ABSTRACT

GOEKE DEE, KYLE ROBERT. Evaluation of Loblolly Pine Growth and Productivity With and Without Municipal Wastewater Irrigation. (Under the direction of Dr. Elizabeth Guthrie Nichols).

The land application of wastewaters to forests is a permitted technology in North Carolina, USA since the late 1990s. These forest water reuse (FWR) systems avoid direct discharge of wastewater to surface waters and utilize soil infiltration to mitigate chemicals of concern in wastewater. Oftentimes, annual irrigated wastewater volume equals mean annual rainfall with weekly irrigation of 50 mm to 75 mm wastewater. Prior studies have evaluated the productivity of hardwood FWR systems for municipal wastewater, but there are no current studies on loblolly pine productivity in these FWR systems. This study evaluated growth metrics, soil fertility, and incremental annual growth for loblolly pine on a 2,139-hectare FWR system in coastal North Carolina. A 200-plot inventory was conducted across both irrigated and non-irrigated forest to determine if irrigation significantly influence tree height, stem diameter, volume, understory biomass, and annual tree growth across five dominant soil types on the site. Overall, irrigation did not significantly impact mean tree height, stem diameter, stem volume, or understory biomass. Mean annual ring widths were not significantly different between irrigated and non-irrigated height-dominant trees from each plot. The main driver for significant growth differences were differences between soils, though measured fertility indices did not show significant differences between soils. The more productive soils aligned with agricultural productivity estimations for the coastal plain of North Carolina. Chronic and substantial irrigation (1000 – 1600 mm/yr) did not impair nor promote loblolly pine productivity for this site.

Evaluation of Loblolly Pine Growth and Productivity With and Without Municipal Wastewater Irrigation

by
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BIOGRAPHY

Kyle Goeke Dee was born on September 20, 1993 in Oak Harbor, Washington. He attended the College of William and Mary where he earned a Bachelor of Science in biology. He has worked as an intern for the US National Park Service as a biological science technician and for the US Forest Service as a forestry technician during his undergraduate years. Kyle took at break from college for two years starting in 2014 and worked a series of manual labor jobs around the country. One of those jobs saw him working on a wildland fire crew in Oregon which was his first exposure to foresters. Through this experience, he was motivated to return to college and pursue a master's degree in forestry. Prior to working on this project with Dr. Elizabeth Nichols, he again served on a wildland fire crew operating out of Fairbanks, Alaska.

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CHAPTER 1: INTRODUCTION

A key limiting factor to the productivity of forested ecosystems in the southeastern United States is drought-induced water stress (Abrahamson et al.,, 1998). Drought has been linked historically to significant losses in radial growth, volume, and basal area in yellow pine species (Amateis et al.,, 2013). Concerns over productivity loss are especially prescient for loblolly pine (*Pinus taeda*, L.) plantations in eastern North Carolina, where intense periods of drought in the spring and fall have preceded and proceeded humid, hot temperatures in the summer; these conditions can increase strain on water resources for pine productivity. The shallow water tables in these relatively flat regions indicate that the local hydrology is tied strongly to rainfall and evapotranspiration, which is highly susceptible to the changing drought and rainfall patterns projected for much of the southern United States (Sun et al.,, 2010). One prevalent silviculture treatment to counter the effects of drought and the reduced water uptake in pine is irrigation during key periods in the growing season to supplement water and nutrient uptake. Studies have shown that irrigation and fertilization can dramatically impact the growth, yield, and wood quality of loblolly pine in both planted and natural settings across multiple geographic regions (Albaugh et al.,, 2004, Love-Myers et al.,, 2010, Samuelson et al.,, 2008).

Paired irrigation and fertilization studies have generally shown positive effects for pine silviculture. Significant positive growth effects were observed for height, basal area, live crown length, diameter, and gross stem mass accumulation for a 9-year loblolly pine study amended with 100 kg/ha foliar nitrogen fertilization and irrigation of 2100 mm annually (Albaugh et al.,, 2004) and a 4-year-old pine study (Samuelson et al.,, 2008). Love-Myers et al., (2010) observed that 100 kg/ha foliar nitrogen fertilization and 650 mm annually of irrigated water maintained loblolly pine earlywood and latewood specific gravity and, consequently, improved wood strength and quality. These studies report improvements due to combined fertilization and irrigation but not irrigation alone. By itself, irrigation had negligible effects on loblolly pine diameter, height, basal area, and volume except in drought years (Albaugh et al 1998, Jokela et al., 2004, Campoe et al., 2013). Hence, under normal rainfall conditions, irrigation does not appear to improve loblolly pine productivity. These findings are particularly germane to this study wherein loblolly pine forests have been irrigated weekly with 25 mm to 50 mm of municipal wastewater since 1998.

In North Carolina, there are 51 municipalities that land apply municipal wastewater onto forested lands (Nielsen 2011). These forest water reuse (FWR) systems utilize slow-rate irrigation which land applies approximately 25 to 50 mm of wastewater weekly based on soil type and season. In total, annual volumes of rainfall plus wastewater exceed the needs of the trees on site (Crites et al., 2014; Gibson et al.,, 2019). Years of normal to above normal rainfall can result in total water inputs of 1524 mm to 1870 mm for FWR systems in temperate North Carolina; hence, FWR forests are subjected to chronically high hydraulic loadings (Nichols 2016, Gibson et al.,, 2019). Forest types that have seen positive productivity response to FWR conditions are native hardwoods (*Taxodium distichum*, L, *Planatus occidentalis*) (Ghezehei et al., 2015). There is no current research on the productivity responses of loblolly pine for FWR sites.

Conventional pine irrigation systems are designed to deliver irrigation water during the growing season when trees are sequestering the most nutrients (Gonzalez-Benecke 2010). The impact of irrigation on loblolly pine production is most demonstrable for drier sites (Linder et al., 1987, Pereira et al., 1994) and less impactful for trees with adequate rainfall and groundwater resources (Jokela et al., 2004). Consequently, irrigation is almost universally coupled with the addition of nitrogen and phosphorus fertilizers. In contrast, FWR sites are managed for the land treatment of wastewater and permitted based on nutrient regulations for surface waters; hence, fertilizer application is uncommon. Forest management of FWR sites is not common expertise for facility and site managers; oftentimes, forest management is not done unless contracted to a consultant. Complications often emerge between maintaining the integrity of wastewater distribution systems and the realities of forest management and machinery. Opportunities to adapt conventional practices of mid-rotation thinning, weed competition management, and prescribed fire have yet to be explored, but the existence of FWR systems provides opportunities to understand loblolly pine response to weekly, year-round irrigation across years of variable rainfall conditions.

This study coupled forest inventory methods with tree core and soil analyses to assess loblolly pine productivity across irrigated and non-irrigated portions of a 2,193-hectare FWR site in coastal North Carolina. Randomized plots across five major soil types with and without wastewater irrigation were established to measure tree height, merchantable height, stem diameter at breast height, understory biomass, and basal area for even-aged stands. These metrics serve as proxies for pine productivity and were accompanied by soil cores and tree cores taken from height-dominant trees at each plot for soil fertility evaluations and year-to-year productivity comparisons. We hypothesized that irrigated trees would yield greater growth metrics than non-irrigated trees because water was provisioned during drought years and wastewater does contain low levels of nutrients. We expected variability in the magnitude of growth metrics across soil types. Study objectives were to determine the degree of statistical variability for long-term productivity and annual growth increments between irrigated and non-irrigated sections of even age tree plantations and to assess the economic impacts of irrigation on the merchantability of the stands after two decades of irrigation.

CHAPTER 2. MATERIALS AND METHODS

2.1 Study Area

The City of Jacksonville Land Treatment Site is a 2,193-hectare forested tract that irrigates 890 hectares of mixed pine and hardwood with secondary-treated municipal wastewater (Birch et al., 2016, McEachran et al., 2018). The site was formerly owned by Weyerhaeuser and was managed as a plantation for loblolly pine. A block irrigation system was established across the 890 hectares in 1998 after purchase by the city of Jacksonville. There are 26 soil types that encompass the entire tract (Figure 1), with planted loblolly pine present on five major soil types: Baymeade fine sand, Norfolk loamy fine sand, Foreston loamy sand, Stallings fine sand, and Autryville loamy fine sand (Table 1). Prior timber inventories occurred in 2002 and 2007 by a local forest consultant. In 2002, 80% of the total planted loblolly stands were cruised, but only 15% were cruised in 2007. These inventories did not delineate between irrigated and unirrigated sections of pine stands but did provide mean volume estimates on a stand-by-stand basis.

Irrigation occurs once or twice per week based on rainfall, wastewater volume in storage lagoons, and season with lower volumes applied from November to May. Irrigation volume varies by soil type with an average of 25 mm to 50 mm of wastewater sprayed in rotating sections of the site using upright irrigation spickets (Birch et al.,, 2016, Gibson et al.,, 2019). The site receives an average of 1,346 mm of rainfall with equivalent wastewater irrigation volumes (Gibson et al.,, 2019). Wastewater undergoes secondary treatment then resides in large reservoirs for 10-14 days prior to irrigation. Using monthly permit records since 2003, the mean values of specific wastewater characteristics are relatively consistent for pH (7.60 ± 0.41), calcium (29 ± 4.8 ppm), potassium (13 ± 1.8 ppm), sodium (85 ± 12 ppm), conductivity (750 ±

116 µS/cm), selenium (411 ± 5.66 ppm), and sulfate (44 ± 5.1 ppm). More variable characteristics were boron (0.6 ± 0.3), organic carbon (14 ± 3.7 ppm), chloride (56 ± 14 ppm), magnesium (1.1 ± 1.7 ppm), and manganese (0.02 ± 0.01 ppm). Mean wastewater characteristics for nutrients were phosphorus (3.0 ± 0.6 ppm), ammonia (8.9 ± 5.0 ppm), nitrate (2.9 ± 3.3 ppm), nitrite (3.8 ± 6.0 ppm), and nitrogen (13 ± 5.8 ppm). When the concentrations for nutrients are converted to an application rate (Table S-1), these values can be compared to fertilization amounts on loblolly pine plantations. Application values on the FWR average phosphorus (0.7 kg/ha), potassium (3.2 kg/ha), nitrogen (3.2 kg/ha), and calcium (7.2 kg/ha) which are values well below recommended fertilization amounts for loblolly pine in the coastal plain (Table S-1).

2.2 Inventory of Irrigated and Non-irrigated Loblolly Pine Stands and Understory Vegetation

Field data collections for productivity and growth were completed over a seven-week period from May 2019 to July 2019. A randomized 2,000-point systematic grid was established for loblolly pine stands across the land treatment site using GIS shapefiles of stand boundaries provided by the current forest manager, GIS shapefiles of irrigation polygons (Birch 2016), an online plotting website (sampleplotter.com), and ArcMap (ESRI, Redlands, CA). Points were stratified by soil type, age and treatment (irrigation or no-irrigation). From the 2,000 total sample points, 100 points were randomly selected with equivalent numbers of points in each of the five soil types. An additional 100 points were then randomly selected with the ratio of plots to soil conforming to the percentage of the total tract that the soils composed. Points were loaded onto GeoPDF format and uploaded into the Avenza mapping app (Avenza Systems Inc, Toronto, ON, Version 3.7.3, 2019) on a IPOD tablet that was Bluetooth connected to a Bad Elf GPS Pro+

(Bad ELF LLC, West Hartfood, CT) for GPS navigation. Similar to prior inventories in 2002 and 2007, variable radius plots were established for each point using a 10-factor wedge prism (JIM-GEM, Jackson, MS). In each plot, tree height and merchantable height were recorded using a Vertex IV Hypsometer (Haglöf Company Group, Langsele, Sweden), and diameter-at-breast-height (dbh) was recorded using diameter tape (US Tape Company, Pennsburg, PA). This tally include loblolly pine greater than > 20 cm dbh. Merchantable was defined as the height from one foot above the stump to the height of the first limbs or physical defect on the tree. In July and August, understory vegetation was inventoried using three 0.5 m x 0.5 m transects per plot at 50 randomly selected plots. Understory vegetation was defined as all woody and herbaceous plant material less than 2 meters. Transects were located 4.5 meters from the previously determined center of each plot at the ordinal directions 0° N, 120° SE, and 210° SW.

Total and merchantable volume was estimated using the following combined-variable prediction equations estimated for stem-volume of Loblolly pine in the coastal plain (Sherill et al., 2011):

(Eq. 1) $V_{tob} = 0.20571 + 0.00237\,(D^2H)$

(Eq. 2) $V_{mob} = (V_{tob})\exp(-0.9360(\textit{top-limit diameter}^{4.8279}/\textit{tree DBH}^{4.6483}))$

The precision of field measurements for total height, merchantable height, and DBH for 20% of the total plots was estimated (n = 20) and a relative percent difference (RPD) was calculated and averaged across each metric. The mean RPD of height and merchantable height were 1.4% and 2.7% respectively. The mean RPD of DBH was 0.4%. One composite soil sample was taken at the center of each randomly selected plot using a soil auger to a 20 cm depth. Soils were analyzed by Waters Agricultural Laboratories, Inc (Warsaw, NC) for available phosphorus, exchangeable potassium, magnesium, calcium and hydrogen, soil pH, cation exchange capacity, percent base saturation of cation elements, manganese, and copper.

2.3 Comparison of Annual Growth between Irrigated and Non-Irrigated Loblolly Pine Stands.

A tree core was taken from the height-dominant tree (n = 2) in each plot using a 46 cm, 3-thread increment borer with a 1.27 cm diameter. Core samples were secured to wood using glue then hand-sanded with progressively more abrasive sandpaper (P220, P320, P400) to provide an even surface for analysis. Each processed core was scanned using a 1200 dots per inch flatbed scanner. The scanned cores were analyzed for width using CooRecorder and CDendro (Cybis Dendrochronology, Saltsjöbaden, Sweden). Growth rings for a given core were cross-dated with CDendro using planting dates to determine actual years for each annual ring and to accurately date individual cores to each other. Average detrended ring width indices were completed in CDendro using parameters for individual mean detrending. The ring width indices were subsequently stratified into precipitation classes based upon available NOAA datasets for mean rainfall over the period the irrigation has been used on the site. A random subsample of similar age trees (within 5 years of each other) of the total cores representing 10% of the total sample was resampled for perpendicular cores. No significant differences were found.

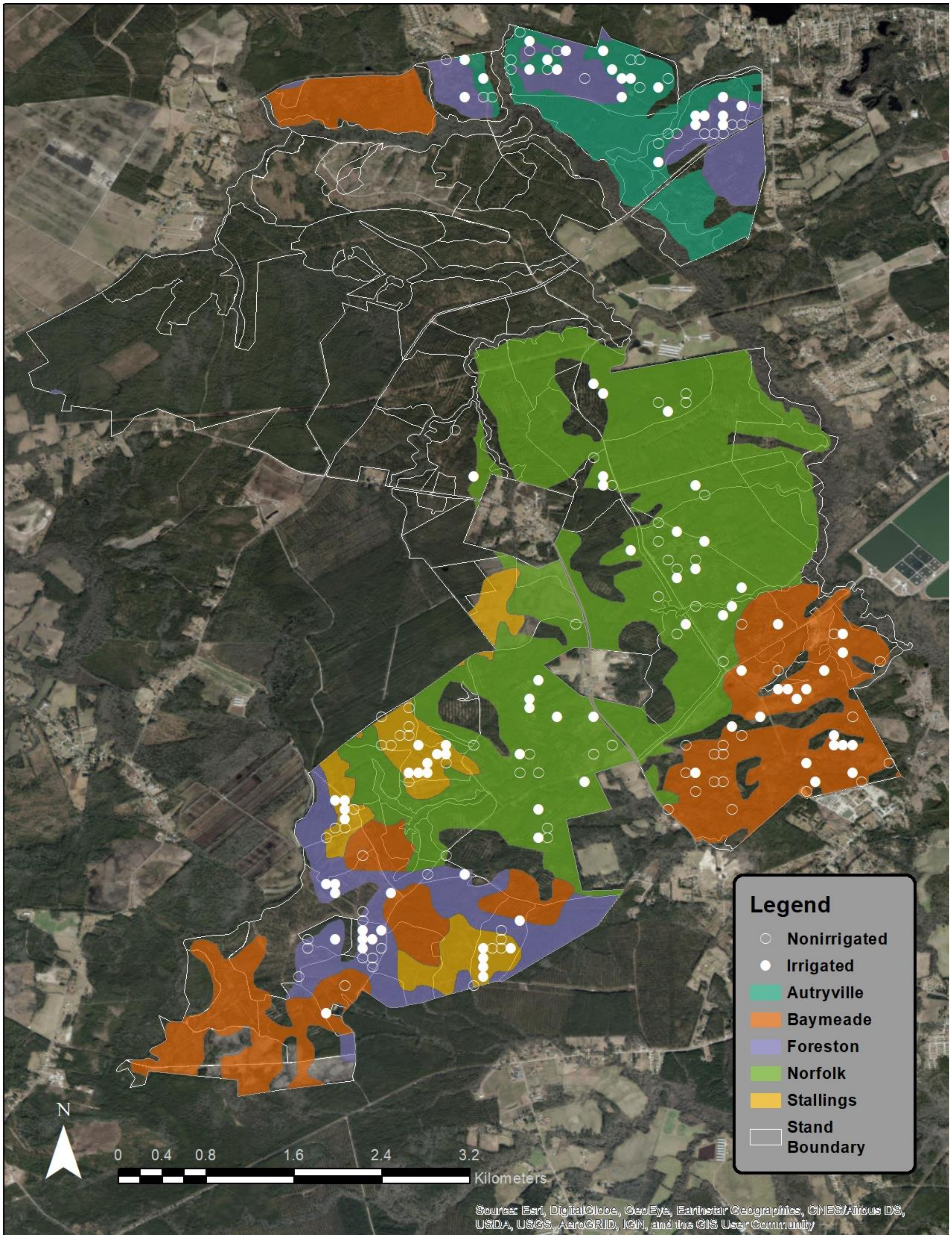

Figure 1 A map of the forest land treatment site and the five dominant soil types. Open circles represent non-irrigated plots and closed circles represent irrigated plots.

2.4 Statistical and Economic Analyses

ANOVA Generalized Linear Models (GLM) (SAS Institute, Cary, NC, Version 9.4, 2019) were used to make statistical comparisons of mean height, dbh, merchantable height, annual growth, and understory productivity between irrigated and non-irrigated stands of given soil types and across soil types ($\alpha < 0.05$). A subsample of 50 soil cores were analyzed using a Mixed model (SAS) for unequal variances to test nutritional differences across soil types and irrigation regimes ($\alpha < 0.05$).

Stumpage calculations were made for each soil type and irrigation mean using volume per hectare estimates that were subsequently converted to metric tons using timber conversion factors (Williams 1968) which was multiplied by the current NCSU Forestry extension quarterly price reports for Q2 2019 (https://forestry.ces.ncsu.edu/forestry-price-data/). Basal area per hectare was estimated by dividing the total number of trees tallied by the total number of plots and multiplying the result by the Basal Area Factor (equation 3). An individual tree factor was calculated for each tree in a soil and irrigation class by dividing the Basal Area Factor by the basal area per tree (equation 4). A volume factor was then calculated for each tree by multiplying the tree factor by the volume (equation 5). The volume/ha was then estimated by multiplying the number of trees in a size class by their volume factors, and then divided that result by the number of points taken (equation 6).

(Eq. 3) $BA/ha =$

$$\frac{(\text{total number of trees tallied})}{\text{to} \quad \text{ber of points}}(BAF)$$

(Eq. 4) $Tree$ $Factor_i =$

$$\frac{BAF}{BA_i}$$

(Eq. 5) $Volume\ Factor_i = (Tree\ Factor_i)(v_i)$

(Eq. 6) $$Vol\ /\ ha = \sum \frac{\left[\left(\left(number\ of\ trees\ tallied\ in\ size\ class\right)\right)\left(VF\right)\right]}{\left(number\ of\ points\ taken\right)}$$

CHAPTER 3: RESULTS

3.1 Soil Fertility

The FWR site has five dominant soil types (Figure 1), Autryville loamy fine sand, Baymeade fine sand, Foreston loamy fine sand, Norfolk loamy fine sand, and Stallings loamy fine sand (Table 1). Significant differences were observed for phosphorus (P), potassium (K), magnesium (Mg), calcium (Ca), and cation exchange capacity (CEC) between some soil types and within select soil types without and without irrigation (Table 1; Table S-2). No significant differences were observed for soil nitrate between soil types or irrigated and non-irrigated soils of the same soil type. For non-irrigated soils, Autryville soils had the lowest mean P concentrations that differed significantly from only Foreston soils which had the highest mean P concentrations of all soil types. Non-irrigated Stallings soils had significantly lower P than Foreston soils, but remaining parameters (K, Mg, Ca, CEC, nitrate) did not differ significantly among non-irrigated soil types. For irrigated soils, Autryville soils had significantly lower mean K concentrations than irrigated Stallings soils; remaining parameters did not differ significantly among the other irrigated soil types.

Some soil fertility parameters were significantly different between irrigated and non-irrigated soils of only two soil types, Autryville and Stalling soils (Table 1). Mean P concentrations were significantly higher in irrigated Autryville soils than non-irrigated Autryville soils. Mean concentrations of P, K, Mg, and Ca were significantly higher for irrigated Stalling soils than non-irrigated Stalling soils. Soil fertility data show no clear trends between fertility indices, percent sand composition, nor between soils with and without irrigation.

Table 1. Mean soil parameters ($\pm$ one standard deviation) of dominant soil types for irrigated and non-irrigated hectares (ha). Values not followed by the same letter are significantly different within a column. Values with no letters were not significantly different across all soil types. An asterisk (*) highlights significant differences between irrigated and non-irrigated soils of the same soil type.

Soil Type (% sand, % silt, % clay)	**Ha prism plots (n_{pp})**	**Irrigation / soil samples (n_s)**	**P** **kg/ha**	**K** **kg/ha**	**Mg** **kg/ha**	**Ca** **kg/ha**	**CEC** **meq**	**NO_3-** **ppm**
Autryville loamy fine sand (80, 14, 6)	11 ha $n_{pp} = 12$	Yes $n_s = 10$	$*37.4^{abc}$ (35.3)	92.1^{ac} (73.9)	179^{abc} (128)	1271^{ab} (1283)	6.77^{ab} (4.02)	1.28 (1.27)
	93 ha $n_{pp} = 12$	No $n_s = 10$	$*10.3^{d}$ (13.2)	50.7^{c} (54.2)	93.5^{ac} (148)	363^{a} (426)	5.42^{a} (2.31)	1.12 (0.509)
Baymeade fine sand (97, 1, 2)	85 ha $n_{pp} = 24$	Yes $n_s = 10$	39.7 (40.7)	124^{ab} (86.3)	221^{ab} (164)	1282 (933)	6.69 (3.84)	0.112 (0.050)
	577 ha $n_{pp} = 24$	No $n_s = 10$	28.9^{acd} (56.6)	118 (99.4)	161 (124)	916 (808)	7.22 (3.10)	0.938 (0.811)
Foreston loamy fine sand (82, 9, 9)	125 ha $n_{pp} = 22$	Yes $n_s = 10$	50.7^{ab} (45.2)	137^{ab} (74.6)	216 (187)	1279 (1292)	7.4 (3.28)	0.076 (0.052)
	144 ha $n_{pp} = 22$	No $n_s = 10$	62.0^{ab} (65.1)	90.1^{ac} (56.5)	200 (204)	1792 (2354)	9.24 (5.21)	0.478 (0.415)
Norfolk loamy fine sand (73, 21, 6)	280 ha $n_{pp} = 25$	Yes $n_s = 10$	101^{b} (86.8)	133^{ab} (58.1)	167 (89.7)	1506 (1274)	7.09 (3.02)	2.61 (1.61)
	500 ha $n_{pp} = 25$	No $n_s = 10$	44.5 (51.9)	97.9^{ac} (41.0)	185 (124)	1365 (1648)	8.97 (3.71)	0.460 (0.447)
Stallings loamy fine sand (87, 10, 3)	21 ha $n_{pp} = 17$	Yes $n_s = 10$	$*67.1^{ab}$ (33.4)	$*170^{b}$ (85.5)	$*313^{b}$ (226)	$*1947^{b}$ (1982)	10.6^{b} (2.15)	0.476 (0.232)
	98 ha $n_{pp} = 17$	No $n_s = 10$	$*32.1^{cd}$ (31.0)	$*78.2^{ac}$ (56.0)	$*85.0^{c}$ (53.7)	$*387^{a}$ (367)	7.61 (1.59)	1.49 (1.48)

3.2 Height, DBH, Merchantable Height, and Understory Vegetation

Soil fertility data would suggest greater tree growth metrics for non-irrigated Foreston soils than non-irrigated Autryville or Stallings soils due to lower P content of these soils and greater tree growth metrics for irrigated Stalling soils than irrigated Autryville soils due to the significantly lower K content of Autryville soils. Likewise, growth metrics for trees on irrigated Autryville and Stalling soils should be greater than growth metrics for trees on their respective non-irrigated soils. However, the actual measured results differed from these expectations.

For non-irrigated soils, there were significant differences across soil types for tree height and merchantable height but not tree diameter (Table 2). Both Stallings and Autryville soils had the highest mean tree height which was significantly higher than all other non-irrigated soils (Table 2; Table S-3). Non-irrigated Foreston soils had the second highest mean total height that differed significantly from non-irrigated Norfolk and Baymeade soils. Mean merchantable height did not differ between non-irrigated Stallings, Autryville, or Foreston soils, but all three soils had significantly higher mean merchantable tree height than non-irrigated Norfolk or Baymeade soils (Table 2; Table S-5). Non-irrigated Baymeade soils had the lowest mean basal area and tree volume than all other non-irrigated soils, and, consequently, significantly greater mean understory mass than the other non-irrigated soils ((Table 2, Table S-4,Table S-5, Table S-6).

Non-irrigated Autryville and Stalling soils had significantly higher mean tree height than non-irrigated Foreston soils despite significantly lower soil P (both soils) and K (only Autryville). Likewise, Baymeade soils had the lowest tree growth metrics and greater understory mass of all soil types although soil fertility values for non-irrigated Baymeade soils were not different than other soils. For non-irrigated soils, tree productivity did not reflect soil fertility differences.

For irrigated soils, Stallings and Autryville had similar mean tree heights that were significantly greater than the other irrigated soil types (Table 2; Table S-4) despite lower K content of Autryville soils.

Table 2. Mean values for tree height, merchantable height, diameter at breast height (DBH), understory mass, basal area, and volume (± one standard deviation) across dominant soil types for irrigated and non-irrigated prism plots. Values not followed by the same letter are significantly different within a column. Values with no letters were not significantly different across all soil types. An asterisk (*) denotes significant differences between irrigation and non-irrigation within a soil type.

Soil Type	**# of trees**	**Total Height (m)**	**Merch Height (m)**	**DBH (cm)**	**Understory Mass (g)**	**Basal Area (m^2)**	**Volume (m^3)**
Autryville	Irrigated n = 153	21.9^{a} (3.25)	18.1^{a} (3.52)	33.0^{a} (7.78)	26.65^{b} (7.83)	1.15^{a} (0.216)	7.78^{a} (3.72)
Autryville	Not Irrigated n = 169	22.0^{a} (3.67)	18.2^{a} (3.93)	30.6 (7.11)	30.92^{b} (11.93)	1.08^{a} (0.440)	8.20^{a} (1.94)
Baymeade	Irrigated n = 210	17.2^{d} (3.68)	12.8^{d} (2.48)	27.5^{c} (8.10)	77.18^{a} (74.51)	0.564^{b} (0.257)	3.14^{b} (1.65)
Baymeade	Not Irrigated n = 245	17.6 ^{d} (3.46)	13.3^{d} (2.36)	28.3^{c} (7.64)	74.09^{a} (44.17)	0.632^{bc} (0.227)	3.57^{b} (1.79)
Foreston	Irrigated n = 249	19.6 ^{bc} (3.50)	*14.4^{d} (3.11)	30.0 (7.89)	46.80^{ab} (20.99)	0.853 (0.443)	5.42 (3.52)
Foreston	Not Irrigated n = 319	20.4^{c} (3.18)	*15.7^{a} (2.88)	29.7^{bc} (7.41)	35.20^{b} (19.57)	1.07^{a} (0.429)	6.95^{a} (3.46)
Norfolk	Irrigated n = 235	18.8^{b} (3.34)	14.2^{c} (2.70)	29.5^{bc} (7.24)	41.12^{ab} (22.11)	0.679^{bcd} (0.336)	4.09^{b} (2.43)
Norfolk	Not Irrigated n = 321	19.0^{b} (3.77)	14.7^{c} (2.92)	28.7^{bc} (8.58)	36.58^{b} (21.02)	0.904^{abd} (0.406)	5.60 (3.30)
Stallings	Irrigated n = 199	22.2^{a} (2.90)	17.6^{a} (2.68)	31.2^{ab} (6.81)	40.64^{ab} (12.64)	1.02^{ad} (0.390)	7.23^{a} (3.02)
Stallings	Not Irrigated n = 182	22.6^{a} (3.47)	17.7^{a} (3.42)	29.4^{bc} (6.00)	50.97^{ab} (26.01)	0.758 (0.366)	5.39 (3.07)

As observed with non-irrigated Baymeade soils, irrigated stands in Baymeade soils had the lowest mean tree heights of all soils. Mean merchantable height was also greatest for irrigated Autryville and Stallings soils (Table S-5) while irrigated Baymeade soils had the lowest merchantable tree height. Mean tree diameter followed the same trends. Mean tree diameter for irrigated Baymeade and Norfolk soils were significantly lower than Autryville, Stalling, and Foreston soil types (Table 2, Table S-6). Mean basal area and tree volume were lowest for irrigated Baymeade soils; there were no significant differences for basal area and tree volume for the remaining irrigated soil types (Table 2, Table S-7, Table S-8). Although irrigated Autryville soils had significantly lower K than irrigated Stallings soils, tree growth metrics were the same. Likewise, lower tree growth metrics for Baymeade soils did not reflect soil fertility differences relative to the other irrigated soils. For irrigated soils, tree productivity did not reflect soil fertility differences.

Irrigated and non-irrigated Autryville and Stalling soils had no apparent differences for tree height, diameter, volume, or understory although their soil fertility values were significantly greater for irrigated than non-irrigated soils (Table 1 & 2). Non-irrigated Foreston soils had significantly higher mean merchantable tree height than irrigated Foreston soils with no apparent soil fertility differences. For all other soils, there were no significant differences between tree growth metric data of irrigated and non-irrigated soils within the same soil type. These findings suggest that two decades of wastewater irrigation have not impacted tree productivity within each soil type.

3.3 Productivity by Age Class, Soil Type, and Irrigation.

Forest management for slow-rate wastewater irrigation recommends harvest rotations of 25 to 28 years to maximize water use by forests (McKim et al., 1982). Because tree age ranged from 27 to 43 years, data were stratified by three relevant age classes to determine if tree productivity differed by age class across soil types to determine if irrigation impacted younger versus older trees over the last 20 years. Irrigation at the site began in 1998 so trees in age class 1 received irrigation after 7 and 11 years of growth without irrigation while trees in age class 2 and 3 received irrigation after 12 to 17 years of growth without irrigation. There were no significant differences in mean tree diameter or height for irrigated and non-irrigated trees within the same soil type for Age Class 1 (27-31 years) (Figure 2, Table S-5). There were significant differences between soil types for this age class. Irrigated and non-irrigated Baymeade soils had the lowest mean tree diameter and height than the other soil types while irrigated and non-irrigated Autryville and Foreston soils had the greatest mean tree diameter and height than the other soil types.

For Age Class 2 (32-36 years), mean tree diameter was not different across soil types except for irrigated Autryville versus irrigated Norfolk soils. Mean tree heights were significantly lower for non-irrigated Baymeade soils, irrigated Foreston soils, and irrigated Norfolk soils versus the other soils (Figure 2). For this age class, mean tree height did differ between irrigated and non-irrigated trees for Foreston and Norfolk soils. For the oldest age class, Age Class 3 (37-43 years), trees in non-irrigated Norfolk soils, irrigated Baymead, and irrigated Norfolk soils had significantly greater diameter than trees than Foreston and Stallings soils. Mean tree diameter for irrigated Foreston soils was greater than non-irrigated Foreston soils. In contrast, there were not significant difference in mean tree height between irrigated and non-irrigated trees for Age Class 3, but mean tree height was greater for Stallings soils than Baymeade and Foreston soils.

These results suggest that irrigation did not impact diameter and height at earlier stages of tree growth (Age Class 1) regardless of soil type or soil fertility. However, significant differences were observed between irrigated and non-irrigated trees of the same soil type and across soil types for Age Class 2 and 3. Data analysis cannot discern if differences in older tree diameter and height for irrigated and non-irrigated Foreston and Norfolk soils result from irrigation treatment for the last twenty years or because of other factors present before irrigation began.

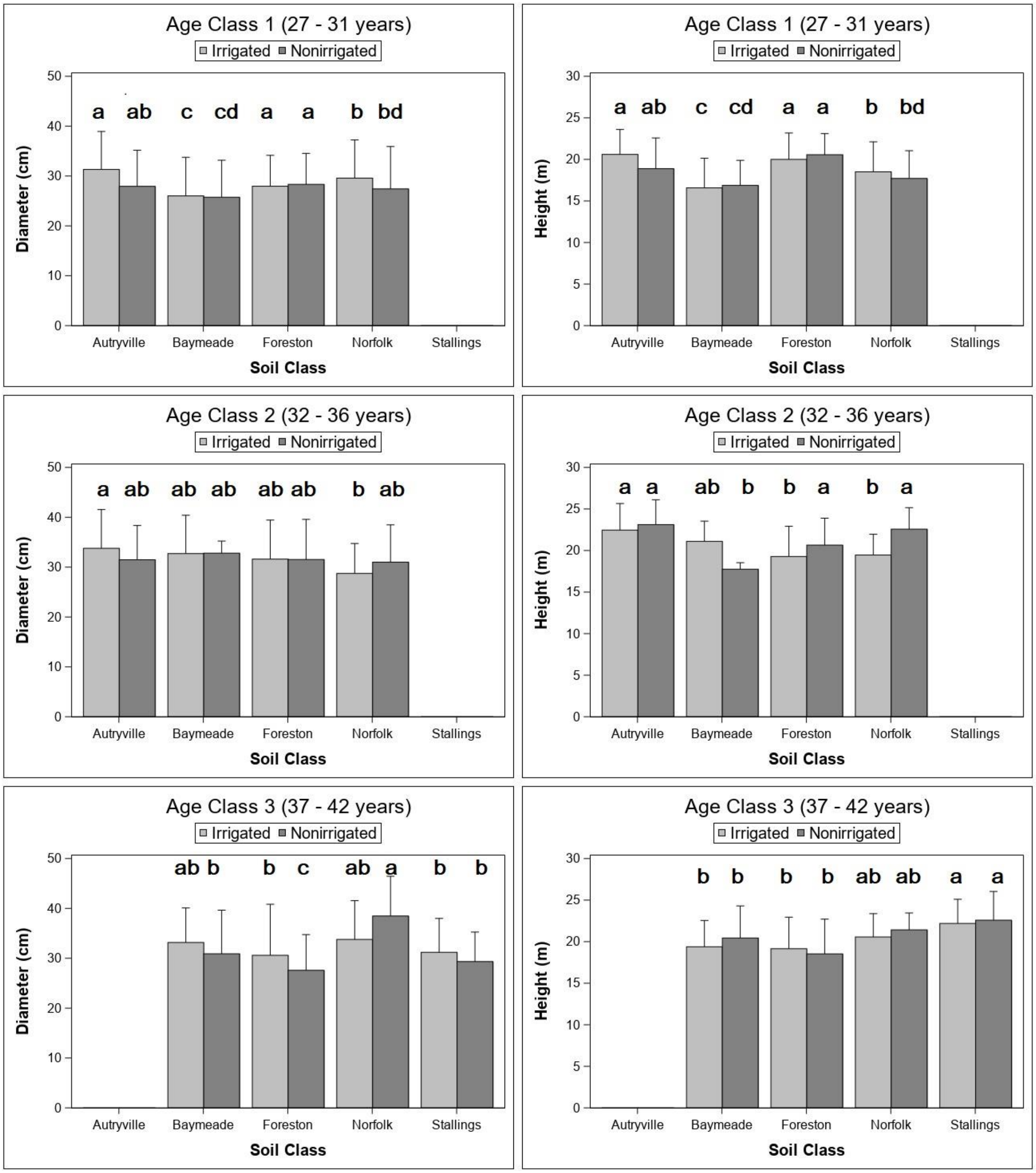

Figure 2: Mean values of diameter at breast height (DBH) and height across dominant soil types for each age class with and without irrigation. Different letters denote significant differences ($p < 0.05$). Error bars represent one standard deviation above the mean.

3.4 Annual Tree Core Increment Comparisons

Initial analysis of tree cores sought to find trends in standardized mean increment width by stratifying growth years by the amount of precipitation at the site according to NOAA 30-year annual rainfall from the period irrigation was present (1998 – 2018). Years were categorized based on deviations from mean annual rainfall (1458 mm). Above average precipitation years were those where rainfall was one standard deviation above the mean, and below average precipitation were one standard deviation below that same mean (Gibson et al.,, 2019). When increment widths were stratified into below normal, normal, and above normal rainfall, there were no significant difference in normalized mean annual increment widths (Table S-9, Table S-10).

When incremental core data were stratified into the same three tree age classes, significant differences were observed in standardized increment width between irrigation regimes for Foreston and Baymeade soils only (Figure 3). Irrigation significantly increased annual increment widths for trees in Foreston soils for age class 2 (32-36 years). Irrigation significantly increased annual increment widths for Baymeade soils for age class 3 (37-42 years). These differences were not reflected in soil fertility data or in the analysis of height and diameter by age class. Figure 3 demonstrably shows that irrigation had no impact on mean annual increment growth for age class 1 within and across soil types and largely no impact on mean annual increment growth for soil types in age class 2 or 3.

3.5 Stumpage Value Estimation

Observed differences in diameter, height, volume, and understory should impact the economic value of stands. Stallings, Autryville, and Foreston stands, which have better growth metrics, yield the highest stumpage value. Baymeade soils, which consistently yield the lowest growth metrics, have the lowest stumpage value. Stallings had a much higher total stumpage value for irrigated than non-irrigated stands that reflects significantly higher fertility values (P, K, Mg,Ca) for irrigated Stallings trees than non-irrigated Stallings trees (Table 1). While there were not significant differences in the basal area per plot calculations within soil types between irrigated and nonirrigated soils (Table 2), estimates for basal area per hectare show higher square footage estimates in nonirrigated stands than irrigated stands (Table 3).

Stumpage values between irrigated and nonirrigated were relatively small for Autryville and Baymeade soils but larger in Foreston and Norfolk soils. Nonirrigated stands in Foreston and Norfolk soils yielded greater stumpage estimates than irrigated stands. There were significant differences in height between Foreston and Norfolk stands in Age Class 2 that would support greater stumpage yields (Figure 2). Nonirrigated stands yielded significantly higher mean total height than irrigated stands in both soils. What this suggests generally is that soils that demonstrated higher growth metrics (Table 2) yielded better economic values in the later age classes.

CHAPTER 4: DISCUSSION

4.1 Soil Fertility and Tree Productivity

Soil fertility is crucial for tree growth and stand productivity (Haywood & Burton 1989, Albaugh et al., 2004), with phosphorus and potassium playing critical roles in sustaining productivity on low performing sites (Fox 2000). Calcium additions have also been positively correlated with reductions in loblolly stem curvature and generally improved growth performance (Espinoza et al., 2012). FWR wastewater is a constant source of both Ca and P with loading rates of 0.7 and 7.2 kg/ha/yr (Table S-3). However, differences in soil fertility were limited to only P and K among some site soil types and irrigation regimes. Soil P and K differences did not yield significant changes to tree growth perhaps because loading rates were more than 90% less than recommended values for managed loblolly pine (Table S-1). Trees in Autryville and Stallings soils, with lower soil P and K content, grew as well or better than trees in the other three soil types. Irrigation did not yield different tree growth for all soils in the youngest age class of trees (27-31 years), but irrigation did matter for tree growth differences for two soils, Foreston and Norfolk, in older age classes whose soils had no significant soil fertility differences.

The five dominant soil types are commonly occurring Ultisols soils characterized as loamy fine sand in the first 20 cm (NRCS, 2019). Our measured soil fertility values for these soils were within ranges provided by the National Resource Conservation Service for magnesium, potassium, and CEC of these soils (Table S-11)(NCRS, 2019). Calcium exceeded the upper NRCS range for most FWR soils, except Norfolk soils (Table S-11) by 20 to 57%. Research has demonstrated that calcium additions in the form of calcium sulfate ($CaSO_4$) at amounts as low as 168 kg/ha have been shown to dramatically improve stem straightness and therefore merchantability of planted loblolly pine (Espinoza et al., 2012). For irrigated portions of the FWR site, calcium loadings averaged 7.2 kg/ha (Table S-1). Calcium is common to municipal wastewaters (Nichols 2016), but high calcium content was observed for both irrigated and non-irrigated soils of the same soil type and relationships between calcium and tree growth differences were not apparent. Stallings soils had significantly more calcium in irrigated soils than non-irrigated soils, but mean diameter and tree height were not different.

Observed tree growth appears consistent with agricultural productivity classifications for the Tidewater region of North Carolina based on the average forestland net present values for soil types (NCDA&CS, 2019). Autryville, Stallings, Foreston, and Norfolk sandy soil series have been classified as “Average Soils” for productivity, and Baymeade soils, which had lower tree growth overall for the FWR site, are classified as low productivity soils. Observed tree productivity of FWR soils appears consistent with NCRS and NCDA&CS soil characterizations and better explains observed differences in tree growth among soil types than soil fertility. The reason that Baymeade is considered a poorer host to loblolly pine likely relates to its physical composition. Research suggests that loblolly pine performs better on soil with lower surface drainage and sand content (Londo & Ezell, 2011; Coyle et al., 2015). Baymeade fine sand had a much higher sand content than any of the other soils measured (Table 1). This higher sand content leads to increased drainage which will lead to the leaching of valuable soil nutrients.

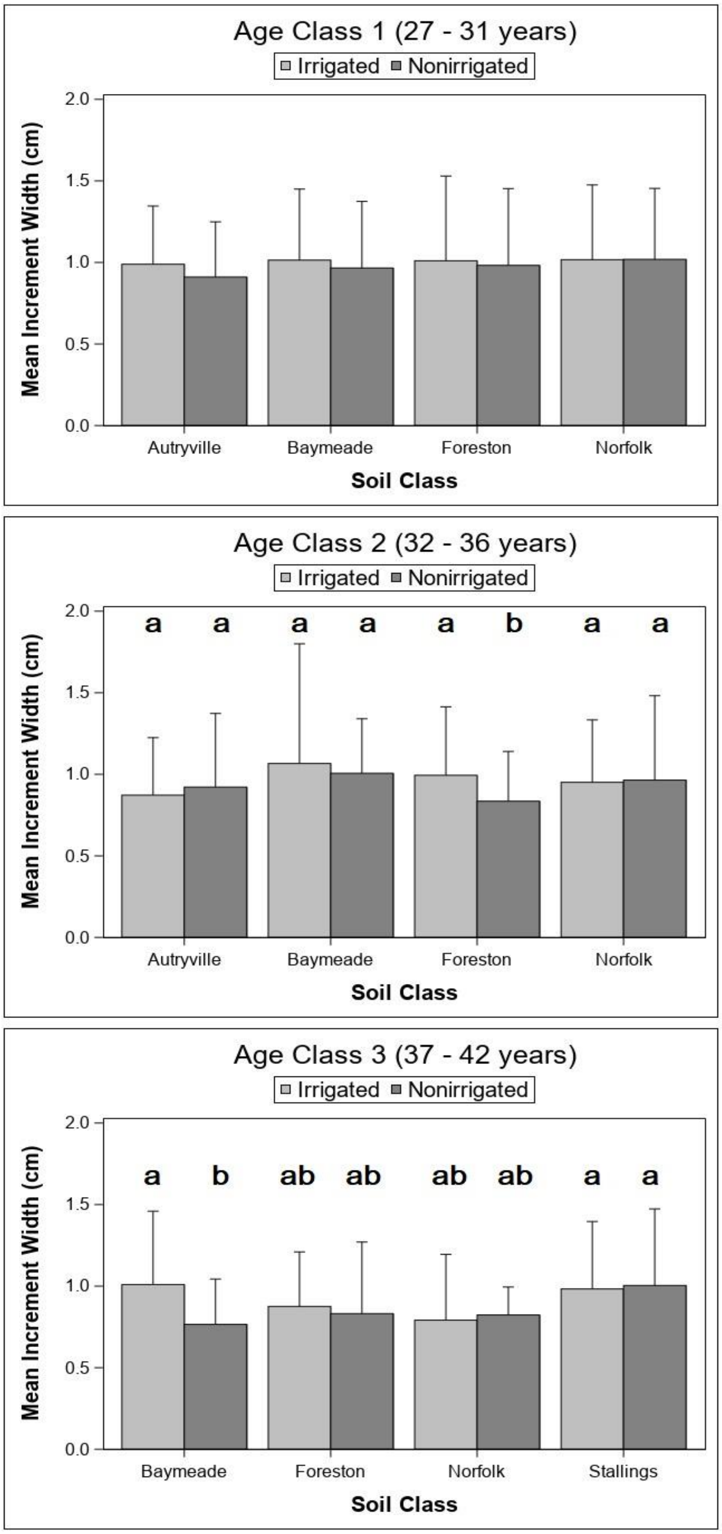

Figure 3: Mean values for standardized incremental width of tree cores across dominant soil types for each age class. Different letters denote significant differences ($p < 0.05$). Error bars represent one standard deviation above the mean.

Table 3: Ranked Comparison of pulpwood, chip-and-saw, and sawtimber values from estimates of basal area (BA) and volume (Vol) per hectare across irrigated and non-irrigated soil types arranged from the highest (top) to the lowest (bottom) based on total values. Product classes and costs were taken from NC State Forestry extension quarterly prices reports for quarter 2 of 2019 (https://forestry.ces.ncsu.edu/forestry-price-data/).

Soil Type	**Estimations**	**Pulpwood (< 23 cm)**	**Chip-and-saw (between 23 and 36 cm)**	**Sawtimber (>36 cm)**	**Total**
Stallings Irrigated	BA/ac (m^2/ha)	4.44	18.6	9.0	32.1
	Vol/ac (m^3/ha)	57.8	727	216	1001
	Green weight (t/ha)	29.4	369.7	109.8	509
	Stumpage ($/ha)	$247	$6,914	$3,125	$10,286
Foreston Non-irrgated	BA/ac (m^2/ha)	7.70	20.8	10.7	39.2
	Vol/ac (m^3/ha)	100.8	417	244	762
	Green weight (t/ha)	51.3	212.0	124.1	387
	Stumpage ($/ha)	$432	$3,965	$3,530	$7,927
Autryville Non-irrigated	BA/ac (m^2/ha)	7.35	17.6	10.3	35.3
	Vol/ac (m^3/ha)	94.1	394	252.8	741
	Green weight (t/ha)	47.9	200.4	128.5	377
	Stumpage ($/ha)	$403	$3,747	$3,656	$7,807
Autryville Irrigated	BA/ac (m^2/ha)	4.98	15.5	11.09	31.6
	Vol/ac (m^3/ha)	66.3	329	267	662
	Green weight (t/ha)	33.7	167.3	135.7	337
	Stumpage ($/ha)	$284	$3,128	$3,861	$7,273
Norfolk Non-irrigated	BA/ac (m^2/ha)	9.40	16.9	8.72	35.0
	Vol/ac (m^3/ha)	108.0	326	200	634
	Green weight (t/ha)	54.9	165.8	101.7	322
	Stumpage ($/ha)	$462	$3,101	$2,894	$6,457
Stallings Non-irrigated	BA/ac (m^2/ha)	4.97	18.6	5.63	29.2
	Vol/ac (m^3/ha)	60.0	417	138	615
	Green weight (t/ha)	30.5	212.0	70.2	313
	Stumpage ($/ha)	$257	$3,965	$1,997	$6,219
Foreston Irrigated	BA/ac (m^2/ha)	6.25	14.5	8.0	28.7
	Vol/ac (m^3/ha)	75	279	178	532
	Green weight (t/ha)	38.1	141.8	90.5	270
	Stumpage ($/ha)	$321	$2,652	$2,575	$5,549
Norfolk Irrigated	BA/ac (m^2/ha)	6.08	12.9	6.50	25.5
	Vol/ac (m^3/ha)	66	246	137	449
	Green weight (t/ha)	33.6	125.0	69.7	228

Table 3 (continued)

	Stumpage ($/ha)	$283	$2,338	$1,982	$4,603
Baymeade Non-irrigated	BA/ac (m2/ha)	8.49	13.6	5.58	27.7
	Vol/ac (m3/ha)	94.6	266	115	475
	Green weight (t/ha)	48.1	135.2	58.5	242
	Stumpage ($/ha)	$405	$2,529	$1,664	$4,598
Baymeade Irrigated	BA/ac (m2/ha)	8.03	12.3	4.45	24.8
	Vol/ac (m3/ha)	73.5	219	90	383
	Green weight (t/ha)	37.4	111.4	45.8	195
	Stumpage ($/ha)	$315	$2,083	$1,302	$3,699

4.2 Comparative Site Index Productivity and Value of Loblolly Pine in eastern NC

Previous forest consultant Site Index evaluations of loblolly pine at the FWR site were 50 and 70 for SI_{25} (Seth Ward, personal communication). Growth curves for loblolly pine on the NC coastal plain(Trousdell 1974) can be compared to average heights by soil and stand type (Table 2) and suggest that FWR trees, regardless of irrigation, are growing within the range of what would be expected for a SI_{25} = 50 – 60 site. There are no soil types that had a predicted SI_{25} below this range, but there are several soils with estimated Site Indices that were above those values (Table S-10). Only Stallings and Autryville sites had mean total heights that exceeded 21.3 m, but these sites were over 25 years old (Table 2). This result suggests that initial evaluations for SI were overestimates, and the trees are growing with a lower site index than initially predicted.

Estimated harvest values for minimally managed loblolly pine in the Tidewater region of North Carolina are approximately $7,183/ha (2019 Use Manual for NC). For FWR stands and their current estimated stumpage values (Table 3), only three soil types and irrigation combinations outperformed the $7,183/ha estimate. Stallings Irrigated, Foreston Non-irrigated, and Autryville Irrigated had stumpage values greater than $7,183/ha. All other soil types and irrigation regimens fall below this estimate for harvest value. This comparison suggests that most of the FWR stands are underperforming for volume production by between 10 – 44% for non-irrigated soils and 14-64% for irrigated soils (Table S-11). Sub-optimal performance may represent genetic differences between trees currently in production versus the genetics of FWR trees which were planted 30 years ago.

4.3 Irrigation and Loblolly Pine

There is limited literature on irrigation on loblolly pine (Heth & Kramer 1975, Lorenz et al., 2006), particularly wastewater irrigation of loblolly pine (Nichols, 2016). Much of the literature focuses on soil fertility, fertilization, weed control, and water use efficiency (Albaugh et al., 2004, Kelting et al., 2000, Ezell & Yeiser 2015, Kim et al., 2017). Increased water availability using irrigation has had highly variable growth effects on loblolly pine. Albaugh et al.,, 1998 reported that irrigation alone provided modest growth improvement to loblolly pine. Other studies found negligible effects of irrigation on overall biomass growth for loblolly pine (Allen et al., 2005) because high water availability provides stable evapotranspiration e for tree growth (Amatya et al.,, 2016). For drier climates, irrigation was significant for pine productivity because of limited water availability (Linder 1989). In drier regions, irrigation significantly increased evapotranspiration of loblolly pine seedlings but did not increase biomass (Barnes 2002). In temperate regions like the coastal plain, water storage in groundwater is not greatly changed by irrigation; hence, trees have adequate water for evapotranspiration and growth from shallow groundwater aquifers (Callahan et al.,, 2012).

4.4 Land Water Reuse Irrigation

A previous study completed at the Jacksonville FWR modeled the impacts of irrigation to evaluate site water balances with and without irrigation (Gibson et al., 2019). While irrigation slightly increased rates of evapotranspiration, increases for storage in groundwater were negligible. Annual drainage did increase with annual irrigation volume, but daily and monthly changes in drainage reflected precipitation not irrigation.

The Jacksonville FWR receives on average 826 mm of treated wastewater annually in addition to 1458 mm of rainfall (Gibson et al, 2019). For the last three years, irrigation volumes were much greater due to significant rainfall events. While irrigation is variable on a monthly basis, annual irrigation is relatively consistent water input on the site (Gibson et al.,, 2019). The combination of irrigation and precipitation was significantly greater than the annual potential evapotranspiration on the site by upwards of 393 mm to 2058 mm (Gibson 2019) for normal and above-normal rainfall years since 1998. Hence, more water is added to the site than is needed for pine growth unless drought conditions prevail. When the FWR site was in drought, irrigation did increase evapotranspiration for irrigated trees.

The amount of excess water for the FWR site far exceeds other irrigation studies on loblolly pine which used 130 mm (Neary et al., 1990) to 700 mm of irrigated water (Albaugh et al., 2004). In both studies, the growth response resulting from irrigation was relatively small; trees responded more to nitrogen and phosphorus nutrient availability than water availability for every measured growth metric. For the FWR site, nitrate concentrations were not different among soil types or irrigation regimes. The wastewater volume to hectare is designed to prevent nutrient export from irrigated trees to groundwater and surface waters which possibly explains lack of growth differences between irrigated and non-irrigated trees and no significant differences of nitrate in soils. One opportunity to improve pine productivity would be added nitrogen fertilization to the site.

4.5 Drainage and Loblolly Pine

Loblolly pine is a moderately flood tolerant species that can tolerate stagnant water inundation without productivity loss relative to other tree species; the effects of flooding on loblolly pine growth depend greatly on drainage (Walker et al., 1961, McKnight et al., 1981, Hook 1984). Hunt (1951) observed that although height growth in loblolly pine saplings was reduced for trees flooded with stagnant water, tree height differences became negligible after a period of seven months once stagnant water was drained and soil moisture was held at field capacity. Intermittent flooded loblolly pines had no reduction in height versus pines held at field capacity in the same study (Hunt, 1951). Gibson et al.,, 2019 observed that increases in total water inputs from irrigation plus rainfall did not change evapotranspiration greatly but did change drainage. The dominant soils on the FWR site are moderate to well-drained soils hence no observed difference in loblolly pine growth when there is intermittent excess water due to irrigation.

Hook et al.,, 1983 observed that when flooded loblolly pines receive nutrient inputs, growth increases. However, growth responses were dependent on whether flooding was intermittent or continuous. Continuously flooded trees, that also received phosphorus, grew significantly less than seasonally flooded trees that were flooded in winter months (DeBell et al., 1984). The exact physiological mechanisms of intermittent flood tolerance are not well understood, but loblolly pine, under intermittent flooding conditions, appears to increase aerenchyma production in roots to limit the effects of water-logging (Kozlowski 1997).

The ability of loblolly pine to withstand semi-frequent inundation and grow as well as pines at field capacity supports findings from this study wherein no significant differences were observed between irrigated and non-irrigated loblolly pine trees for soil types, particularly Age Class 1 trees (27 to 31 years). While water inputs were consistent throughout the year, weekly and monthly inputs are designed to allow drainage and avoid water-logging conditions. In fact, the land application permit for the land treatment site does not allow pooling of wastewater on soil surfaces (Birch et al.,, 2016). The FWR site is a large-scale study of how loblolly pine can tolerate intermittent excess water on a weekly basis without significant reductions in pine productivity. The literature to date suggests that additional fertilization would improve overall site productivity more so than reductions in irrigation volumes.

CHAPTER 5: CONCLUSIONS

The goals of this study were to quantify the growth and productivity differences between irrigated and nonirrigated tracts of planted loblolly pine grown under land water treatment management. Results suggest that though growth differ among soil types, irrigation has minimal effects. Soil fertility did not have significant predictive power for observed differences between tree growth in irrigated or non-irrigated soils. Stand productivity differences were significant with Autryville and Stallings soils yielding higher mean total tree heights than all other soils, and higher tree volume and diameter than Baymeade soils. Observed basal differences were not reflected in significant differences of mean annual growth between soils. Additionally, differences in growth were not reflected by soil fertility metrics but were consistent with forest productivity estimates for the coastal plain in eastern NC.

When stratified by age class, there were differences between irrigated and nonirrigated stands of the same soil type for tree height, diameter, and mean increment width. These differences were not consistent across all soils. The differences between soils is still significant within age classes which highlights how important soil classification is as a predictor for site productivity.

Additional comparisons of stand stumpage values with estimated use values for loblolly pine grown in eastern NC suggests that both irrigated and non-irrigated soils are underperforming in terms of volume production. Given the age of the trees in this study, low volume production is likely the result of the genetics of original planted pine. Advanced genetic stock of loblolly in conjunction with advances in silviculture have improved performance even on marginal sites to levels that would yield greater growth than observed at the FWR site. The introduction of younger seedlings of superior planting stock in conjunction with the incorporation of more active understory management could improve loblolly productivity and yield new insights into the potential differences between irrigation regimes.

CHAPTER 6: FUTURE RESEARCH

This thesis studies the productivity differences between irrigated and nonirrigated pine grown under land water management with minimal management inputs. Future research on the site that can capture the interactions of irrigation and silvicultural management techniques are needed to fully assess the nature of pine growth on these sorts of sites. One such suggested technique would be the addition of phosphorus fertilizer inputs onto irrigated stands. Past research on irrigated pine has seen additions of phosphorus complement irrigation and lead to productivity increases above those of irrigation alone (Albaugh et al., 2008).

Another avenue of research on the LTS would be to focus the study on younger stands of trees. Most of the paired irrigation and fertilization studies done on loblolly focus on trees that are between 4-10 years old, as this is generally seen as being the time when they are most receptive to these inputs (Samuelson et al., 2008, Linder et al., 1987). Recent Jacksonville LTR management has seen some of the older stands on the site harvested, which provides an opportunity for replanting trees that could serve as objects of study in future irrigation efforts. While our study did not see any significant differences between irrigated and nonirrigated trees in the younger age classes studied, there would be a benefit in looking at even younger pine trees as there is no current research on the subject.

Additional inquiries could be made into the effects of regular understory maintenance on irrigated stands. The use of herbicides and mechanical felling have long been associated with commiserate improvements in stand growth for loblolly pine (Haywood et al., 2003, McInnis et al., 2004). Prescribed fire is another method to mitigate understory growth that has yielded more mixed effects on loblolly pine sites (Marino et al., 2002, McInnis et al., 2004). The incorporation of either of these understory management techniques in conjunction with irrigation could elucidate whether when paired with other treatments, irrigation has a significant effect on growth.

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APPENDICES

Table S-1. Mean concentration (± one stand deviation) and application rates for nutrients tested at the Jacksonville FWR. Recommended fertilizer application rates come from Jokela & Hall 2000.

	Mean concentration (mg/L)	**Application Rate (kg/ha)**	**Recommend Application Rate for Loblolly (kg/ha)**
Potassium	13 (1.8)	91.4	34
Phosphorus	3.0 (0.6)	21.1	30 - 57
Nitrogen	13 (5.8)	91.4	170
Boron	0.6 (0.3)	4.22	1.5
Calcium	29 (4.8)	204	-
Sulfate	44 (5.1)	309	-
Organic Carbon	14 (3.7)	98.4	-
Chloride	56 (14)	394	-
Magnesium	1.1 (1.7)	7.0	-
Manganese	0.02 (0.01)	0.1	-
Sodium	85 (12)	598	-
Ammonia	8.9 (5.0)	62.6	-
Nitrate	2.9 (3.3)	20.4	-
Nitrite	3.8 (6.0)	26.7	-
Selenium	411 (5.66)	2889	-

Table S-2. Mixed model results run with a general Satterthwaite approximation to adjust for unequal variance for soil fertility parameters (α = 0.05).

	CEC		Calcium		Magnesium		Potassium		Phosphorus		NO3	
Groups	**t stat**	**p**	**t stat**	**p**	**t stat**	**p**	**t stat**	**p**	**t stat**	**p**	**t stat**	**p**
AUTNONIRR * AUTIRR	-0.92	0.37	-2.12	0.057	-1.23	0.234	-1.43	0.171	-2.27	0.043	0.12	0.911
AUNONTIRR * BAYNONIRR	-1.47	0.160	-1.91	0.077	-1.10	0.286	-1.87	0.083	-1.01	0.336	0.92	0.410
AUNONTIRR * BAYIRR	-0.90	0.385	-2.83	0.015	-1.81	0.087	-2.29	0.036	-2.17	0.053	0.22	0.829
AUTNONIRR * FORNONIRR	-2.12	0.055	-1.89	0.090	-1.32	0.204	-1.59	0.129	-2.46	0.034	0.95	0.397
AUTNONIRR * FORIRR	-1.57	0.136	-2.13	0.057	-1.63	0.122	-2.93	0.010	-2.71	0.021	0.60	0.575
AUTNONIRR * NORNONIRR	-2.57	0.021	-1.86	0.092	-1.49	0.155	-2.19	0.043	-2.02	0.071	0.95	0.397
AUTNONIRR * NORIRR	-1.39	0.183	-2.69	0.021	-1.35	0.198	-3.28	0.004	-3.27	0.009	0.61	0.570
AUTNONIRR * STALNONIRR	-2.38	0.031	-0.12	0.904	0.17	0.869	-1.05	0.311	-1.86	0.096	0.62	0.568
AUTNONIRR * STALIRR	-3.43	0.004	-2.47	0.033	-2.55	0.022	-3.77	0.002	-5.00	0.000	-0.11	0.914
AUTIRR * BAYNONIRR	-0.28	0.783	0.74	0.469	0.28	0.782	-0.65	0.525	0.40	0.692	1.96	0.121
AUTIRR * BAYIRR	0.05	0.964	-0.02	0.984	-0.57	0.577	-0.91	0.378	-0.13	0.897	0.19	0.858
AUTIRR * FORNONIRR	-1.19	0.252	-0.61	0.549	-0.25	0.807	0.07	0.946	-1.05	0.313	2.03	0.112
AUTIRR * FORIRR	-0.39	0.701	-0.01	0.990	-0.48	0.635	-1.33	0.201	-0.73	0.476	0.97	0.360
AUTIRR * NORNONIRR	-1.27	0.220	-0.14	0.889	-0.09	0.931	-0.21	0.834	-0.36	0.727	-0.88	0.418
AUTIRR * NORIRR	-0.20	0.843	-0.41	0.686	0.20	0.846	-1.38	0.184	-2.15	0.053	0.97	0.361
AUTIRR * STALNONIRR	-0.61	0.555	2.08	0.063	1.72	0.112	0.46	0.655	0.34	0.737	1.14	0.296
AUTIRR * STALIRR	-2.08	0.052	-0.91	0.379	-1.52	0.149	-2.22	0.040	-1.93	0.070	-0.24	0.819
BAYNONIRR * BAYIRR	0.34	0.738	-0.94	0.361	-0.92	0.373	-0.17	0.867	-0.49	0.632	-1.02	0.367
BAYNONIRR * FORNONIRR	-1.05	0.309	-1.11	0.289	-0.51	0.617	0.76	0.460	-1.21	0.242	0.50	0.634
BAYNONIRR * FORIRR	-0.13	0.896	-0.75	0.463	-0.79	0.443	-0.47	0.642	-0.95	0.356	-0.88	0.431
BAYNONIRR * NORNONIRR	-1.14	0.268	-0.78	0.452	-0.43	0.673	0.58	0.573	-0.64	0.530	-1.55	0.197
BAYNONIRR * NORIRR	0.10	0.925	-1.24	0.234	-0.14	0.893	-0.43	0.673	-2.21	0.043	-0.77	0.483
BAYNONIRR * STALNONIRR	-0.35	0.733	1.85	0.088	1.74	0.105	1.06	0.306	-0.15	0.882	-1.53	0.200
BAYNONIRR * STALIRR	-2.05	0.057	-1.52	0.153	-1.86	0.085	-1.30	0.211	-1.84	0.087	-0.93	0.405
BAYIRR * FORNONIRR	-1.25	0.230	-0.64	0.536	0.25	0.805	1.06	0.306	-0.92	0.373	1.06	0.349
BAYIRR * FORIRR	-0.45	0.658	0.01	0.996	0.04	0.965	-0.32	0.753	-0.57	0.575	0.50	0.632
BAYIRR * NORNONIRR	-1.35	0.194	-0.14	0.891	0.55	0.592	0.89	0.391	-0.23	0.820	-0.93	0.390
BAYIRR * NORIRR	-0.26	0.799	-0.45	0.659	0.90	0.386	-0.26	0.796	-2.03	0.064	0.52	0.624
BAYIRR * STALNONIRR	-0.69	0.503	2.78	0.017	2.45	0.032	1.38	0.188	0.45	0.659	0.55	0.608
BAYIRR * STALIRR	-2.17	0.043	-0.96	0.355	-1.04	0.313	-1.22	0.240	-1.65	0.117	-0.33	0.754
FORNONIRR * FORIRR	0.94	0.362	0.60	0.556	-0.20	0.846	-1.56	0.139	0.45	0.658	-0.96	0.391
FORNONIRR * NORNONIRR	0.13	0.895	0.47	0.645	0.19	0.848	-0.35	0.731	0.66	0.516	-1.57	0.192
FORNONIRR * NORIRR	1.13	0.277	0.34	0.741	0.45	0.658	-1.68	0.109	-1.14	0.269	-0.85	0.442
FORNONIRR * STALNONIRR	0.94	0.370	1.86	0.094	1.70	0.119	0.45	0.661	1.28	0.222	-1.68	0.168
FORNONIRR * STALIRR	-0.64	0.533	-0.16	0.875	-1.17	0.258	-2.51	0.024	-0.22	0.827	-0.95	0.394
FORIRR * NORNONIRR	-1.00	0.333	-0.13	0.898	0.45	0.659	1.42	0.177	0.28	0.780	-1.28	0.257
FORIRR * NORIRR	0.23	0.823	-0.40	0.697	0.75	0.467	0.10	0.924	-1.63	0.125	0.03	0.977
FORIRR * STALNONIRR	-0.17	0.866	2.08	0.062	2.11	0.059	1.88	0.078	1.03	0.318	0.00	0.997
FORIRR * STALIRR	-1.89	0.075	-0.89	0.385	-1.03	0.319	-0.98	0.340	-0.93	0.367	-0.66	0.539
NORNONIRR * NORIRR	1.24	0.230	-0.21	0.833	0.35	0.727	-1.57	0.135	-1.77	0.097	-0.68	0.535

Table S-2 (continued)

NORNONIRR * STALNONIRR	1.04	0.316	1.82	0.098	2.28	0.041	0.83	0.422	0.63	0.539	1.28	0.255
NORNONIRR * STALIRR	-0.91	0.373	-0.71	0.485	-1.56	0.141	-2.45	0.029	-1.16	0.264	1.31	0.261
NORIRR * STALNONIRR	-0.47	0.644	2.64	0.023	2.42	0.029	2.04	0.059	2.34	0.038	0.51	0.624
NORIRR * STALIRR	-2.15	0.047	-0.59	0.563	-1.88	0.085	-1.17	0.261	1.16	0.270	-0.03	0.976
STALNONIRR * STALIRR	-2.08	0.060	-2.44	0.036	-3.07	0.012	-2.78	0.014	-2.30	0.036	-0.67	0.534

Table S-3. GLM results of total height(m) across all Jacksonville LTS plots (α = 0.05).

Effect	**DF**	**TYPE III SS**	**Mean Square**	**F Value**	**Pr > F**
Irrigation	1	3.6	3.6	0.34	0.557
Soil	4	1423	356	34.08	<.0001
Soil * Irrigation	4	110	27.6	2.64	0.0322
Age Class	2	847	424	40.6	<.0001
Soil * Age Class	5	1210	242	23.2	<.0001
Irrigation * Age Class	2	34.9	17.4	1.67	0.1884
Soil * Irrigation * Age Class	5	253	50.5	4.84	0.0002

Table S-4. GLM results of measured understory mass (g) across a random subsample of Jacksonville LTS plots (α = 0.05).

Effect	**DF**	**TYPE III SS**	**Mean Square**	**F Value**	**Pr > F**
Irrigation	1	31.82	31.82	0.03	0.8675
Soil	4	42120	10530	9.25	<.0001
Soil * Irrigation	4	2078	520	0.46	0.7677

Table S-5. GLM results of measured merchantable height (m) across all Jacksonville LTS plots (α = 0.05).

Effect	**DF**	**TYPE III SS**	**Mean Square**	**F Value**	**Pr > F**
Irrigation	1	1467	1467	15.4	<.0001
Soil	4	81969	20492	215	<.0001
Soil * Irrigation	4	1146	286	3.01	0.0171

Table S-6. GLM results of DBH(cm) across all Jacksonville LTS plots (α = 0.05).

Effect	**DF**	**TYPE III SS**	**Mean Square**	**F Value**	**Pr > F**
Irrigation	1	157	157	2.88	0.0901
Soil	4	1152	288	5.27	0.0003
Soil * Irrigation	4	617	154	2.83	0.0236
Age Class	2	3913	1957	35.8	<.0001
Soil * Age Class	5	1905	381	6.97	<.0001
Irrigation * Age Class	2	63.6	31.8	0.58	0.5589
Soil * Irrigation * Age Class	5	628	125.5	2.30	0.0429

Table S-7. GLM results of basal area (m^2) across all Jacksonville LTS plots (α = 0.05).

Effect	**DF**	**TYPE III SS**	**Mean Square**	**F Value**	**Pr > F**
Irrigation	1	7.61	7.61	0.51	0.4773
Soil	4	641	160	10.67	<.0001
Soil * Irrigation	4	188	47.1	3.14	0.0158

Table S-8. GLM results of volume (m^3) across all Jacksonville LTS plots (α = 0.05).

Effect	**DF**	**TYPE III SS**	**Mean Square**	**F Value**	**Pr > F**
Irrigation	1	0.145	0.145	1.71	0.1915
Soil	4	2.56	0.64	7.53	<0.0001
Soil * Irrigation	4	1.31	0.33	3.88	0.0038
Age Class	2	7.32	3.66	43.1	<0.0001
Soil * Age Class	5	2.33	0.466	5.48	<0.0001
Irrigation * Age Class	2	0.109	0.055	0.64	0.5256
Soil * Irrigation * Age Class	5	1.23	0.247	2.91	0.0127

Table S-9. GLM results of standardized mean incremental width across all Jacksonville LTS plots (α = 0.05).

Effect	**DF**	**TYPE III SS**	**Mean Square**	**F Value**	**Pr > F**
Irrigation	1	0.722	0.722	3.96	0.0466
Soil	4	4.72	1.18	6.47	<.0001
Soil * Irrigation	4	1.51	0.378	2.07	0.0822
Age Class	2	4.85	2.42	13.3	<.0001
Soil * Age Class	5	0.962	0.192	1.06	0.3832

Table S-9 (continued)

Irrigation * Age Class	2	0.074	0.037	0.2	8.154
Soil * Irrigation * Age Class	5	2.03	0.407	2.23	0.0485
Precipitation Class	2	1.87	0.933	5.06	0.0064
Soil * Precip Class	8	0.474	0.059	0.32	0.9583
Irrigation * Precip Class	2	0.168	0.084	0.46	0.6335
Soil * Irrigation * Precip Class	8	0.997	0.124	0.68	0.7133

Table S-10. Normalized mean values for incremental width across all sampled trees (n = 200) stratified into three precipitation classes.

Soil Type	**Irrigation**	**Precipitation Classes**	**Increment Width (cm)**
Autryville	Yes	Low	0.900 (0.329)
		Average	0.858 (0.366)
		High	0.940 (0.365)
	No	Low	0.973 (0.444)
		Average	0.903 (0.374)
		High	0.900 (0.423)
Baymeade	Yes	Low	1.05 (0.436)
		Average	0.990 (0.429)
		High	1.01 (0.466)
	No	Low	0.967 (0.391)
		Average	0.906 (0.426)
		High	0.911 (0.368)
Foreston	Yes	Low	1.01 (0.434)
		Average	1.04 (0.523)
		High	0.955 (0.428)
	No	Low	0.958 (0.387)
		Average	0.858 (0.401)
		High	0.889 (0.397)
Norfolk	Yes	Low	1.01 (0.411)
		Average	0.946 (0.384)
		High	0.979 (0.482)
	No	Low	1.04 (0.498)
		Average	0.979 (0.444)
		High	0.989 (0.424)
Stallings	Yes	Low	1.03 (0.433)
		Average	1.01 (0.369)
		High	0.949 (0.421)
	No	Low	1.03 (0.436)
		Average	0.984 (0.439)
		High	1.01 (0.498)

Table S-11. Table of values for NRCS soil fertility estimates, predicted site index, and stumpage value differences from Use Manual Estimates for eastern NC. An asterisk (*) represents a soil fertility measure that was exceeded on the LTS.

Soil + Irrigation	K kg/ha	Mg kg/ha	Ca kg/ha	SI_{25} Estimate	Value Difference from $7,183
Autryville Irrigated	12.5 - 88.9	38.4 - 499	320 - 1024 *	70	$90.29
Autryville Nonirrigated					$623.82
Baymeade Irrigated	38.4 - 115	125 - 750	704 - 1056 *	62	-$3,483.50
Baymeade Nonirrigated					-$2,585.30
Foreston Irrigated	12.5 - 250	76.8 - 230	384 - 1152 *	59	-$1,634.31
Foreston Nonirrigated					$743.87
Norfolk Irrigated	100 - 500	115 - 307	857 - 2755	65	-$2,579.97
Norfolk Nonirrigated					-$725.63
Stallings Irrigated	12.5 - 250	38.4 - 499	704 - 1075 *	57	$3,103.39
Stallings Nonirrigated					-$964.40

Raw data tables can be publicly accessed at

https://drive.google.com/drive/folders/1XBKa0sHpnYzH5x90e74aTTdB2xk8aC_a