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Watershed Response to Longleaf Pine Restoration on the Santee Experimental Forest: Establishment Report and Baseline Assessment

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COVER IMAGE: Regeneration treatment on watershed 77, Santee Experimental Forest. (Forest Service photo by Hope Fillingim)

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ABSTRACT

This report describes the framework of a long-term project on the Santee Experimental Forest comparing hydrological processes and vegetation dynamics between two research watersheds: one formerly dominated by loblolly pine (*Pinus taeda*) and currently being restored to longleaf pine (*P. palustris*), and the other an unmanaged mixed pine-hardwood reference watershed. Along with descriptions of the watersheds and the silvicultural methods used in the longleaf pine restoration, this report provides baseline data on overstory conditions, soils, leaf area index, and coarse woody debris across the watersheds. A subcomponent of the project is to monitor the success of different methods for restoring longleaf pine, and this report provides an initial assessment of the effects of harvest operations across silvicultural treatments within the longleaf pine restoration watershed.

Keywords: Paired watershed hydrology, longleaf pine restoration, loblolly pine conversion, silviculture, overstory inventory, soils.

KEY MESSAGES:

1. This report presents baseline data for an ongoing paired watershed study on the effects of longleaf pine restoration.

2. Multiple silvicultural methods were used to convert loblolly pine plantations to longleaf pine.

3. Harvests successfully reduced overstory basal area across treatments, creating suitable conditions for longleaf pine restoration efforts; monitoring of residual tree growth is ongoing.

Contents

Introduction

Santee Experimental Forest headquarters site after Hurricane Hugo, September 29, 1989. (Forest Service photo by Carl Trettin)

The Santee Experimental Forest is within the Francis Marion National Forest in the lower Coastal Plain of South Carolina. This experimental forest was established in 1937 as a forest research program studying silviculture on heavily deforested lands and was initially focused on numerous aspects of loblolly pine (*Pinus taeda*) silviculture including hydrology (Young and Klawitter 1968) and prescribed fire (Richter et al. 1982). In the 1980s, its program expanded to include forested wetlands. On September 22, 1989, Hurricane Hugo, a Category 4 storm, landed on Sullivan's Island, SC, and traveled inland northwesterly through the South Carolina Coastal Plain and into North Carolina. Hurricane Hugo destroyed much of the forest overstory on the Francis Marion National Forest, including a substantial portion of the experimental forest (Hook et al. 1991).

Since the late 1960s, researchers have used watershed 77 (WS77) and reference watershed 80 (WS80) on the Santee Experimental Forest for paired watershed studies focused on loblolly pine silviculture, now part of a long-term record that supports contemporary comparative analyses of hydrology and water quality (Amatya and Trettin 2007). This paired watershed approach, in which two neighboring watersheds (one treatment and one reference) are monitored concurrently during calibration (pre-treatment) and post-treatment periods (Amatya et al. 2021; Clausen and Spooner 1993; Jayakaran et al. 2014; Loftis et al. 2001; Ssegane et al. 2013, 2017), has been extensively used to assess effects of silvicultural practices on water yield, other hydrologic variables, and ecosystem services (Bliss and Comerford 2002, Bosch and Hewlett 1982, Brown et al. 2005, Chescheir et al. 2025, Neary 2016, Tomer and Schilling 2009).

For several decades, WS77 has been managed as loblolly pine plantations and is currently being restored to longleaf pine (*P. palustris*), which was the dominant species on 37 million ha across the Southeastern United States (Frost 1993)—including much of the Coastal Plain and portions of the Piedmont (Kirkman and Jack

2017)—prior to European settlement. In 2018, a new long-term experiment was initiated on WS77 and WS80 (Trettin et al. 2019), a mixed pine-hardwood forest, to evaluate different treatments for longleaf pine restoration on water resources, carbon (C) stocks and fluxes, and ecosystem services at the watershed scale. The fundamental hypothesis for the study is that restoring a forest to longleaf pine dominance will yield more water than the previous loblolly pine forests. This hypothesis is based on reports derived from tree- and plot-scale research suggesting that longleaf pine consumes less water through transpiration than loblolly pine due to both the typically low-density management of longleaf pine and lower water use requirements for metabolic functioning (Ford et al. 2004, McLaughlin et al. 2013, Vose et al. 2003). Most recently, Ning et al. (2025) found significant differences in evapotranspiration, evapotranspiration/precipitation ratio, and water yield/precipitation ratio between longleaf and loblolly pine forests, and these differences are explained by surface properties and management histories. Compared to loblolly, the longleaf pine forests generally had lower evapotranspiration due to their significantly ($p < 0.05$) lower leaf area index but higher land surface temperature and albedo. One study found that slash pine used on average 50 percent more water than longleaf pine, due to differences in transpiration rates during periods of low soil moisture, which were primarily driven by the greater leaf area of slash pine (Gonzalez-Benecke et al. 2011). Another study found that longleaf pine had higher leaf water potential than loblolly or slash pine, suggesting that longleaf pine would be better adapted to drier environments, though the study did not find differences in stomatal conductance or water use efficiency between the species (Samuelson et al. 2012). Interestingly, a recent report by Younger et al. (2023) studying U.S. Geological Survey-gauged watersheds, with drainage areas varying from 20 to 938 km^2, affirmed that watersheds with a significant proportion of longleaf pine yield more water as compared to those dominated by loblolly pine.

Baseline hydrology data for WS77 and WS80 are reported in Amatya et al. (2021) and Amatya and Trettin (2019b), and additional data are published in the Research Data Archive of the U.S. Department of Agriculture (USDA), Forest Service (Amatya and Trettin 2019a, 2021). Details of the data monitoring techniques and access are reported by Amatya et al. (2022b). Mean annual streamflow for the post-Hurricane Hugo calibration period, assuming a full forest recovery after Hurricane Hugo, 2011–2019, was 391.5 mm/year for WS77 and 309.4 mm/year for WS80 (Amatya et al. 2021).

The new study on the Santee Experimental Forest will further refine the perspective on the forest water response to longleaf pine restoration since the site affords the capabilities to address the prior conditions (e.g., loblolly pine plantations) with the restored longleaf pine forest conditions. Watershed-scale longleaf pine restoration research is needed to answer questions regarding longleaf pine stand effects on hydrologic and biogeochemical processes that can have important implications for water resources management and C sequestration, as well as the delivery of other ecosystem services. Researchers will use stream discharge measurements to assess water yield (Amatya et al. 2021) along with regulating factors such as soil moisture, tree canopy layer, leaf area index, and ground vegetation. Because studies on hydrologic responses to loblolly pine management have been conducted over the last 50 years, the initial decade of this new study will focus on the conversion phase. This relationship allows for simulation validation for assessing hydrologic, vegetation, and soil responses, which should then provide a solid foundation for applications in other areas where longleaf pine restoration is possible. The following is an overview of the baseline assessments intended to support this new experiment.

Background and Methods

History and Characteristics of the Paired Watersheds

The treatment watershed, WS77, is a 155-ha, first-order watershed that is paired with a 160-ha, first-order reference watershed, WS80 (fig. 1). WS77 is synonymous with Santee Experimental Forest's unit 11, while WS80 falls within the 206-ha unit 5 but excludes a small tributary that drains elsewhere (fig. 2). These watersheds are part of the headwaters of Huger Creek, a fourth-order stream and a major tributary of the East Branch of Cooper River, which drains into Charleston Harbor. This low-gradient watershed, with elevations ranging from about 9.75 m toward the northwest to about 5.79 m at the outlet, drains into Fox Gulley Creek via a 1.26-km-long stream farther down to Turkey Creek, a tributary of Huger Creek. Vegetation on WS77 is dominated by loblolly pine, a result of earlier silvicultural research. In contrast, vegetation on WS80 is dominated by bottomland oaks (*Quercus* spp.) with a loblolly pine component and other bottomland hardwoods present, a result of natural regeneration following the large-scale blowdown of the forest during Hurricane Hugo in September 1989.

During early years (1969–1976) of calibration of WS77 and WS80, researchers established a statistically significant relationship for monthly flow between treatment and reference watersheds (Binstock 1978) to evaluate the effects of partial prescribed burning from 1976 to 1980 (Richter et al. 1982). No significant

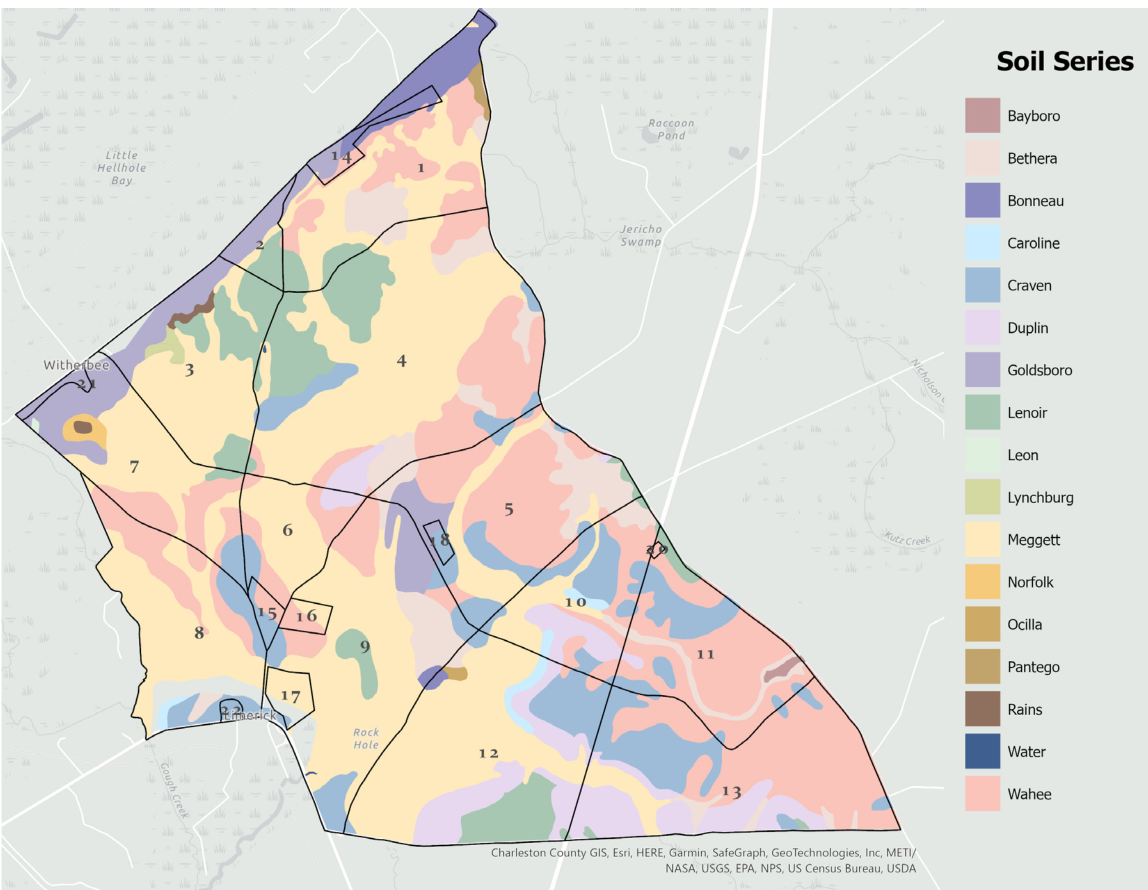

Figure 1—Twenty-two units of the Santee Experimental Forest within the Francis Marion National Forest. Unit 11 is watershed 77 (WS77), the treatment watershed, and unit 5 contains watershed 80 (WS80), the reference watershed. The soil series were extracted from the USDA Natural Resources Conservation Service's soils database.

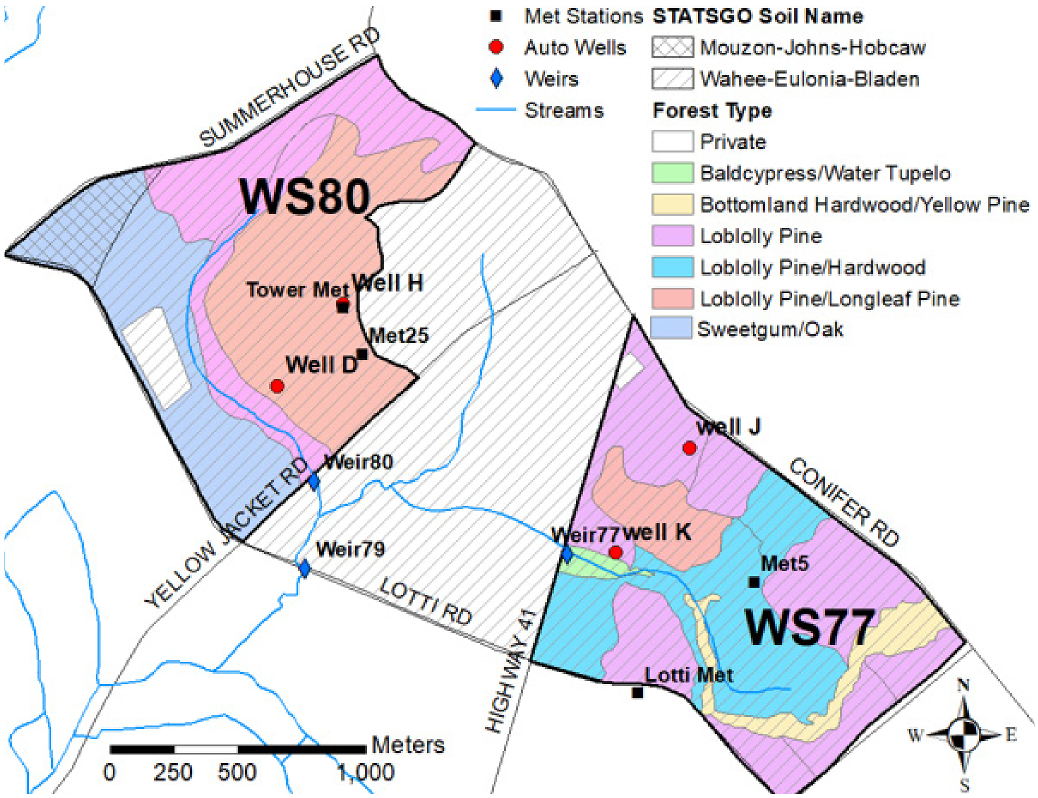

Figure 2—Watershed boundaries for the treatment (WS77) and reference (WS80) watersheds with forest type highlighted (from Amatya et al. [2021]).

difference was found in streamflow nor stream water chemistry. That monthly flow relationship reversed for 10 years starting 3 years after Hurricane Hugo in response to significant stand damage (Hook et al. 1991). Analyzing streamflow data through 2011, Jayakaran et al. (2014) reported that, by 2004, the forest stand recovered and the monthly flow relationship between treatment and reference watersheds returned to a relative state similar to that of the pre-hurricane historic period. However, Amatya et al. (2021) suggested that a relationship from the recent 2011–2019 data period, encompassing wet and dry years as well as a longer time for forest recovery, with no significant difference from the pre-Hugo 1969–1978 monthly flow relationship, is likely more representative for its application in studies of treatment effects thereafter. Thus, this established, predictable, and statistically significant relationship between WS77 and WS80 makes the paired watershed approach the best method on a short-term basis for a watershed-scale longleaf pine restoration study (Amatya et al. 2021). On a longer time scale, the hydrologic modeling approach could be used for predicting effects of fully restored longleaf pine (Amatya et al. 2022a).

Soils on the watersheds are poorly to moderately well drained, sandy clay loam surface soils overlaying clay, typified by the Wahee and Craven soil series in the uplands and the Meggett and Bethera soil series in the riparian zones (fig. 1). Field sampling by a USDA Natural Resources Conservation Service crew in 2023 explored the composition of the soils in more detail. The lab results (Ryan 2025) for WS77 showed 4.8–38.8 percent clay, 42.5–62.0 percent silt, and 7.2–47.9 percent sand in surface soils and 7.9–72.6 percent clay, 13.9–70.3 percent silt, and 3.1–63.1 percent sand in deeper soils (down to the C horizon). Results for WS80 were 8–22.7 percent clay, 38.3–58.1 percent silt, and 19.9–53.7 percent sand in surface soils and 23.8–65.2 percent clay, 8.2–48.3 percent silt, and 7.7–67.9 percent sand in deeper soils.

The climate is warm-humid temperate, with an average daily temperature of 17.8 °C and annual rainfall of around 1370 mm (Dai et al. 2013). More details on the watersheds are described by Amatya and Trettin (2007, 2019b), Amatya et al. (2021), Amoah et al. (2013), Dai et al. (2013), and Harder et al. (2007).

Silvicultural Treatments Within the Treatment Watershed

Based on stakeholder inputs, researchers developed three silvicultural prescriptions to convert the forest stands on WS77 from loblolly pine to longleaf pine. These prescriptions reflect systems that were operationally viable and consistent with the multiple management objectives of both public and private lands. The three silvicultural treatments in this study include:

1. Regeneration cut—Where natural longleaf pine regeneration was not feasible, existing stands were clearcut, leaving 15–25 trees/ha and followed by planting longleaf pine seedlings at a 2.1- x 3-m spacing (1,536 seedlings/ha). This treatment encompasses 78.2 ha.

2. Thinning—Stands with some longleaf pine present were thinned to retain an overstory canopy and foraging trees for red cockaded woodpecker (*Picoides borealis*), providing conditions for possible longleaf pine regeneration. The stands were thinned to approximately 15 m^2/ha of basal area. This treatment encompasses 28.5 ha.

3. Group selection—In areas without existing longleaf pine, a hybrid approach provided a potential alternative to clearcutting. Small openings of roughly 300–900 m^2 were cut and the balance of the stand was thinned to 15 m^2/ha. The openings were planted with longleaf pine at a 2.1- x 3-m spacing (1,536 seedlings/ha). This treatment encompasses 19.2 ha.

WS77, while characterized as a loblolly pine forest, was a mosaic of loblolly pine stands that originated from silvicultural studies in the late 1970s and early 1980s, with bottomland hardwoods in the riparian zone. Researchers assigned the three silvicultural treatments to areas within WS77 based on existing loblolly pine stand structure, with approximately 73 percent of the watershed designated for conversion to longleaf pine. Approximately 39 ha of mature loblolly pine were retained to sustain red cockaded woodpecker foraging, and the balance of the unharvested area is within the riparian zone. The woodpecker’s habitat area is considered the “control” for silvicultural treatment comparisons. South Carolina Best Management Practices (South Carolina Forestry Commission, n.d.) were used in determining a treatment layout and, as a result, riparian zones were not harvested and remain bottomland hardwoods. A prescribed burn was conducted in March 2018 to prepare the watershed for harvesting. Figure 3 illustrates the treatment areas and harvesting timeline.

Following the harvest operations, which concluded in 2021, a prescribed burn was conducted in March 2022 across the entire watershed, and herbicide was applied to the regeneration cut treatment in September 2022. Foliage of targeted vegetation species less than 2 m tall was sprayed with a mixture of triclopyr, imazapyr, a water soluble dye, and a nonionic surfactant.

The planting stock was containerized longleaf pine seedlings from Bodenhamer Nursery in North Carolina sourced from CSX property in Dorchester County, SC. The regeneration and group selection treatments were hand planted in March 2023 at 2.1- x 3-m spacing. A planned pre-planting prescribed fire could not be implemented before the planting contractors were onsite. A prescribed burn therefore took place on February 10, 2024.

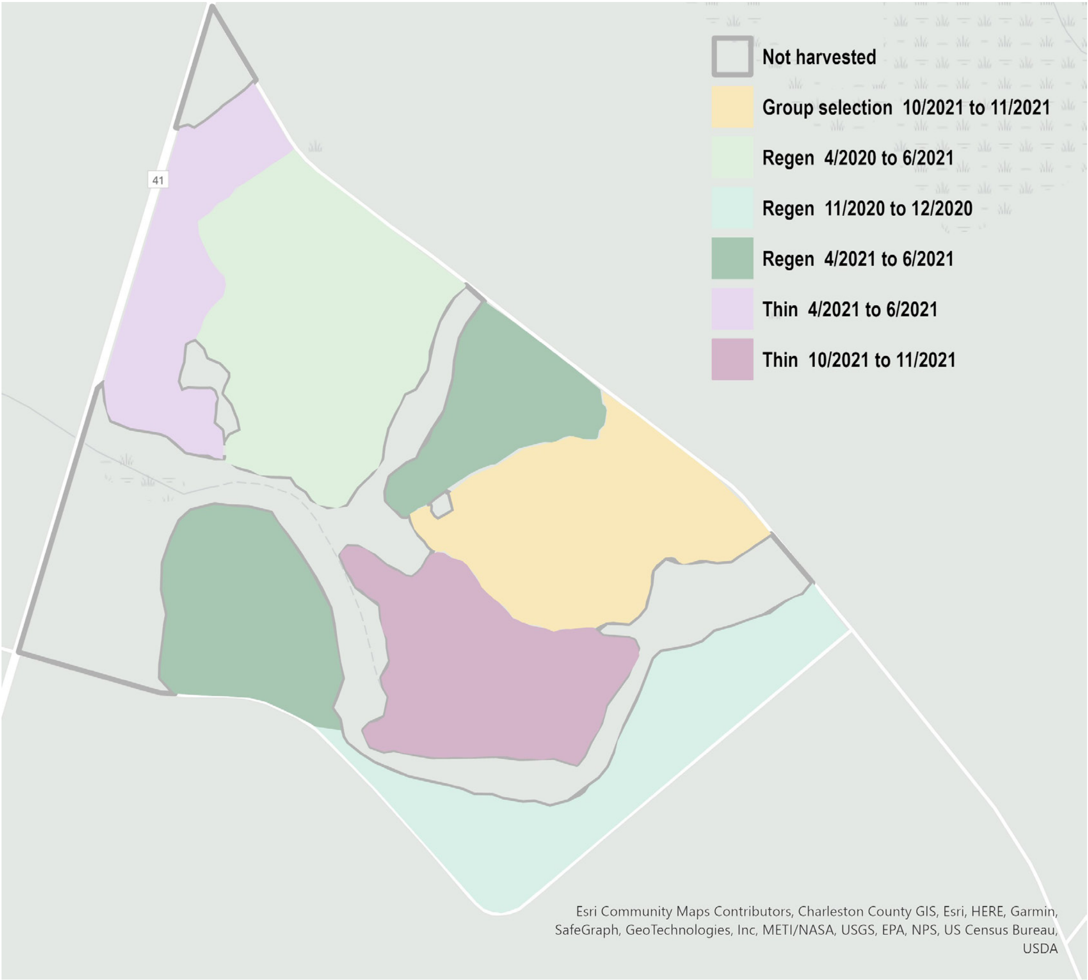

Figure 3—Silvicultural treatments (unharvested control, group selection, regeneration cut, and thinning) and the start and finish dates for the harvest operations on watershed 77 (WS77). Harvesting started in April 2020 and was completed in November 2021.

Forest Inventory Data Collection

In 1991, researchers established 0.04-ha circular inventory plots in units 11 and 5 (fig. 1) to study the effects of Hurricane Hugo. Ten percent of those plots were intended to provide a basis for a permanent inventory plot network on the Santee Experimental Forest; in 2013, those plots were reestablished and measured, providing the basis for the characterization of the paired watersheds' vegetation before the silvicultural treatments were installed. Researchers used an objectively positioned grid to select the plot locations, with the intent of providing inventory estimates of the respective units.

For the purposes of assessing watershed-scale pre- and post-harvest forest conditions in the treatment watershed (unit 11, WS77), researchers conducted measurements in 2018 (pre-harvest) and 2022 (post-harvest) on all plots (n = 28 for 2018; n = 30 for 2022). To facilitate comparison among the silvicultural treatments within WS77, two additional plots were added post-harvest within the unharvested "control" area for a total of 4 control plots, 5 group selection plots, 13 regeneration plots, and 8 thinning plots. In unit 5 (containing WS80), all plots (n = 32 overall; n = 25 in WS80) were measured in 2018, and in 2022 every third plot (n = 10 overall; n = 9 in WS80) was remeasured (see fig. 4 for distribution of the plots).

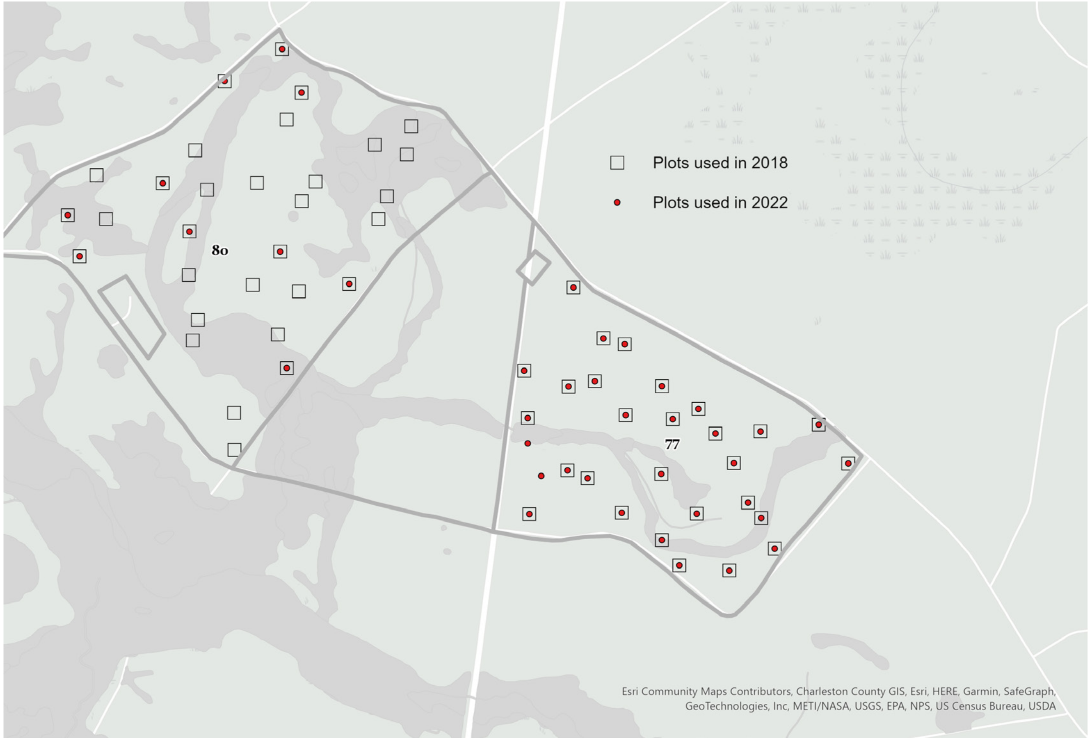

Figure 4—Map of overstory plots inventoried in 2018 and 2022 on units 11 (treatment watershed 77 [WS77]) and 5 (containing reference watershed 80 [WS80]).

For each overstory tree within a plot, researchers measured diameter at breast height (DBH, cm) and tree height (m) and recorded species. In WS77 post-harvest, estimated lean (0–90 degrees) and crown damage were also noted. Standing dead trees in all plots were measured and noted as dead. Overstory trees were defined as having DBH ≥7.6 cm. A 0.0016-ha circular plot was established in the center of some of the 0.04-ha plots for inventory of seedlings (defined as trees with DBH <2.54 cm) and saplings (defined as trees with DBH ≥2.54 cm and <7.62 cm). All seedlings and saplings ≥1.37 m tall within the 0.0016-ha subplot were identified by species and tallied.

Plot measurement quality assurance

A two-person crew measured all trees in the plot for height and DBH. Crewmember 1 measured trees while crewmember 2 recorded the data. After all trees were measured and recorded, crewmember 2 remeasured five trees and verified their species, and crewmember 1 did the recording. For height, if more than two trees were off by 1.0 m or more from the original measurement, then all overstory trees in the plot were remeasured. For DBH, if more than two trees were off by 0.3 cm or more from the original measurement, then all overstory trees in the plot were remeasured.

A second two-person crew visited 18 percent of the permanent inventory plots and remeasured five trees in each selected plot for height and DBH. For height, if more than two trees were off by 1.0 m or more from the original measurement, then all overstory trees in the plot were remeasured. For DBH, if more than two trees were off by 0.3 cm or more from the original measurement, then all overstory trees in the plot were remeasured.

Forest measurement calculations

Tree basal area (cm^2) was calculated with the following equation:

$$Tree\ basal\ area = \pi \times \left(\frac{DBH}{2}\right)^2$$

Biomass of living trees and necromass of standing dead trees were calculated with the following equations (Shroeder et al. 1997) using the overstory data separated by the live/dead classification:

Hardwood biomass (kg/tree):

$$Hardwood\ biomass = 0.5 + \frac{25{,}000DBH^{2.5}}{DBH^{2.5} + 246{,}872}$$

Conifer biomass (kg/tree):

$$Conifer\ biomass = 0.5 + \frac{15{,}000DBH^{2.7}}{DBH^{2.7} + 364{,}946}$$

Forest calculations were converted from English to metric units for all tables and graphs (Kelly, n.d.)

Leaf area index measurements

Leaf area index (LAI) is a unitless measure of total leaf surface area per unit of ground area and is useful in ecological water-use models and to quantify light availability. LAI measurements in the treatment watershed allowed researchers to characterize the canopy and ground vegetation before and after the silvicultural treatments. Surveys of the three silvicultural treatments are reported from July to November in 2019 (pre-treatment) and 2022 (post-treatment), although measurements have been ongoing.

Researchers used a LI-COR LAI-2000 plant canopy analyzer instrument to measure LAI along three transects each in the regeneration cut, group selection, and thinning treatments. Measurements were taken every 5 m along each transect both at breast height and at ground level to allow for calculations of both understory and overstory LAI. Data were processed using FV2200 software to calculate the LAI for each transect. The three calculated LAI values for each treatment from three transects for both canopy and canopy plus understory levels were averaged to generate an estimate of LAI for that treatment location, canopy level, and date.

Coarse woody debris measurements

As part of an assessment of existing C stocks in the watersheds, researchers sampled coarse woody debris in both watersheds using modifications of the method of Brown (1974), with 1.37-m-high planar-intersect transects. Coarse woody debris was divided into three size classes, which were tallied along specific lengths of the transects. The size classes are: 10-hour fuels with diameters of 0.64–2.51 cm, 100-hour fuels with diameters of 2.54–7.59 cm, and 1,000-hour fuels with diameters ≥7.62 cm. Diameter measurements were recorded for the 1,000-hour fuels.

Pre-harvest sampling was done in unit 5 (containing WS80) in 2017 and in WS77 in 2020. In unit 5, 25 random transects were used. In WS77, 2 transects in each of 12 overstory plots (3 per planned treatment, excluding control areas) were used. All pre-harvest transects were 18.3 m long. Ten-hour fuels were tallied on the first 1.8 m of the transects, 100-hour fuels on the first 3.6 m, and 1,000-hour fuels along the entire length.

Post-harvest measurements on WS77 in 2022 used 100-m-long transects, with 4 transects in the control area, 11 transects in the regeneration cut treatment, 7 transects in the thinning treatment, and 6 in the group selection treatment. Ten-hour fuels were tallied on the first 2 m of the transects, 100-hour fuels on the first 4 m, and 1,000-hour fuels along the entire length.

The mass of the coarse woody debris in the forest was then calculated with the following equations (Brown 1974):

For 10-hour and 100-hour fuels:

$$\frac{Biomass}{Acre} = \frac{11.64 \times n \times d^2 \times s \times a \times c}{Nl}$$

For 1,000-hour fuels:

$$\frac{Biomass}{Acre} = \frac{11.64 \times \sum d^2 \times s \times a \times c}{Nl}$$

where
d^2 = squared average diameter
s = specific gravity
n = tally number
a = angle correction factor
c = 1
Nl = length of the sampling plane

Soil and forest litter collection and analysis

Researchers sampled soils in 12 of the overstory plots in WS77 in 2018 to provide a baseline for assessing the stand treatment effects on the two major soil series (Wahee and Craven). The intent is to utilize these plots as a basis for assessing changes in soil physical and chemical properties associated with the longleaf pine restoration process and subsequent stand development. Soils were sampled on each plot to a depth of 1 m. A 10- x 10-m grid was superimposed within the 0.04-ha vegetation plot; using the plot center, the center of the 100-m^2 grid was positioned over the plot, with the corners marked permanently.

The sample locations were determined by randomly selecting a grid intersection, which was recorded to prevent future resampling. In 2018, three grid points were selected per plot. Two types of soil cores and forest floor samples were taken at each point. Soil samples were collected from the surface down to 30 cm using an AMS slide hammer and corer (4.8 cm in diameter and 30.0 cm in length). Additional soil cores were taken down to 100 cm using a bucket auger and segmented into sections of 0–10, 10–20, 20–30, 30–50, 50–75, and 75–100 cm. The thickness of the forest floor was measured and recorded, and forest floor samples were collected using a 27- x 27-cm square and separated into Oi (raw leaves) and Oe + Oa (partially and well decomposed leaves) horizons. Samples of the same type and depth from the three points per plot were combined to yield one composite sample per plot.

The forest litter samples were oven dried at 60 °C, weighed and composited, and then ground using a Wiley mill (2-mm mesh). Samples for total C and nitrogen (N) analyses were pulverized and weighed before being shipped to the Forest Service's Coweeta Hydrologic Laboratory for analysis. For laboratory quality assurance (QA), duplicates were run on every 15th sample. The bulk samples are retained in Santee Experimental Forest's sample archive.

Mineral soil samples were prepared for lab analysis by drying at 60 °C to constant mass and grinding to pass a 2-mm standard sieve; coarse fragments were weighed and discarded. Subsamples were subsequently dried to 105 °C to provide an air-dry/oven-dry ratio. Samples for total C and N were pulverized and weighed before analyses at Coweeta Hydrologic Laboratory. Bulk density samples were dried and weighed for each 10-cm layer from 0 to 30 cm. A bulk density of 1.38 g/cm^3 was assumed for core samples deeper than 30 cm. For QA in the laboratory, duplicates were run on every fifteenth sample in each test for accuracy of testing procedures. Samples are stored in sections of 0–10, 10–20, 20–30, 30–50, 50–75, and 75–100 cm. The bulk samples are retained in Santee Experimental Forest's sample archive.

The equations used to calculate total C and N (Mg/ha) are as follows:

Mineral soils:

$$Total\ C = BD \times int \times 100 \times (\%C/100)$$
$$Total\ N = BD \times int \times 100 \times (\%N/100)$$

where
BD = bulk density (g/cm^3)
int = interval length (cm)

Litter layer:

$$Total\ C = mass \times (\%C/100)$$
$$Total\ N = mass \times (\%N/100)$$

where
mass = mass (Mg/ha)

Hydrology monitoring and measurements

Historic rainfall, streamflow, water quality, and weather data collected on the paired watersheds since 1964 are described in Amatya and Trettin (2007), Amatya et al. (2006), Binstock (1978), Dai et al. (2013), and Richter et al. (1982). The established hydrology and climate monitoring stations on the Santee Experimental Forest (fig. 5) are used to support monitoring for this study (Amatya et al. 2022a). Those include a full meteorological station at the experimental forest's headquarters (approximately 2 km from WS77), an above-canopy meteorological station on WS80 (discontinued in April 2022 and now replaced by an eddy covariance flux tower), and three field meteorological stations within the watersheds that also include air and soil temperatures (Amatya et al. 2022a). Compound V-notch weirs measure streamflow

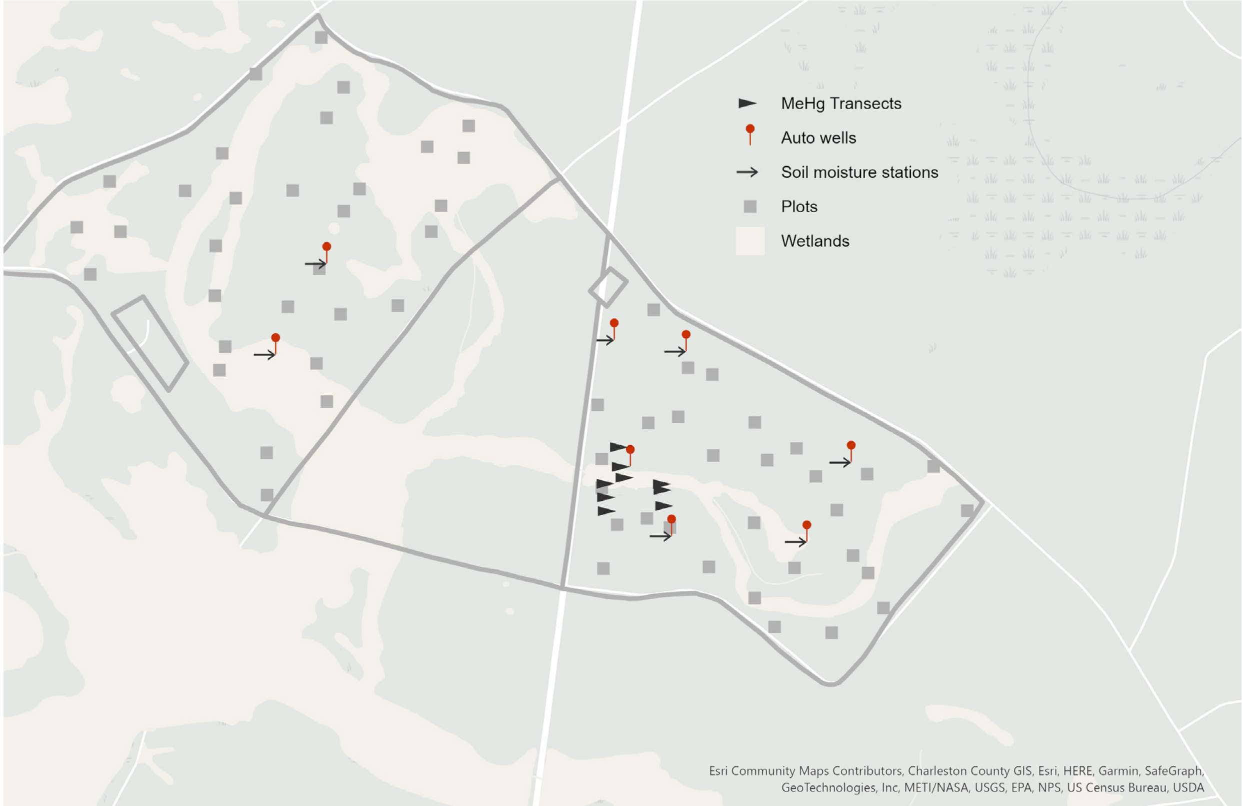

Figure 5—Distribution of forest inventory plots on units 11 (treatment watershed 77 [WS77]) and 5 (containing reference watershed 80 [WS80]) along with water table and soil moisture monitoring stations with a wetlands layer from the U.S. Fish and Wildlife Service's National Wetlands Inventory.

at the outlet of each watershed, and water quality samples are obtained using flow proportional sampling upstream of the weir. Water table depth within the watersheds is monitored in wells selected to represent the network of manual wells that were established in 1991. Those wells are being augmented to provide measurements of the restoration treatments on the dominant soil series (Wahee and Craven). Change in soil water storage is a major factor in determining whether longleaf pine affects the stand water balance and hydrologic response to storm events. To support the associated assessments, shallow ground water wells (2.5–3.0 m deep) and soil moisture monitoring stations were installed on both watersheds and within the different silvicultural treatments on WS77. Where practical, existing wells are utilized; however, several new wells have been installed. Each of the wells is instrumented with a WL-16 water level logger. Each site has also been instrumented with a Stevens Hydra soil moisture monitoring station, configured to measure three depths (30, 60, and 90 cm) initially in 2019 that were changed to 15, 45, and 60 cm in 2022.

Spatial database and graphics

Spatial information and graphics associated with this project are available (Kelly, n.d.). Additionally, personnel at the College of Charleston's Santee Cooper Geographic Information Systems Laboratory developed an ArcGIS Story Map to provide remote sensing and low-elevation drone imagery of the WS77 treatment areas documenting the transition through the harvest operations period (Levine et al. 2023). That imagery and associated layers are also available (Cizler 2023).

Baseline Assessment

Preliminary Forest Inventory Data and Initial Effects of Harvests

This baseline assessment encompasses data that were collected in 2018 (pre-treatment) and 2022 (post-treatment). Forest overstory data are summarized to compare the treatment watershed (WS77) with the reference watershed (WS80) for both of those years. Note that a subset of plots were measured in WS80 in 2020, creating incongruities in the comparisons.

Table 1 shows the pre-harvest (2018) and post-harvest (2022) comparison of the structural attributes of the forests on WS77 and WS80, as well as the inventory for the entire unit 5 (containing WS80). In 2018, WS77 was a loblolly pine forest with bottomland hardwoods in the wetlands; its average stand diameter and biomass were larger than in WS80, though with fewer trees.

WS80 is composed of mixed pine-hardwoods in the uplands and bottomland hardwoods in the wetlands; it has developed without silvicultural intervention since Hurricane Hugo in September 1989. The stand density and diameter distribution in WS80 for 2018 are relatively uniform (fig. 6), containing many more trees with smaller diameters than WS77. In contrast, the distribution of the large-diameter loblolly pine in WS77 in 2018 likely reflects prior silvicultural research. Before 1989, WS77 was used for several subwatershed-scale studies under loblolly pine silviculture, including site preparation, spacing, and competition control. The resultant stands from those studies were young (e.g., 8–10 years) when Hurricane Hugo impacted the area; due to the young age, most of the loblolly survived the storm. Following 1989, WS77 was managed at the watershed scale.

Table 1—Overstory data for the treatment and reference watersheds in 2018 (pre-harvest on watershed 77 [WS77]) and 2022 (post-harvest on WS77) and for the entire unit containing watershed 80 (WS80)

	Unit 5 (containing WS80)		Reference watershed (WS80)		Treatment watershed (WS77)	
	2018	2022	2018	2022	2018	2022
Live biomass						
Average DBH (cm)	17.59	19.24	17.73	19.24	25.66	29.66
Average tree height (m)	16.20	17.65	16.39	17.71	20.57	22.15
Basal area (m^2/ha)	34.68	36.99	35.00	36.01	27.24	15.60
Biomass (Mg/ha)	197.34	222.53	199.57	215.51	157.18	95.49
Number of trees/ha	1,128.94	976.05	1,117.9	958.22	536.56	265.22
Necromass						
Average DBH (cm)	12.17	15.05	12.12	15.41	14.76	24.76
Average tree height (m)	10.00	7.76	9.63	7.65	10.77	13.49
Basal area (m^2/ha)	1.35	1.63	1.49	1.69	2.24	2.01
Biomass (Mg/ha)	6.06	8.04	6.71	8.49	10.61	12.30
Number of trees/ha	98.07	82.37	106.75	80.31	123.55	37.07

DBH = diameter at breast height.

Values are averages across plots; n = 32 for unit 5, 2018; n = 10 for unit 5, 2022; n = 25 for WS80, 2018; n = 9 for WS80, 2022; n = 28 for WS77, 2018; n = 30 for WS77, 2022.

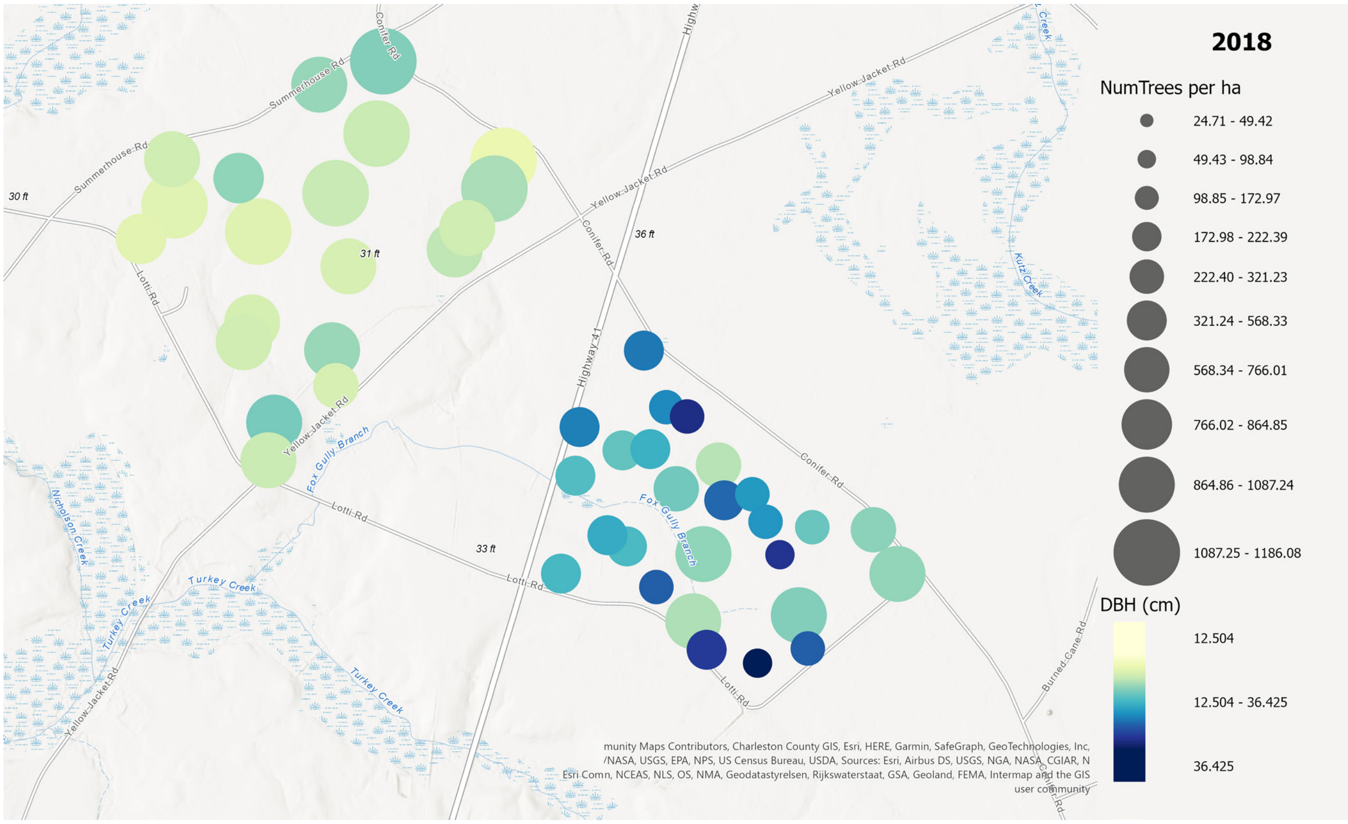

Figure 6—Map illustrating the average diameter at breast height (DBH in cm; color scale) and the number of live trees/ha (circle size) in each measured plot for 2018.

The 2022 measurements on WS77 reflect the stand conditions following the harvest (fig. 3), which reduced the number of trees significantly, but the resultant stands have a larger mean diameter (fig. 7) and tree height. Despite only one-third of the plots in WS80 being remeasured in 2022, the subsample provides an estimate that was very similar to the stand conditions in 2018 (fig. 6). The average biomass and basal area are both larger in WS80 than in WS77 in 2018 and 2022 (table 1).

Within the treatment watershed, certain areas were left unharvested to sustain red cockaded woodpecker foraging habitat and serve as the “control” silvicultural treatment in this report. The stand structural attributes in the control area were slightly smaller (table 2) than those of the whole watershed (table 1) in 2018. The wide variation in stand metrics among the harvest treatment areas in 2018 reflects the prior use of those areas, and indeed the 2018 stand conditions affected the treatment assignment; for example, the very high stocking in 2018 in the thinned treatment area (fig. 3) predisposed it to thinning.

The regeneration cut treatment (fig. 3) had a target retention similar to a clearcut with reserves, leaving only 58 trees/ha and reducing basal area by 82 percent (table 2). The thinning treatment reduced basal area by 21 percent, and the group selection treatment reduced basal area by 30 percent; because of the pre-treatment conditions of the thinned stand, the post-harvest basal area was still roughly twice that of the group selection treatment. The average DBH and height of residual trees in all harvested treatments increased following harvests.

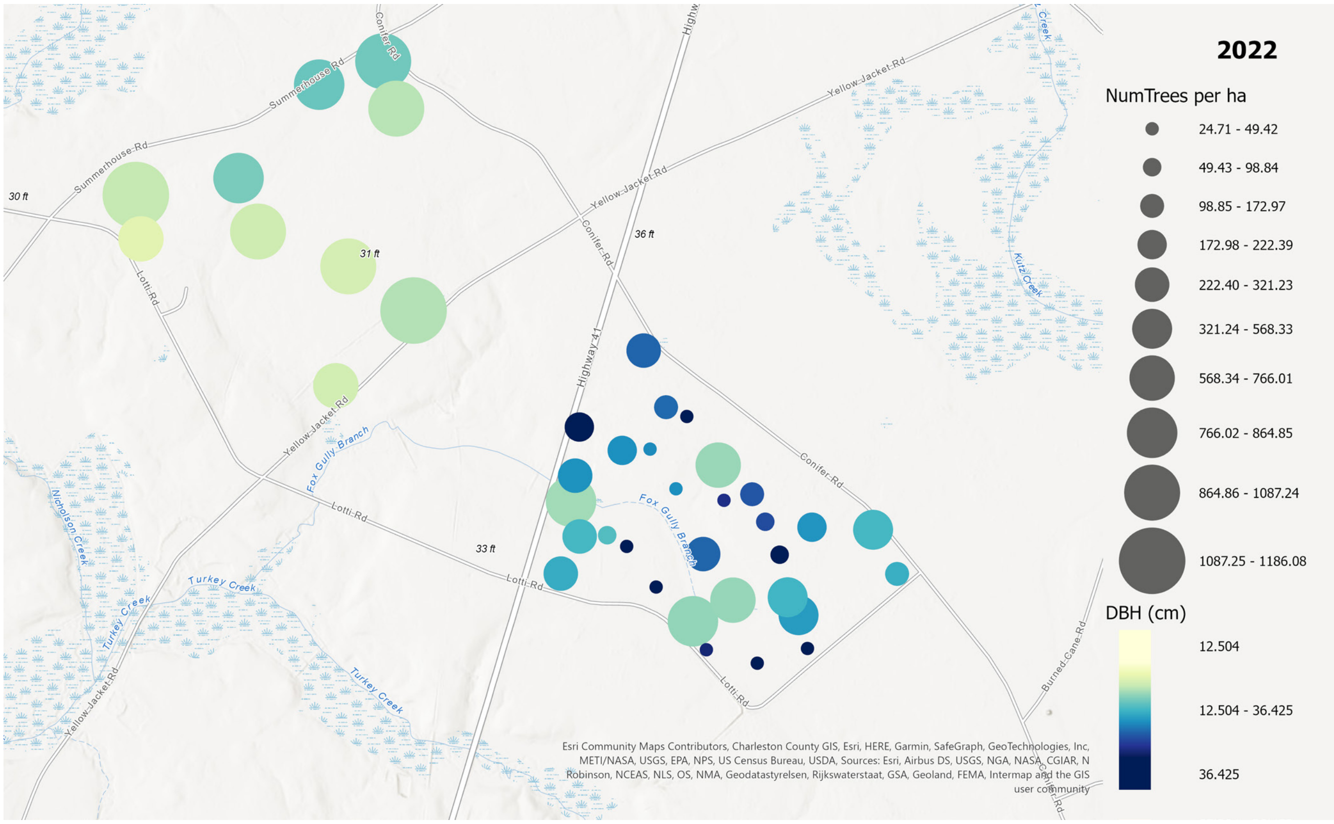

Figure 7—Map illustrating the average diameter at breast height (DBH in cm; color scale) and the number of live trees/ha (circle size) in each measured plot for 2022.

Table 2—Treatment watershed 77 (WS77) overstory data by silvicultural treatment type before (2018) and after (2022) harvest

	Control		Group selection		Regeneration cut		Thinning	
	2018	2022	2018	2022	2018	2022	2018	2022
Live biomass								
DBH (cm)	—	22.48	26.03	30.53	28.61	33.53	20.93	26.62
Tree height (m)	—	17.47	21.09	22.92	22.14	23.89	19.14	22.50
Basal area (m^2/ha)	—	23.95	21.15	14.89	26.13	4.70	38.33	30.31
Biomass (Mg/ha)	—	144.01	128.50	94.72	153.41	29.63	205.66	179.82
Number of trees/ha	—	537.44	370.65	216.21	407.72	57.66	1,013.11	539.50
Necromass								
DBH (cm)	—	40.30	15.52	18.27	14.85	28.30	13.70	18.11
Tree height (m)	—	17.45	10.09	8.17	10.53	20.30	11.59	8.21
Basal area (m^2/ha)	—	1.58	2.78	1.02	0.66	0.46	2.83	0.73
Biomass (Mg/ha)	—	10.39	13.52	8.88	3.32	2.96	12.48	3.66
Number of trees/ha	—	12.36	160.62	18.53	30.89	6.18	181.21	24.71

DBH = diameter at breast height.

Values are averages across 4 plots for control (controls were not included in 2018), 4 plots for group selection, 12 plots for regeneration cut, and 6 plots for thinning treatments. Four of the 30 overstory plots were determined to be on the edge of treatment boundaries and were not included in treatment-level comparisons.

Following the harvest in 2022, 19 percent of observed trees in watershed WS77 were classified as having some degree of lean. For those trees with any degree of lean, the average observed was 12 degrees, with a range of 5–85 degrees of lean. Lean was not reported for WS80.

In 2018, there were approximately 650 sprouts and seedlings/ha in watershed WS77 averaged across 13 plots, primarily sweetgum (*Liquidambar styraciflua*). None of the sampled plots in WS77 contained saplings in 2018, and WS80 was not inventoried for seedlings and saplings in 2018. In 2022, there were approximately 1,250 seedlings/ha in WS77 averaged across 24 plots, with the highest concentration in the group selection treatment, though that was not analyzed statistically. No saplings were present in the plots inventoried in WS77 in 2022. In unit 5 (containing reference WS80) in 2022, there were approximately 550 seedlings/ha and 365 saplings/ha averaged across 10 plots. Seedlings and sprouts in 2022 were again primarily sweetgum in both watersheds, though the composition was more mixed in W80 and included American holly (*Ilex opaca*) and redbay (*Persea borbonia*), among others. Saplings included sweetgum, red maple (*Acer rubrum*), post oak (*Q. stellata*), and water oak (*Q. nigra*).

Timber cruisers from Francis Marion National Forest estimated that 5540 t of pulpwood and 8725 t of sawtimber were removed during the harvest of the three treatments.

Initial Coarse Woody Debris Data

Coarse woody debris (CWD) measured in 2017 for unit 5 (containing reference WS80) averaged 6.6 Mg/ha (table 3). The relatively high CWD loading reflects that all CWD downed in Hurricane Hugo was left onsite and the watershed has not received any management activities in over 60 years. Coarse woody debris measured on WS77 in 2020 prior to the harvests ranged from 0.8 to 2.2 Mg/ha. CWD measured in 2022 post-harvest ranged from 0.7 to 2.0 Mg/ha (table 3). Note that CWD in the control treatment area of WS77 was not measured in 2020.

Table 3—Coarse woody debris (CWD) for unit 5 (containing reference watershed 80 [WS80]) and treatment watershed 77 (WS77)

	Pre-treatment	Post-treatment
	Total CWD (Mg/ha)	
WS80	6.64	—
WS77 Regeneration cut	0.77	1.40
WS77 Thinning	2.17	1.98
WS77 Group selection	1.15	1.95
WS77 Control	—	0.72

CWD on unit 5 was measured in 2017 and is being used to describe WS80. No post-treatment measurements were made in WS80 as harvests were done only in WS77.

Pre-treatment results for WS77 were recorded in 2020 and no transects were measured in the unharvested control area.

Post-treatment results for WS77 were recorded in 2022.

Initial Leaf Area Index Data

Following harvests, overstory LAI—averaged from July through November—decreased 80 percent in the regeneration treatment, 54 percent in the group selection treatment, and 28 percent in the thinning treatment, while understory LAI increased 7 percent in the regeneration treatment, decreased 8 percent in the group selection treatment, and decreased 1 percent in the thinning treatment (figs. 8 and 9). Note that no analysis was done to determine the significance of these differences, which were very slight in the understory, and that sampling dates varied slightly between years.

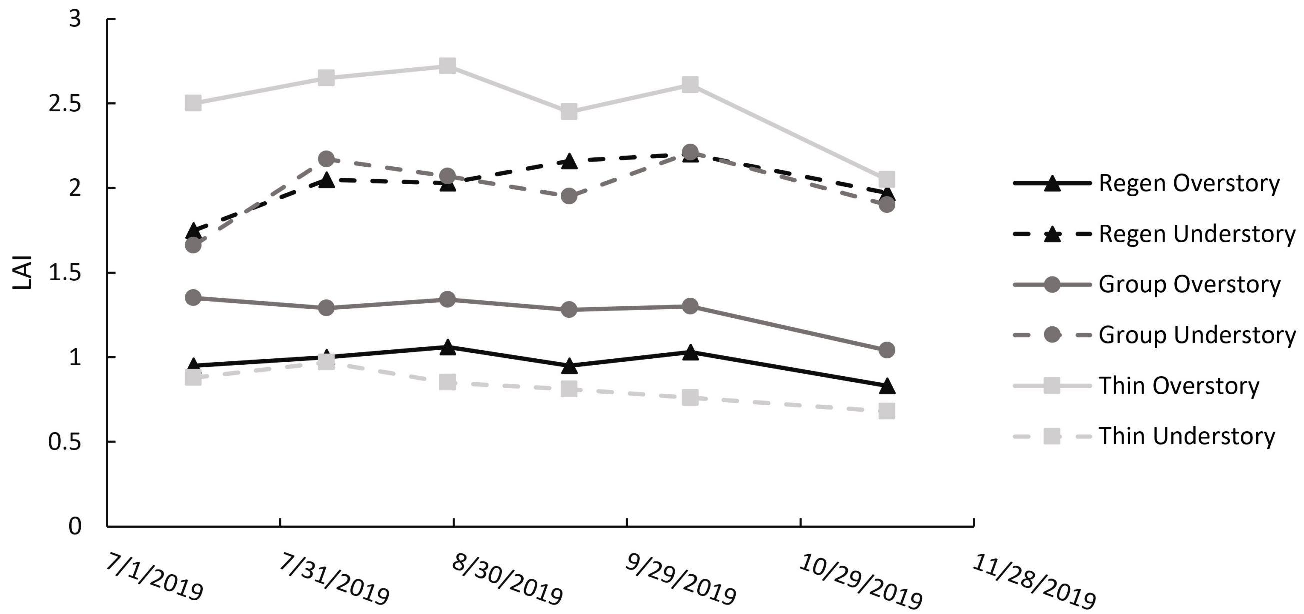

Figure 8—Canopy and understory leaf area index (LAI) measured in planned silvicultural treatment areas within watershed 77 (WS77), 2019.

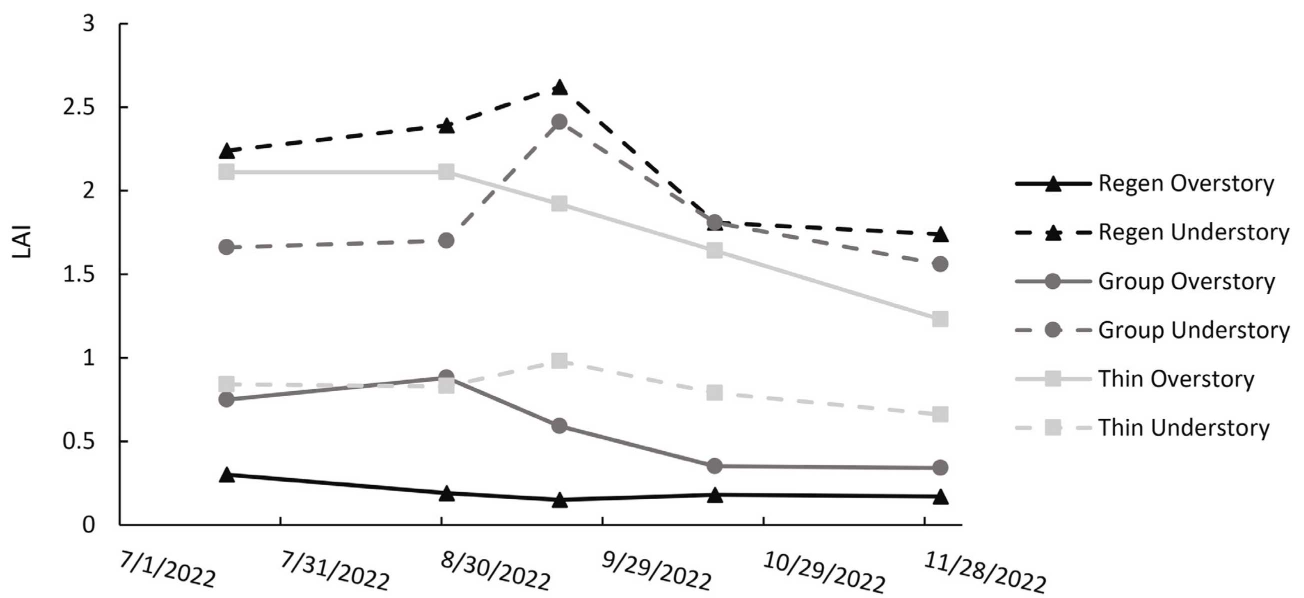

Figure 9—Canopy and understory leaf area index (LAI) measured in silvicultural treatment areas within watershed 77 (WS77), 2022.

Initial Soil and Litter Data

Analyses of total soil C and N among the treatments in WS77 reflect relatively large differences among the Wahee and Craven soils in the regeneration cut (table 4) but a relatively small range with the Wahee soil that is common to each of the treatments. Researchers considered existing stand conditions when determining treatment locations, so it is likely that pre-1989 silvicultural treatments have influenced these pools. Among the three treatments, thinning had the highest C and N stock in the forest floor layer (table 4). Within the upper 100 cm of the mineral soil, the regeneration cut treatment had the highest soil C content (fig. 10A). The total N content among treatments varied inconsistently with C content (fig. 10B), with the thinning treatment having the highest N content and the lowest C:N (49.1). Soils in the group selection treatment stored the least amount of C and N resulting in a C:N ratio of 72:1. Soil N was generally restricted to the upper 30 cm of the soil, with concentrations generally below detection limits in the lower depths; the N content in the surface 0–10 cm of soil is the primary driver of the apparent differences among treatments (table 4). These data demonstrate some possible preexisting differences in soil C and N stocks before the current treatments were installed, so future soil assessments considering site and soil responses to the longleaf pine restoration treatments will need to include these baseline data in analyses. The 2018 soil samples are stored in the Santee Experimental Forest's sample archive.

Table 4—Total carbon (C) and nitrogen (N) in the upper 100 cm of soils within treatment watershed 77 (WS77) by planned treatment

Treatment (soil series)	Horizon	Total C (Mg/ha)	Total N (Mg/ha)
Group selection	Forest floor	10.16	0.21
Thinning	Forest floor	24.96	0.59
Regeneration cut	Forest floor	13.78	0.22
Group selection (Wahee)	0 to 100 cm	400.44	5.49
Thinning (Wahee)	0 to 100 cm	462.01	9.39
Regeneration cut (Wahee)	0 to 100 cm	433.50	6.00
Regeneration cut (Craven)	0 to 100 cm	283.08	1.44

Values are averages across three plots per planned treatment in the thinning and group selection treatments. In the regeneration cut treatment, three plots are in the Wahee soil series and three plots are in the Craven soil series. All six plots are averaged for the forest floor values. Measurements were done in 2018 prior to harvests.

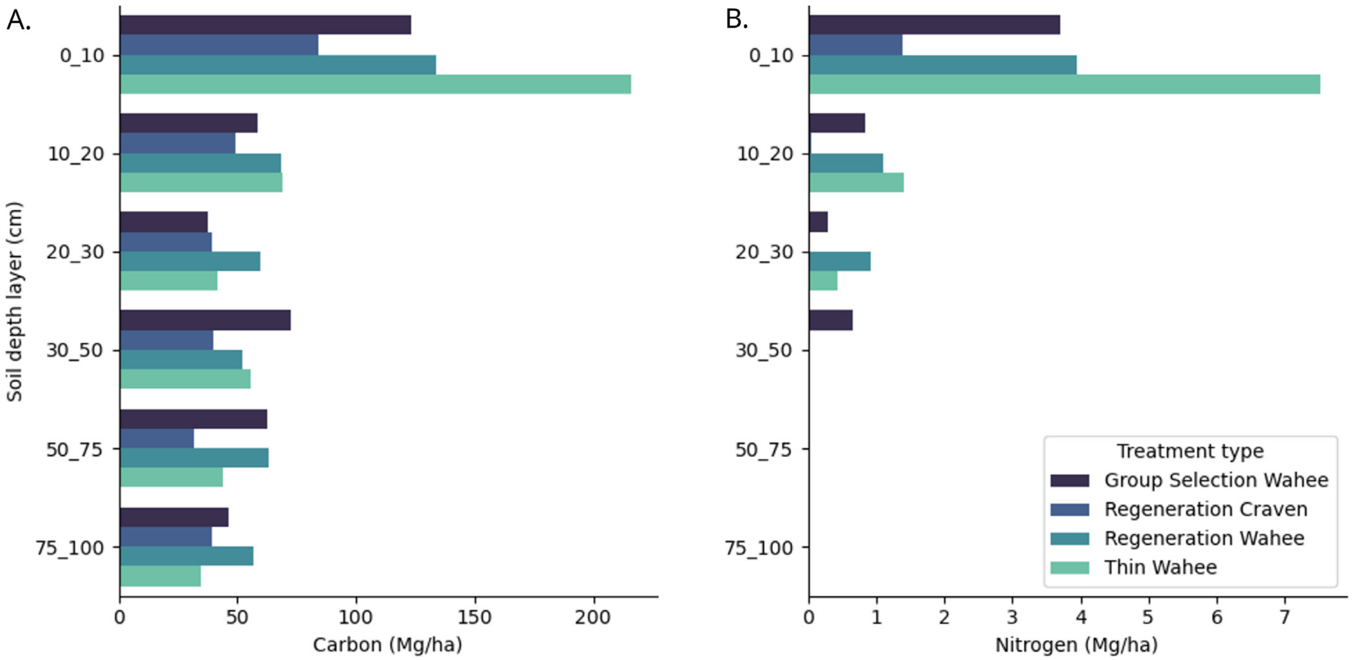

Figure 10—(A) Carbon and (B) nitrogen by soil depth grouped by treatment and soil types for watershed 77 (WS77) as measured in 2018.

Summary and Future Work

In summary, this report describes the framework of a new long-term project comparing hydrological processes and C dynamics between a watershed being restored to longleaf pine and an unmanaged reference watershed. It provides a permanent reference for the baseline condition of the overstory, soils, and woody debris data across the watersheds as well as the effects of the harvest operations across the silvicultural treatments within the treatment watershed.

As this is a long-term experiment, researchers will periodically conduct many of the measurements described in this report throughout the project's duration. Overstory measurements and soil sampling in each watershed will be repeated every 5 years. LAI measurements are ongoing approximately bimonthly. The hydrometeorological data will be monitored continuously throughout the course of the project.

Using both monitoring and modeling approaches, this project provides a rare opportunity to study the long-term effects of forest management—particularly of longleaf pine restoration—on hydrology at a watershed scale and addresses the important issue of how forest management might improve water availability. Simultaneously, the different silvicultural strategies within the treatment watershed will allow researchers to monitor the success of different methods for restoring longleaf pine to help inform future forest management.

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This report describes the framework of a long-term project on the Santee Experimental Forest comparing hydrological processes and vegetation dynamics between two research watersheds: one formerly dominated by loblolly pine (*Pinus taeda*) and currently being restored to longleaf pine (*P. palustris*), and the other an unmanaged mixed pine-hardwood reference watershed. Along with descriptions of the watersheds and the silvicultural methods used in the longleaf pine restoration, this report provides baseline data on overstory conditions, soils, leaf area index, and coarse woody debris across the watersheds. A subcomponent of the project is to monitor the success of different methods for restoring longleaf pine, and this report provides an initial assessment of the effects of harvest operations across silvicultural treatments within the longleaf pine restoration watershed.

Keywords: Paired watershed hydrology, longleaf pine restoration, loblolly pine conversion, silviculture, overstory inventory, soils.