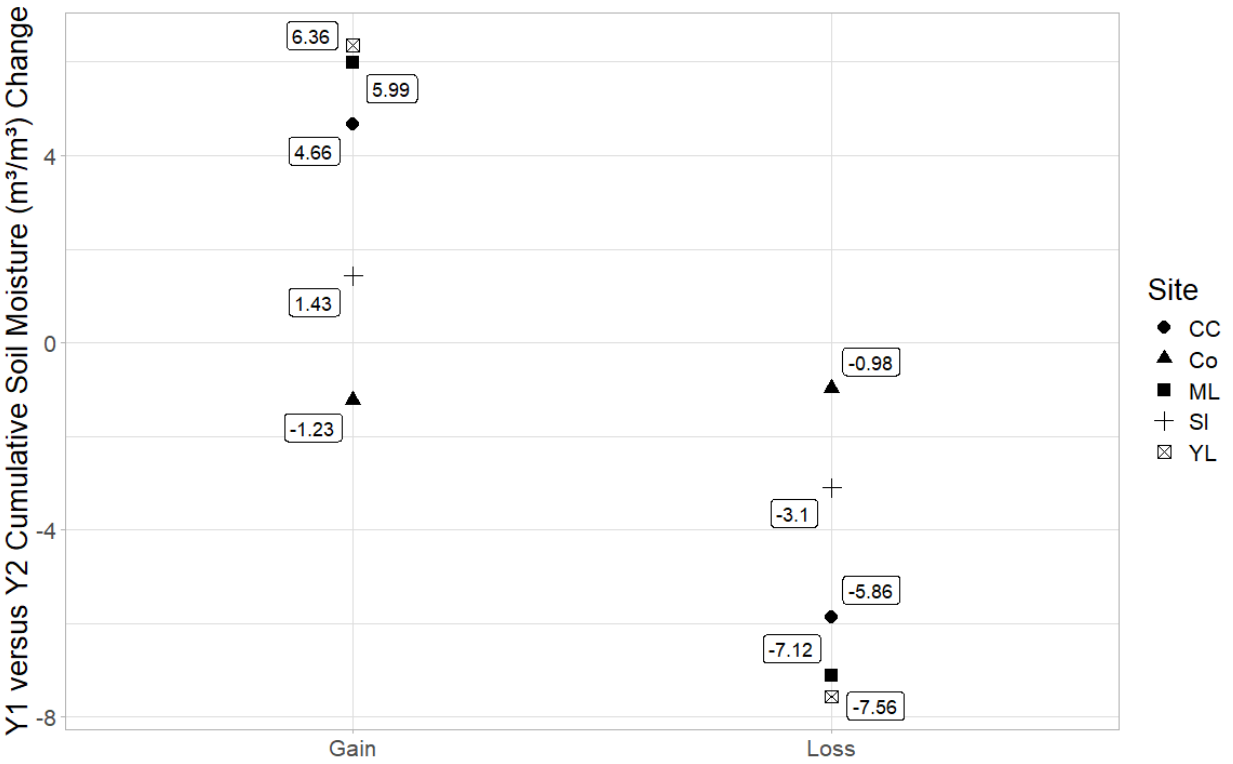

**Fig 4.** Despite much larger amounts of rainfall in year one of monitoring, increases in the amount of Y1 to Y2 cumulative soil moisture gain and loss were observed in all four treatment areas. A relatively small amount of change was observed in the no-treatment control area.

### *3.2 Matric Potential and SMR: Before and After Treatments*

When modeling SMR curves for shallow (Figure S1) and deep (Figure S2) sensor locations, we observed relatively larger changes in SMR characteristics at deeper levels. This is best described by relatively more days in Y2 (treatments) where TSM and matric potential were higher at lower sensor depths. For all four treatments areas, changes in average matric potential and TSM were higher following treatments when compared to our control (Table 2). There were no significant changes regarding where TSM and matric potential related along the curve, but following treatments, more days were observed in conditions where soil moisture availability was higher (Figure S2). SMR curves at shallow sensor depths demonstrated similar patterns but not as dramatic of changes, indicating the possible importance of monitoring at lower depths (>60 cm) in studies like ours.

Following restoration activities, there was 9.58x10$^{-3}$ m$^{3}$/m$^{3}$ more average TSM at treatments versus our control in lower soil levels, and 5.23x10$^{-3}$ m$^{3}$/m$^{3}$ more average TSM at treatments versus our control in upper soil levels. Average change in MP at treatments was 11.4 kPA greater than our control at lower soil levels and 4.59 kPA greater than our control at upper soil levels. Our overall conclusion was that soil moisture availability increased in areas receiving treatments.

**Table 2**. Summaries of mean MP and TSM at upper and lower soil levels for each monitoring site on Brushy Creek. Pretreatment and post-treatment periods are summarized, along with their differences for each site.

| | **Pretreament** | | | | **Post-Treament** | | | | **Difference** | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Mean MP (kPA) | | Mean TSM (m$^{3}$/m$^{3}$) | | Mean MP (kPA) | | Mean TSM (m$^{3}$/m$^{3}$) | | Mean MP (kPA) | | Mean TSM (m$^{3}$/m$^{3}$) | |
| | *Upper* | *Lower* | *Upper* | *Lower* | *Upper* | *Lower* | *Upper* | *Lower* | *Upper* | *Lower* | *Upper* | *Lower* |
| **ML** | -6.85 | -6.76 | 0.0689 | 0.102 | -6.23 | 2.26 | 0.0755 | 0.114 | 0.62 | 9.02 | 0.0066 | 0.012 |
| **YL** | -8.86 | -12.6 | 0.0634 | 0.0767 | -11.2 | -2.81 | 0.0656 | 0.0906 | -2.34 | 9.79 | 0.0022 | 0.0139 |
| **Sl** | -3.56 | -1.03 | 0.0807 | 0.0777 | -3.34 | 2.54 | 0.0899 | 0.0879 | 0.22 | 3.57 | 0.0092 | 0.0102 |
| **CC** | -6.34 | -26.6 | 0.0776 | 0.0948 | -5.71 | 1.08 | 0.0817 | 0.113 | 0.63 | 27.68 | 0.0041 | 0.0182 |
| **Co** | -7.92 | -28.6 | 0.0848 | 0.1 | -13.2 | -27.5 | 0.0845 | 0.104 | -5.28 | 1.1 | -0.0003 | 0.004 |

When modeling Y1 to Y2 changes in matric potential and TSM versus changes in plot-level LAI, we observed strong relationships between deep sensor locations and LAI changes (Figure 5). Decreases in LAI were significantly related to increases in TSM ($R^2 = 0.80$, $P = 0.039$) and matric potential ($R^2 = 0.94$, $P = 0.007$). Changes in LAI were not significantly related to TSM ($R^2 = 0.28$, $P = 0.360$) and matric potential ($R^2 < 0.01$, $P = 0.920$) at shallow sites, again indicating that effects of treatments are more measurable at deeper soil levels. Y1 to Y2 changes in lateral subsurface flow ($Q$) were significantly related to changes in plot-level LAI ($R^2 = 0.78$, $P = 0.048$), with reductions in LAI indicating decreases in $Q$. Decrease in Q are more characteristic of a recharge site, and are described as decreases in the amount of water entering the soil column at monitoring sites.

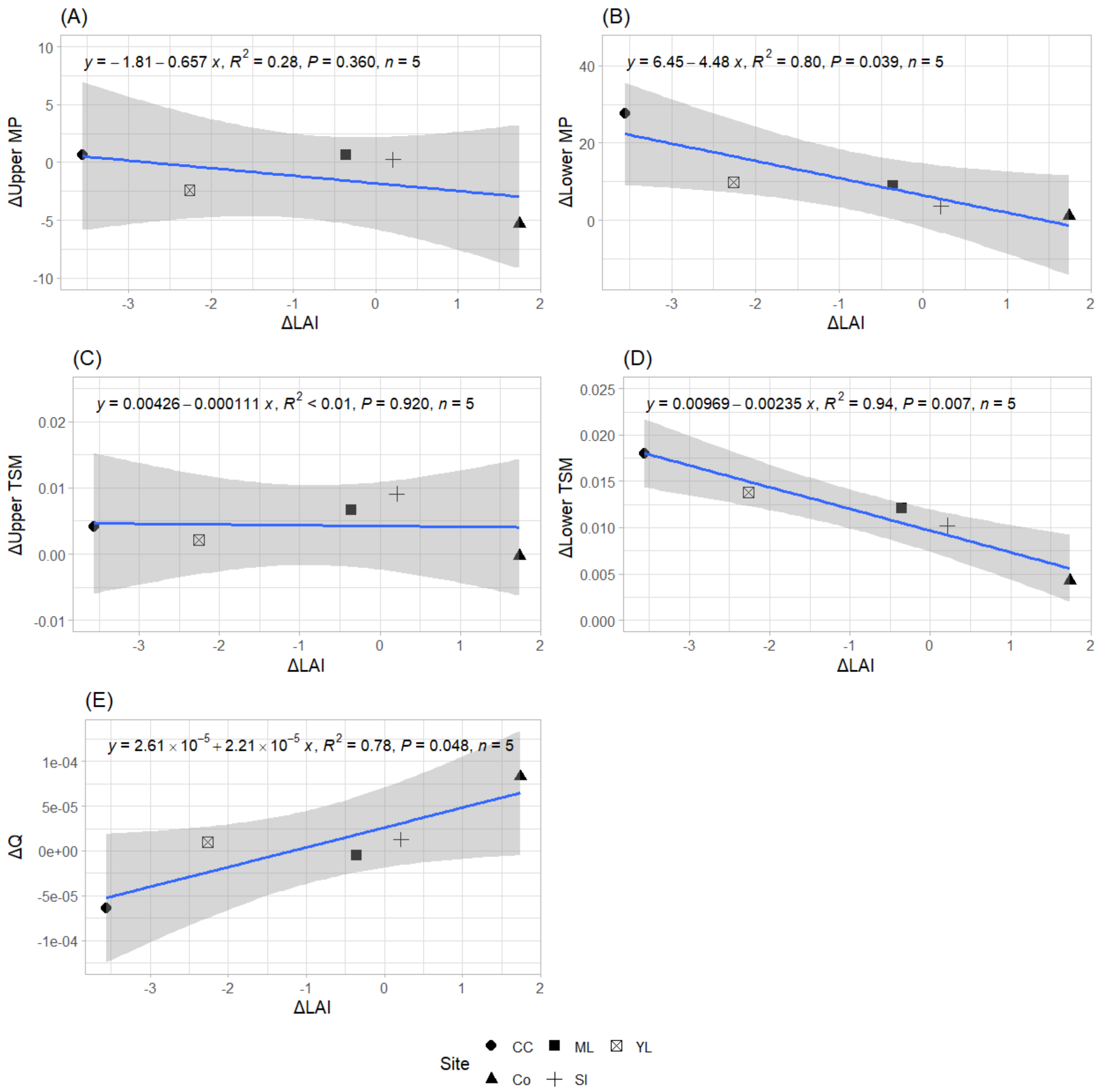

**Fig 5.** (A) Relationship of change in upper matric potential (MP) and LAI from year one to year two on Brushy Creek; (B) lower MP and LAI, (C) upper total soil moisture (TSM) and LAI, (D) lower TSM and LAI, and (E) lateral subsurface flow (*Q*) and LAI.

### *3.3 LAI and Water Yield Regression – Drying and Wetting Periods*

Analysis of seasonal trends in water yield showed significant relationships between changing LAI, pretreatment and post-treatment, and water yield at monitoring sites. Logarithmic regression indicated that a reduction of LAI generated more water yield during drying seasons (late-Spring to late-Summer) when compared to wetting seasons (late-Fall to early-Spring) (Figure 7). While these modeled relationships did not explain a robust amount of the variance for both drying ($R^2 = 0.30$) and wetting ($R^2 = 0.35$) periods, they were statistically significant ($P < 0.05$) and did not violate any regression assumptions.

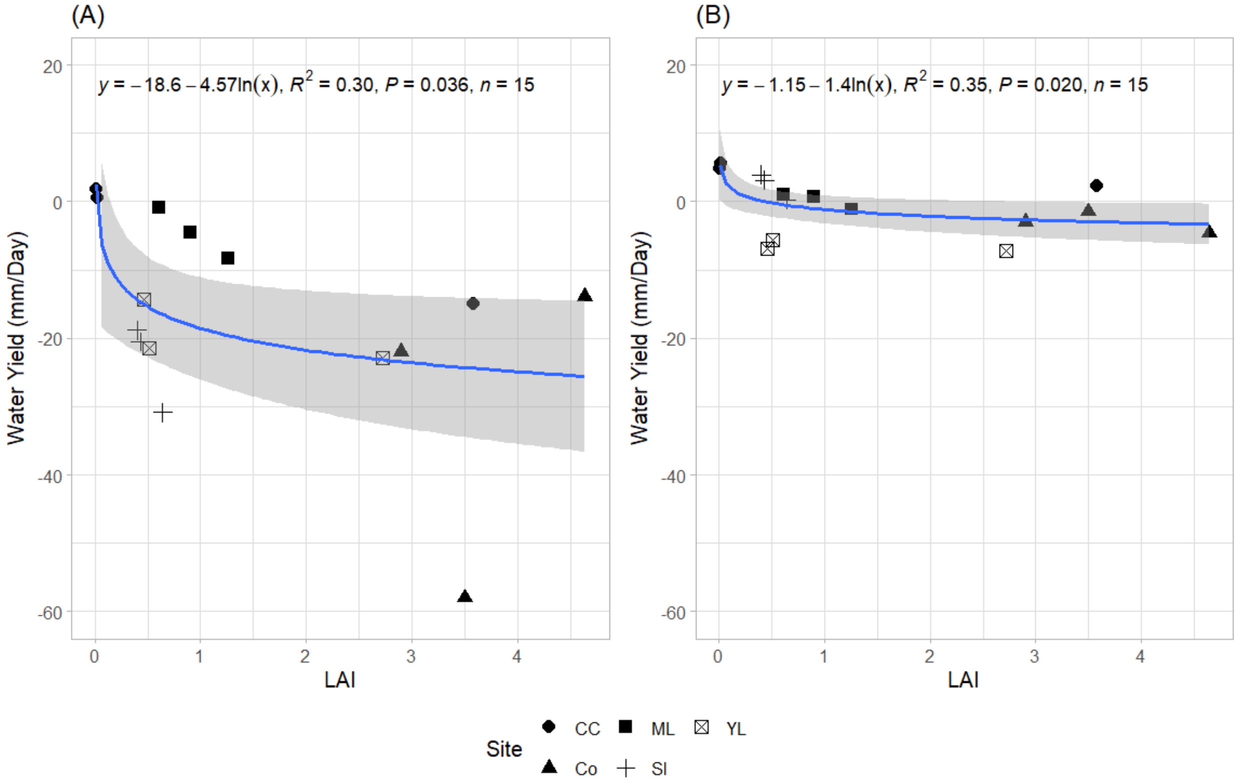

**Fig 7.** Logarithmic regression of mm/Day water yield versus plot level LAI data collected on Brushy Creek for wetting and drying periods.

When comparing wetting and drying seasonal water yield at each monitoring site, areas where timber harvest and brush management occurred experienced consistent and relatively large increases in water yield (Table S1 & S2). When averaging the two post-treatment periods of seasonal water yield, and subtracting the period of pretreatment water yield, the ML, YL and CC treatments experienced

5.6, 5.0 and 16.2 mm/day increases in water yield respectively during the drying season. During the wetting season, those same sites experienced 1.9, 0.9 and 3.0 mm/day increases in water yield, indicating a change regardless of season but a less dramatic one during wetting periods where soil conditions are at field capacity or saturation. We noted reductions in water yield during the drying period for both the Sl and Co sites, at -4.3 and -13.9 mm/day respectively. This indicates that brush management alone might not be an effective means for increasing water availability but is still more impactful than no management at all. Large differences in annual rainfall from year 1 (2,224 mm) to year 2 (1,506 mm) are also a potential explanation for some of these trends. The Sl and Co sites also experienced -1.0 and -0.1 mm/day reductions in water yield during the wetting periods, respectively.

When attempting to validate our soil ET values using ET measurements made at our weather station, we observed the strongest relationship occurring on non-rainy days during the drying period. The same drying periods used in our analysis above were used, and major outliers in soil ET values were omitted from the analysis (0-10 mm day$^{-1}$). Statistical significance was identified for four of five monitoring stations, with the Co area being the only non-significant example (Figure 6). Explanation of variance was low when modeling weather station ET and Soil ET ($R^2 < 0.19$-$0.36$), but weather station ET was modeled in a notably different environment than all five monitoring areas. These results indicated a reasonably consistent validation of our modeled soil ET values and ET measured separately at the weather station.

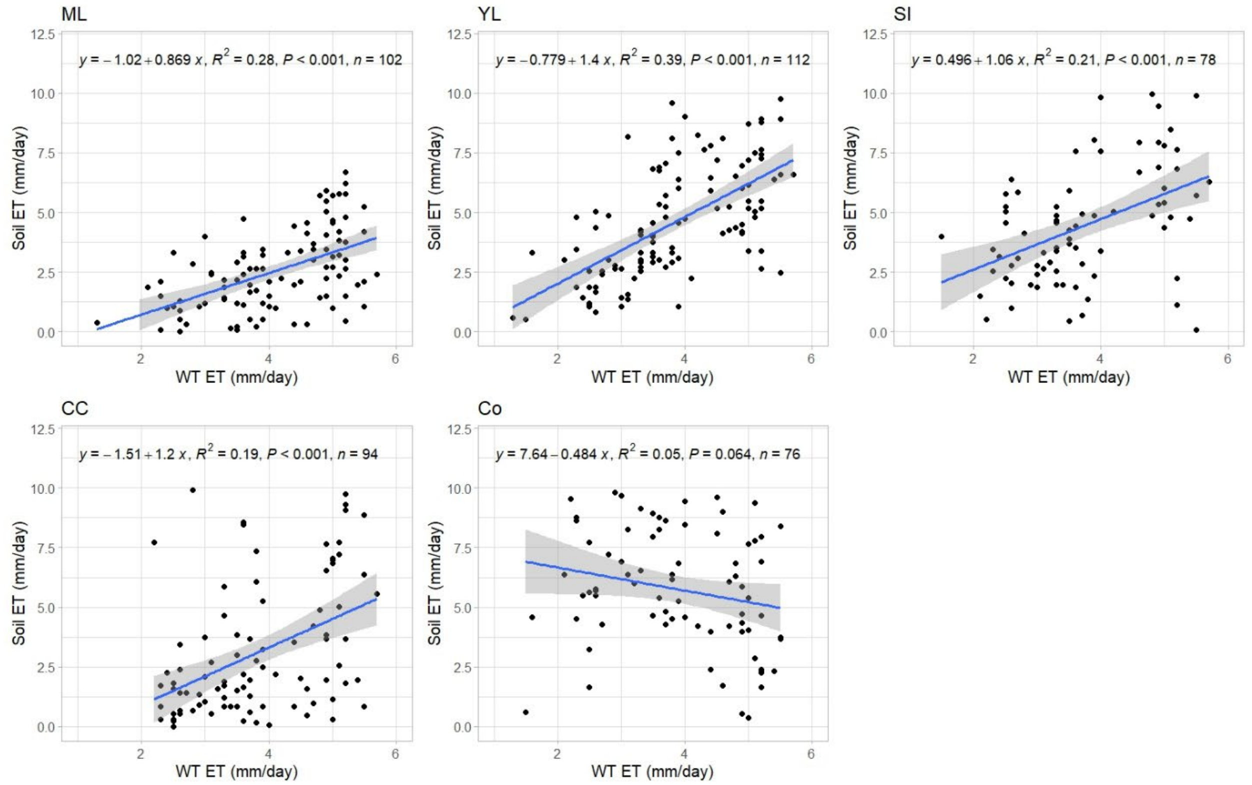

**Fig. 6.** Soil ET at monitoring sites versus modeled ET at the weather station had a statistically significant relationship for four of five monitoring sites but there was a large amount of variance when performing a linear regression for all sites.

### *3.4 LAI and Water Yield Regression – Annual*

When excluding the YL area on Brushy Creek, a significant relationship occurred between both stand and plot-level LAI and water yield using logarithmic regression (Figure 8). This included pretreatment and post-treatment data points on Brushy Creek, demonstrating a consistent relationship between LAI and water yield following treatments. As mentioned, the exception was the YL area, where a significant reduction in water yield occurred following treatments in year 2. The YL area was characterized by a plantation type structure and younger tree age, so this may have contributed to the outlier results. Young trees would predictably have more water intensive needs, suggesting that certain forest systems, such as plantations, might not be suitable candidates for managing water resource benefits.

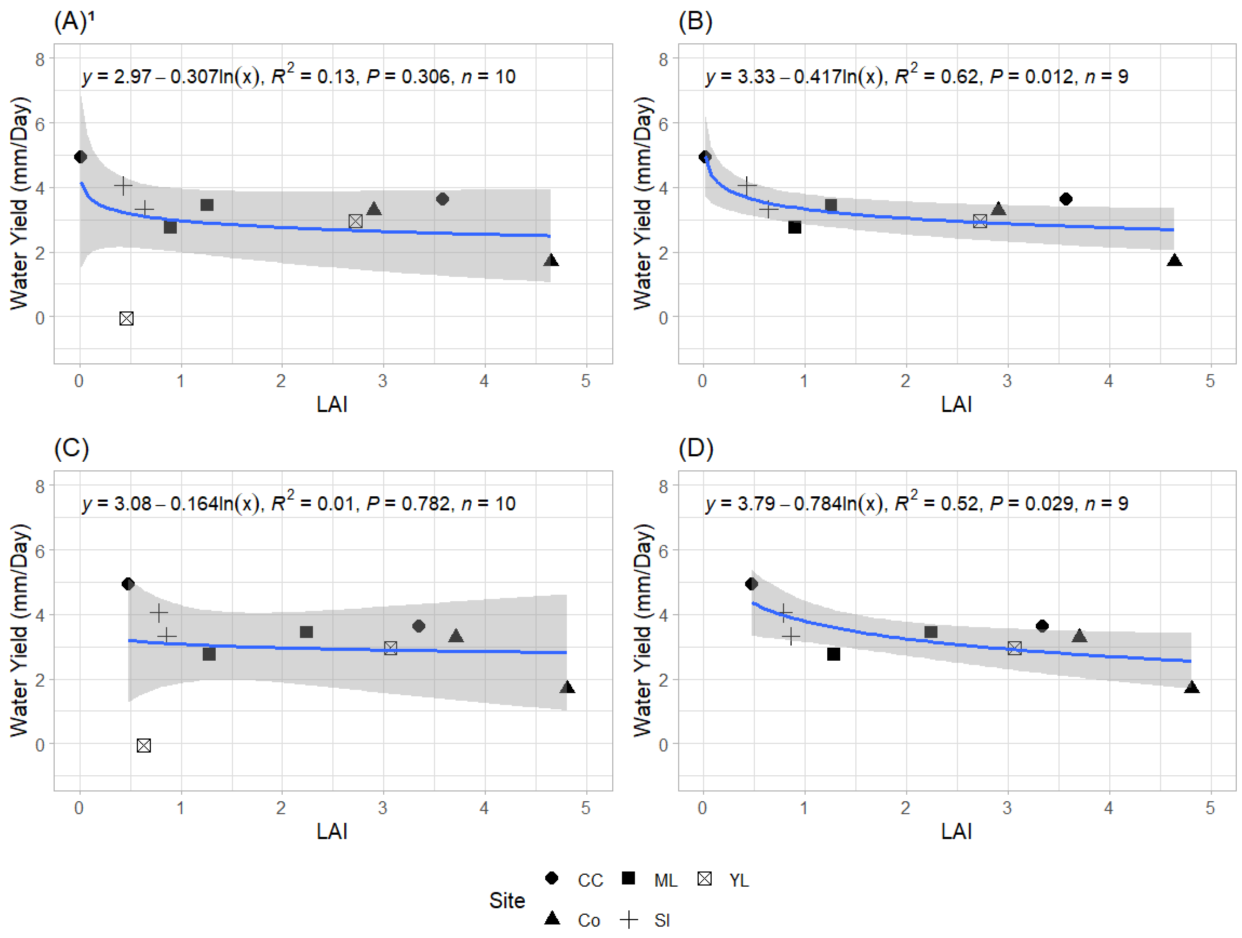

**Fig 8.** (A) Relationships of plot-level LAI and water yield in Y1 & Y2 that includes the YL outlier and (B) does not include the YL outlier. (C) Relationships of stand-level LAI and water yield in Y1 & Y2 that includes the YL outlier and (D) does not include the YL outlier.

When analyzing a calendar year, water yield did not increase from Y1 to Y2 across monitoring sites, except for the clear-cut treatment area (Table S3). It's important to note, however, a significant amount of rainfall occurred in Y1 relative to Y2. This further suggests that the timing, amount of rainfall, but also, the amount of rainfall within a specific time periods (i.e. magnitude of rainfall pulses), are all factors impacting water yield at the site. This is especially important to note when considering rainfall in 2024 (2,224 mm), where not only was the average annual rainfall exceeded drastically (~1300 mm), but significant rainfall events happened on several occasions within small time periods.

Using our stand-level water yield versus LAI curve to generate estimates of water yield, practices that include timber harvest experienced the largest change. When averaging stand-level LAI before (2.65) and after (0.95) in our two thinned stands (ML & YL), we estimated a 29.35 cm $yr^{-1}$ increase in water yield. Our already thinned area (Sl) that received brush control treatments experienced a marginal increase in LAI (0.78 → 0.86) and a corresponding marginal decrease in water yield (-2.77 cm $yr^{-1}$). The CC treatment area demonstrated the largest reduction in stand-level LAI (3.35 → 0.47) and corresponding increase in water yield (56.21 cm $yr^{-1}$). In clearcut situations, we would anticipate decreases in this initial dramatic increase in water yield as the stand grows. Long-term monitoring could identify whether maintaining an open pine structure is relatively less water intensive compared to the dense, intensively managed loblolly pine that was clearcut.

# Discussion

### *4.1 Water Yield and LAI in Southern Forests*

We observed noteworthy increases in the amount of cumulative soil moisture entering and exiting the soil column where treatments occurred, whereas there was little change in the untreated control. Additionally, significant relationships were modeled between changes in LAI, and changes in subsurface flow, deep matric potential, and deep TSM before and after treatments. These in contrast to no measurable relationship between changing LAI and shallow matric potential and shallow TSM, suggesting that forest restoration activities had the largest impact on soil moisture characteristics at depths below 60 cm. Despite a small sample size, these relationships at deeper soil levels were consistently strong and indicate that reduced LAI is a reasonable predictor of increased ecosystem available water where forest restoration occurred. Reduced sapwood area (thinning), reduced amounts of invasive brush, and increased amounts of herbaceous groundcover were some of the structural shifts that promoted those changes.

Like previous work (Acharya et al., 2020; Acharya et al., 2022; McLaughlin et al., 2013), our current results provide additional evidence that LAI has a noteworthy relationship with water yield in a southern forest system. We also provided evidence that a 29.35 cm yr$^{-1}$ increase is possible in thinning and brush management scenarios where a 1.7-unit LAI reduction occurred. Acharya et al., 2022 reported a similar albeit linear relationship, where a 1-unit reduction of LAI resulted in 10 cm yr$^{-1}$ increase in water yield. Our results indicate this relationship might be non-linear and variable across seasons, with open managed pine stands maintaining approximately 1-unit of LAI for our study. We also contend that this is arguably the first example where treatments were executed, and a pretreatment and post-treatment analysis was conducted to demonstrate how restoration impacted water yield in the western portion of the longleaf pine species range.

These results suggest the circumstances of how and when you quantify water yield are understandably quite complex. Furthermore, the scale and ecohydrological setting of our site are major factors in our results, with other scenarios yielding potentially different outcomes (Sun et al., 2005; Van Dijk and Keenan 2007). Within a site, results can vary based on annual rainfall, how much of that rainfall is occurring during certain parts of the year, and how large those isolated rainfall events are within each season. For example, a large rainfall event during the wetting season, where soil moisture is mostly at field capacity, is going to yield results different from a similar rainfall event in the middle of the drying season. Future data collection should focus on quantifying additional components of the water budget, with deep drainage, groundwater recharge, and streamflow being practiced examples (Nachabe et al., 2005; Younger et al., 2023). This would provide more confidence regarding where additional water availability can be accounted for.

Additionally, a focus on the scale of the impact, and its quantification at the watershed level would be important, too.

### *4.2 Effective Management Strategies for Increasing Water Yield*

In our study and other examples (Pisarello et al., 2022), forest thinning appears to be a standout strategy for increasing water yield while also maintaining an existing forest structure. The important designation is that forested landcover and the associated benefits were retained, while also managing for a less water-intensive forest type. This also decreased the magnitude of the disturbance compared to, for example, our clearcut regeneration treatment. In clearcut scenarios, which in other studies have demonstrated relatively large water yield increases (Pisarello et al., 2022), there are some important caveats to consider. While a large increase in water yield was observed and should be expected initially, a newly established stand will use increased water resources in subsequent years. An important question is whether a recently established but fire-maintained longleaf stand is less water-intensive than its intensively managed loblolly pine counterpart. This will require long-term monitoring for our study or others.

Already thinned areas where brush management is implemented may experience a relatively small change in soil moisture conditions, and potentially negligible or no increase in water yield. This would suggest that a reduction in sapwood area (thinning), and low-density forest structures in general, are a better strategy for increasing water yield.

### *4.3 Focusing on Longleaf Pine to Benefit Water Resources*

The forest structure associated with fire-maintained, historical longleaf pine ecosystems has demonstrated relatively low evapotranspiration and increased streamflow compared to other forest types in the southeastern United States (Brantley, 2013; Qi et al., 2022; Younger et al., 2023; Liu et al. 2025). For most or all these studies, eddy covariance flux data, in-situ streamflow measurements, and simulated streamflow were located east of the Mississippi River. Our site adds a case study of increased water yield that is located, not only west of the Mississippi River, but at the western-most extent of the longleaf pine range. In one study, southern pine species was not a significant contributor to changes in water yield, whereas variables such as LAI were more impactful (Acharya et al., 2023). It might be that southern forest of different pine species provide opportunities for managing water resources benefits, but with several important considerations regarding longleaf pine, specifically. For example managing for open pine conditions in the south often includes the use of prescribed burning, and longleaf pine is widely known to be a relatively fire-adapted and tolerant species (Brockway and Lewis, 1997; Stambaugh et al., 2011; Hanberry et al., 2018). Evidence also suggests that longleaf pine is relatively drought tolerant (Samuelson et al., 2012), and resilient to major disturbances such as wildfire conditions and wind damage from events such as hurricanes that occur regularly in the region (Johnsen et al., 2009; Rutledge et al., 2021). Therefore, while longleaf pine as an overstory species may not be necessary to create a forest condition that benefits water resources, establishing or maintaining longleaf forests could arguably be the better strategy when attempting to create long-term, climate-resilient forests. This, combined with a robust network of longleaf pine support groups and cost-share opportunities available, indicate there are existing opportunities to generate more water-conscious forests in the southeastern United States. As the feasibility of creating water benefits using longleaf pine restoration is more confidently identified, it may eventually provide more programmatic opportunity for landowners to establish longleaf. This might also offset some of the lost economic opportunity that landowners experience when foregoing more conventional, loblolly plantation style management (Susaeta and Gong 2019; English et al., 2024).

## Conclusions

Our studies findings were that increased soil moisture availability and water yield were the result of restoration treatments in longleaf pine areas of southeast Texas. Amongst forest attributes we sampled, LAI was a relatively strong predictor of changes in soil moisture characteristics at the site. A 1.7-unit reduction in LAI translated to a 29.35 cm $yr^{-1}$ increase in water yield where forest thinning is applied in similar scenarios. Forest thinning and management for open, herbaceous groundcover using prescribed fire was an effective approach for promoting long-term water resources benefits. Clearcut conversions to longleaf pine from intensively managed loblolly pine resulted in significant increases in water yield, but long-term monitoring is required to assess whether these changes persist. Both longleaf pine and other southern pine forest managed for openness using prescribed fire provide likely opportunities for increasing water yield. Given longleaf pine's fire and drought adapted characteristics, it could provide a relatively climate resilient solution to maintaining less water-intensive forested landcover.

## Supplemental Information

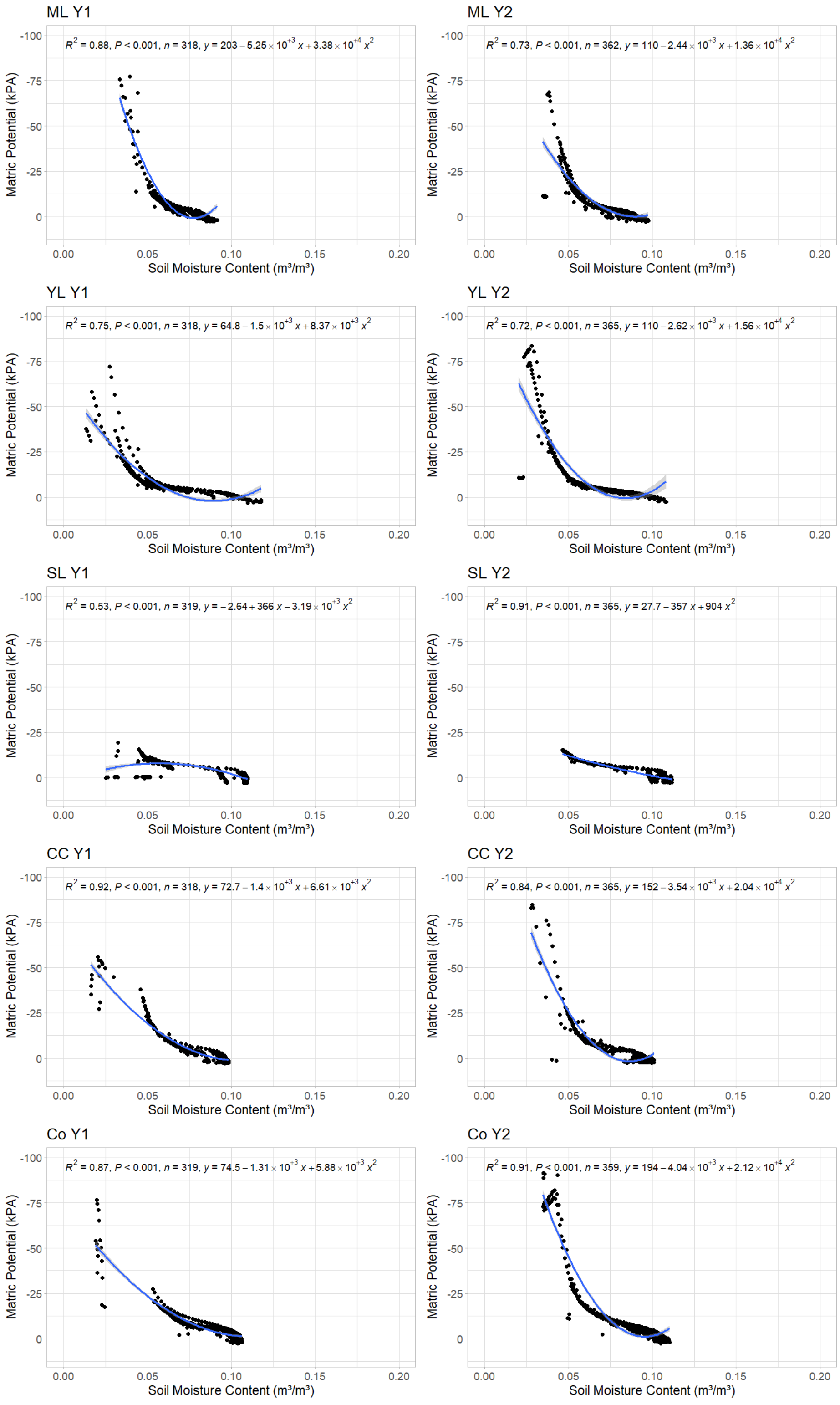
ML Y1
$R^2 = 0.88$, $P < 0.001$, $n = 318$, $y = 203 - 5.25 \times 10^{+3}\,x + 3.38 \times 10^{+4}\,x^2$
ML Y2
$R^2 = 0.73$, $P < 0.001$, $n = 362$, $y = 110 - 2.44 \times 10^{+3}\,x + 1.36 \times 10^{+4}\,x^2$
YL Y1
$R^2 = 0.75$, $P < 0.001$, $n = 318$, $y = 64.8 - 1.5 \times 10^{+3}\,x + 8.37 \times 10^{+3}\,x^2$
YL Y2
$R^2 = 0.72$, $P < 0.001$, $n = 365$, $y = 110 - 2.62 \times 10^{+3}\,x + 1.56 \times 10^{+4}\,x^2$
SL Y1
$R^2 = 0.53$, $P < 0.001$, $n = 319$, $y = -2.64 + 366\,x - 3.19 \times 10^{+3}\,x^2$
SL Y2
$R^2 = 0.91$, $P < 0.001$, $n = 365$, $y = 27.7 - 357\,x + 904\,x^2$
CC Y1
$R^2 = 0.92$, $P < 0.001$, $n = 318$, $y = 72.7 - 1.4 \times 10^{+3}\,x + 6.61 \times 10^{+3}\,x^2$
CC Y2
$R^2 = 0.84$, $P < 0.001$, $n = 365$, $y = 152 - 3.54 \times 10^{+3}\,x + 2.04 \times 10^{+4}\,x^2$
Co Y1
$R^2 = 0.87$, $P < 0.001$, $n = 319$, $y = 74.5 - 1.31 \times 10^{+3}\,x + 5.88 \times 10^{+3}\,x^2$
Co Y2
$R^2 = 0.91$, $P < 0.001$, $n = 359$, $y = 194 - 4.04 \times 10^{+3}\,x + 2.12 \times 10^{+4}\,x^2$
Matric Potential (kPA)
-100
-75
-50
-25
0
0.00
0.05
0.10
0.15
0.20
Soil Moisture Content (m³/m³)

**Fig. S1**. Shallow soil moisture release curves at all treatments in Y1 (pretreatment) and Y2 (post-treatment) on Brushy Creek.

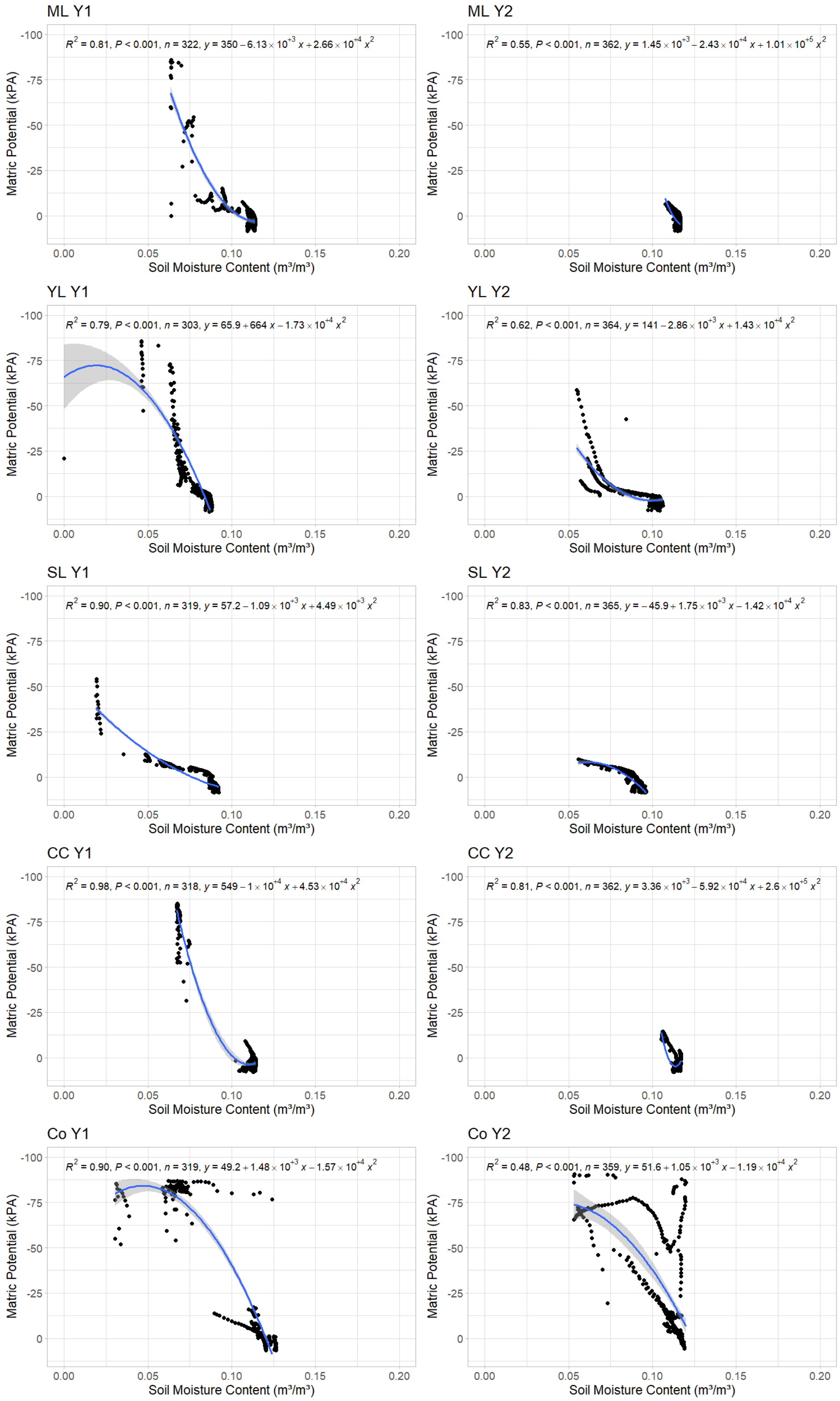

**Fig. S2**. Deep soil moisture release curves at all treatments in Y1 (pretreatment) and Y2 (post-treatment) on Brushy Creek.

**Table S1**. Modeled water yield during the various drying periods in Y1 and Y2 on Brushy creek.

| Site | Avg Daily ET (mm) - All | Non Rainy Days | LAI | Percip (mm) | Total Water Yield (mm) - All | Monitoring Period |
|---|---|---|---|---|---|---|
| BRUSH YEAR 1 | | | | | | |
| Mature Longleaf | 3.19 | 23 | 1.26 | 26 | -191 | 6/8/2024-7/7/2024 |
| Young Longleaf | 7.00 | 20 | 2.72 | 26 | -458 | 6/8/2024-7/7/2024 |
| Slash/Lob | 6.24 | 23 | 0.43 | 26 | -472 | 6/8/2024-7/7/2024 |
| Clear-cut | 4.87 | 23 | 3.58 | 26 | -345 | 6/8/2024-7/7/2024 |
| Brushy/Control | 6.61 | 23 | 2.9 | 26 | -506 | 6/8/2024-7/7/2024 |
| BRUSHY YEAR 2 | | | | | | |
| Mature Longleaf | 0.64 | 49 | 0.61 | 26 | -41 | 9/6/2024-10/30/2024 |
| Young Longleaf | 3.40 | 49 | 0.51 | 26 | -1054 | 9/6/2024-10/30/2024 |
| Slash/Lob | 3.04 | 49 | 0.4 | 26 | -923 | 9/6/2024-10/30/2024 |
| Clear-cut | 0.28 | 49 | 0.01 | 26 | 91 | 9/6/2024-10/30/2024 |
| Brushy/Control | 8.25 | 49 | 3.5 | 26 | -2843 | 9/6/2024-10/30/2024 |
| BRUSHY YEAR 2 | | | | | | |
| Mature Longleaf | 2.96 | 33 | 0.90 | 50 | -151 | 6/18/2025-8/2/2025 |
| Young Longleaf | 6.02 | 33 | 0.46 | 50 | -471 | 6/18/2025-8/2/2025 |
| Slash/Lob | 11.24 | 33 | 0.64 | 50 | -1019 | 6/18/2025-8/2/2025 |
| Clear-cut | 1.37 | 33 | 0.02 | 50 | 17 | 6/18/2025-8/2/2025 |
| Brushy/Control | 5.89 | 33 | 4.64 | 50 | -458 | 6/18/2025-8/2/2025 |

**Table S2**. Modeled water yield during the various wetting periods in Y1 and Y2 on Brushy creek.

| Site | Avg Daily ET (mm) - All | Non Rainy Days | LAI | Percip (mm) | Total Water Yield (mm) - All | Monitoring Period |
|---|---|---|---|---|---|---|
| BRUSH YEAR 1 | | | | | | |
| Mature Longleaf | 2.11 | 19 | 1.26 | 31 | -21 | 2/16/2024-3/8/2024 |
| Young Longleaf | 4.66 | 19 | 2.72 | 31 | -138 | 2/16/2024-3/8/2024 |
| Slash/Lob | 0.33 | 19 | 0.43 | 31 | 60 | 2/16/2024-3/8/2024 |
| Clear-cut | 0.72 | 19 | 3.58 | 31 | 42 | 2/16/2024-3/8/2024 |
| Brushy/Control | 2.87 | 19 | 2.9 | 31 | -56 | 2/16/2024-3/8/2024 |
| BRUSH YEAR 2 | | | | | | |
| Mature Longleaf | 1.63 | 24 | 0.61 | 52 | 25 | 1/13/2025-2/11/2025 |
| Young Longleaf | 4.99 | 24 | 0.51 | 52 | -137 | 1/13/2025-2/11/2025 |

| | | | | | | |
|---|---|---|---|---|---|---|
| Slash/Lob | 0.18 | 24 | 0.4 | 52 | 95 | 1/13/2025-2/11/2025 |
| Clear-cut | -0.29 | 24 | 0.01 | 52 | 117 | 1/13/2025-2/11/2025 |
| Brushy/Control | 2.88 | 24 | 3.5 | 52 | -35 | 1/13/2025-2/11/2025 |
| BRUSH YEAR 2 | | | | | | |
| Mature Longleaf | 1.49 | 21 | 0.9 | 38 | 13 | 2/27/2025-3/27/2025 |
| Young Longleaf | 5.34 | 21 | 0.46 | 38 | -145 | 2/27/2025-3/27/2025 |
| Slash/Lob | 1.66 | 21 | 0.64 | 38 | 6 | 2/27/2025-3/27/2025 |
| Clear-cut | -1.03 | 21 | 0.02 | 38 | 117 | 2/27/2025-3/27/2025 |
| Brushy/Control | 4.18 | 21 | 4.64 | 38 | -98 | 2/27/2025-3/27/2025 |

**Table S3.** Modeled water yield during for both wetting and drying periods during Y1 and Y2 on Brushy creek.

| **Site** | **Year** | **Avg Daily ET (mm) - All** | **Non Rainy Days** | **LAI: Plot Level** | **LAI: Stand Level** | **Percip (mm)** | **Total Water Yield (mm) - All** | **Monitoring Period** | **mm/Day Water Yield (non-rainy)** |
|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | | | |
| Mature Longleaf | 1 | 1.99 | 243 | 1.26 | 2.24 | 2224 | 836 | 9/21/2023-8/7/2024 | 3.44 |
| Young Longleaf | 1 | 4.99 | 243 | 2.72 | 3.06 | 2224 | 485 | 9/21/2023-8/7/2024 | 2.00 |
| Thinned Slash/Lob | 1 | 0.71 | 243 | 0.43 | 0.78 | 2224 | 986 | 9/21/2023-8/7/2024 | 4.06 |
| Clear-cut | 1 | 1.61 | 243 | 3.58 | 3.35 | 2224 | 881 | 9/21/2023-8/7/2024 | 3.62 |
| Brushy/Control | 1 | 2.35 | 243 | 2.9 | 3.71 | 2224 | 794 | 9/21/2023-8/7/2024 | 3.27 |
| | | | | | | | | | |
| Mature Longleaf | 2 | 2.26 | 276 | 0.90 | 1.28 | 1506 | 763 | 8/8/2024-8/7/2025 | 2.76 |
| Young Longleaf | 2 | 5.51 | 276 | 0.46 | 0.63 | 1506 | -12 | 8/8/2024-8/7/2025 | -0.04 |
| Thinned Slash/Lob | 2 | 1.61 | 276 | 0.64 | 0.86 | 1506 | 917 | 8/8/2024-8/7/2025 | 3.32 |
| Clear-cut | 2 | -0.25 | 276 | 0.02 | 0.48 | 1506 | 1360 | 8/8/2024-8/7/2025 | 4.93 |
| Brushy/Control | 2 | 3.50 | 276 | 4.64 | 4.81 | 1506 | 466 | 8/8/2024-8/7/2025 | 1.69 |

# Declarations

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**Ethics approval and consent to participate:** Not applicable

**Consent for publication:** Not applicable

**Availability of data and material:** Data can be made upon request and contingent on approval of all the various project stakeholders.

**Competing interests:** The authors declare that they have no competing interests.

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**Authors' contributions:**

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