



Loblolly pine site index and mean annual increment estimates by soil classification in the Coastal Plain

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SUMMARY

Site index estimates have been used by private timber producers for decades. These estimates are used to predict the growth rates of specific tree species or genera in natural stands or plantations. Occasionally, estimates have been created for specific soil types or associations. Private non-industrial forest landowners are the primary owners of forest land in the southeastern U.S., and publicly available soil productivity estimates are primarily used by them and private consulting foresters. Loblolly pine (*Pinus taeda*) is the most significant timber species in the Southeast and publicly available site index estimates were originally developed for the Coastal Plain region decades ago by the United States Department of Agriculture (USDA) Forest Service. Due to more advanced forest management practices and the advent and prevalence of planted stands, these estimates are outdated. This study, which was funded by the Natural Resources Conservation Service (NRCS), aims to update soil productivity site index and mean annual increment estimates for loblolly pine in the Southeast by Cooperative Research in Forest Fertilization (CRIFF) soil groups with modifications to two of the groups. Updated estimates will provide forest landowners with the best data for making informed management choices.

INTRODUCTION

The southern United States is a significant producer of timber for the global marketplace, with 51% of all US lumber being produced in the South, as of 2017 (Howard and Liang, 2019). The Southeast is a particularly productive region. In 2022, over 2.5 million cubic feet (MCF) of lumber was produced by Florida, Georgia, and South Carolina alone (USDA Forest Service, 2024). Of this, 18% was produced in Florida, 30% in South Carolina and 52% in Georgia. Forestland in the Southeast is primarily privately owned (86% in 2019), and two-thirds of this area is owned by non-industrial, private forest landowners (NIPFLs) (Oswalt and others, 2019; Butler and Wear, 2013). The acreage owned by NIPFLs is one factor that makes individual forest-owner management decisions highly influential on forestry practices in the Southeast.



The majority of industry owned forestland has become intensively managed. Management may include: chemical and mechanical site preparation, post-plant herbaceous weed control, fertilization, midrotation competition control, and other cultural practices. This trend has followed for NIPFLs, although they tend to undertake less-intensive management due to economic reasons. As part of this management, foresters and landowners use site productivity assessments to inform decisions such as optimal rotation age, regeneration cutting strategies, and species selection for planting. Site index (SI) is the most commonly used metric to assess site productivity and is quantified by the average dominant or codominant tree height in a stand at a given base age (Geyer and Lynch, 1987). Site index is defined as “a measure of actual or potential productivity for a single species or a group of species expressed in terms of average height of a certain number of codominant and dominant trees in the stand at an index age after (usually 25 or 50 years) (Geyer and Lynch, 1987). Site index is based on tree height instead of diameter because diameter growth is heavily influenced by competing vegetation and stand stocking. Site index for planted pine stands is usually expressed as base age 25 years, while natural stands are base age 50 years with base age 25-year estimates being much more common for loblolly pine. Site productivity, in terms of stem volume, varies over time and can be measured using mean annual increment (MAI). Mean annual increment is calculated for unthinned stands by dividing the total stand volume (or weight) by the age of the stand. Stand density, measured in trees per acre (tpa) can greatly impact MAI.

Private forest landowners and forest managers need estimates of MAI and SI to make informed management decisions regarding species selection based on soil types, growth and yield, and rotation ages. The most readily accessible SI and MAI data for private landowners and consulting foresters is contained in the Natural Resources Conservation Service’s (NRCS) Web Soil Survey website (NRCS, 2019). The loblolly pine SI and MAI estimates that are available on Web Soil Survey were developed during the early 1950s for naturally regenerated stands (Coile and Schumacher, 1953a; 1953 b). There have been significant changes in loblolly pine productivity and management practices over the past 70+ years, so these estimates are no longer accurate. These improvements include stand fertilization, site-specific mechanical and chemical site preparation, post-plant herbaceous weed control, genetically improved seedlings, and midrotation management, which all have led to shorter rotations. Environmental factors such as increased temperature, atmospheric CO₂, and N deposition have likely contributed to productivity increases. Site index and MAI estimates must be updated to keep up with changes in forest management. This paper describes a study conducted to update SI and MAI estimates for planted loblolly pine stands in the Coastal Plain region of Georgia with applicability to similar Coastal Plain soils in neighboring states.

There are many qualities by which to classify soils. Trees require three essential resources for growth: sunlight, water and nutrients. Soil provides trees with two of three essential resources. These resources for vegetation growth are water and nutrients. The University of Florida’s Cooperative Research in Forest Fertilization (CRIFF) soil classification system groups soils based on soil drainage class, presence/depth to an argillic (Bt) horizon (small increase in clay content which slows soil water infiltration and increases nutrient availability), and the presence/depth to a spodic (Bh) horizon (Jokela & Long, 2018). This system is used to group Coastal Plain soils into eight categories (H, A, B, C, D, E, F, and G) to assist with species selection for planting efforts and management decisions such as fertilization. Pines generally are not planted on CRIFF H soils. Soil groups and their qualities are described in Figure 1.

CRIFF Forest Soil Classification

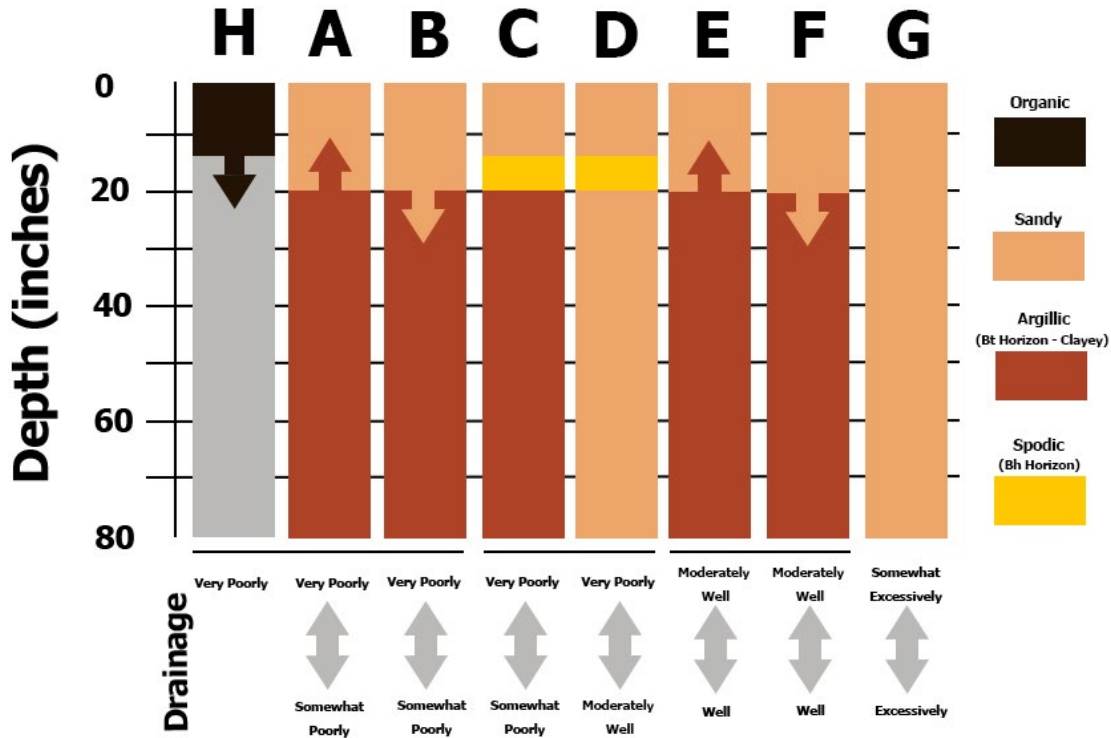


Figure 1: A method of classifying soil types based on the University of Florida’s Cooperative Research in Forest Fertilization (CRIFF) classification system. This system of classifying soils was specifically created for soils in the Coastal Plain region of northern Florida and southern Georgia. The figure was redrawn from Jokela and Long (2018).

The most important timber species in the Southeast is loblolly pine. Loblolly pine forest types are dominant on over approximately 61 million acres in 12 southeastern U.S. states and comprise over half of all standing pine volume (USDA Forest Service, 2025; Baker and Langdon, 1990). The natural range of loblolly pine covers the southeastern U.S. from eastern Texas through Delaware (Figure 2). Profitable and sustainable management of loblolly pine requires a great deal of environmental information, including estimates of SI and MAI on a given soil type. The following will summarize a research paper by Zhao et al., (2024a) which calculated SI and MAI estimates based on modified CRIFF soil types for loblolly pine stands with operational management (i.e., chemical and mechanical site preparation, first- or second-year herbaceous weed control, open-pollinated loblolly pine genetics, and preferably no history



Figure 2: The native range of loblolly pine. Maps courtesy of the Silvics of North America (Baker and Langdon, 1990).

of fertilization) in the Coastal Plain region.

METHODS

This study used a modified version of the CRIFF soil classification system which splits groups “B” and “F” into three subgroups each. All other CRIFF groups were unaltered for classification purposes. The subgroups were categorized based on observed depth to the Bt horizon. If the Bt horizon was between $\geq 20-40$ ”, it was grouped as B1 or F1, $\geq 40-60$ ” Bt horizon was classified as B2 or F2, and $\geq 60-80$ ” Bt horizon was either B3 (the B3 class also included no Bt through 80” with Fluvaquents being a common example) or F3. This was incorporated into the CRIFF soil classification system because the depth to the Bt horizon is a significant factor for individual tree growth as it slows water infiltration from sandier textured overlying horizons and has more nutrient holding capacity than overlying E or A horizons (if present). The modified CRIFF soil groups are A, B1, B2, B3, C, D, E, F1, F2, F3, and G. Soils were classified into the modified CRIFF soil groups by soil drainage class, the presence/ depth of an argillic (Bt) horizon, and presence/ depth to a spodic (Bh) horizon. Depth to seasonal high-water table and depth to chroma ≤ 2 (a gray soil color produced by reduced iron indicating a wet soil condition for part of the year) were also tallied in each plot. The modified CRIFF soil groups and their qualities are shown in Figure 3. Soil profile delineation was conducted by NRCS soil scientists and to a lesser extent by UGA personnel.

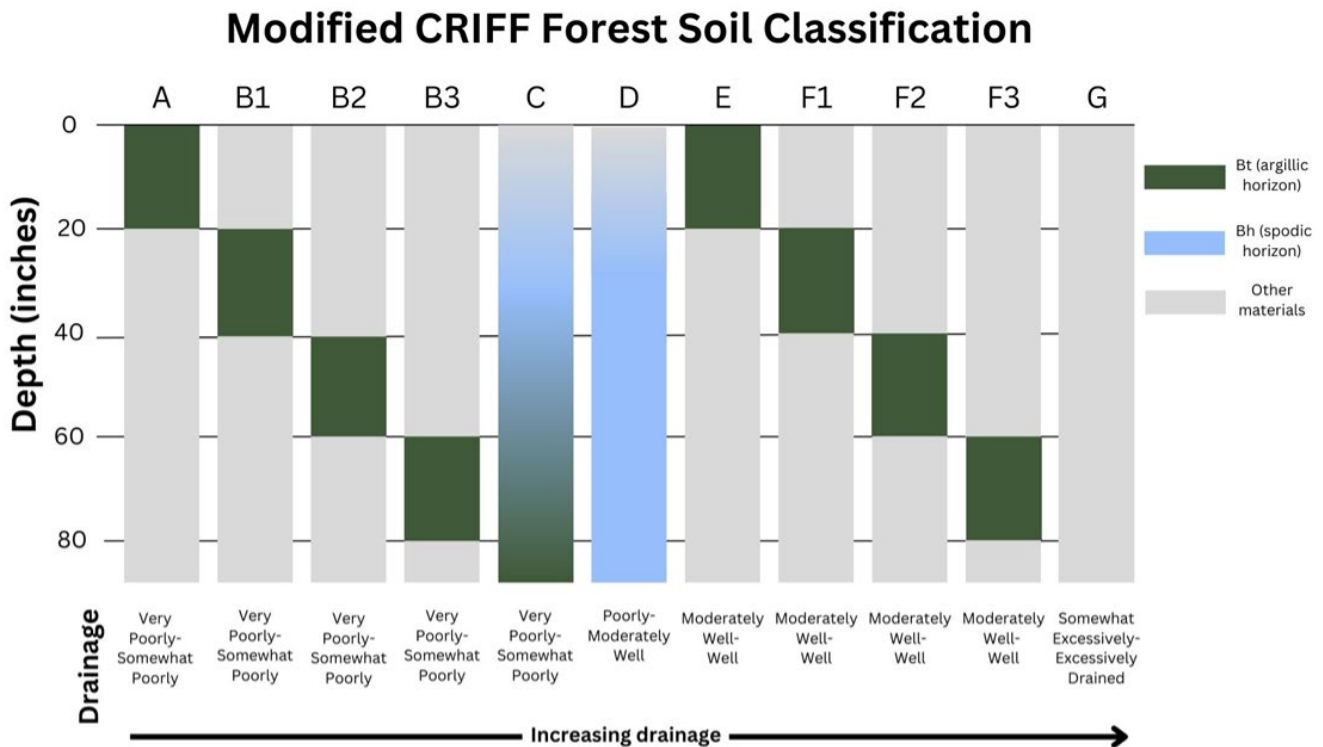


Figure 3: The modified University of Florida Cooperative Research in Forest Fertilization (CRIFF) soil classification system used in the site index and mean annual increment analyses. Soils are sorted by increasing drainage, and argillic/spodic horizon depths are noted in green and blue, respectively. The H classification is excluded because it is not suitable for pine growth.

STUDY AREAS

A total of 139 plots were inventoried for the study, and 126 were used in analyses. All plots were in Georgia, located on NIPFLs’ properties, state-owned land, or forest industry land, but most of the plots are on privately owned land. The plots are spread across the Coastal Plain of Georgia with the northernmost plot located in Baldwin County and the southernmost plot in Echols County. Plot locations are shown in Figure 4. The University of Georgia’s Plantation Management Research Cooperative (PMRC) Coastal Plain culture and density (CPCD) study sites are included because data from 15 installations were used for comparison to this study for SI and MAI estimates by CRIFF soil groups.

The CPCD study was conducted by the UGA PMRC at 15 installations within the Lower Coastal

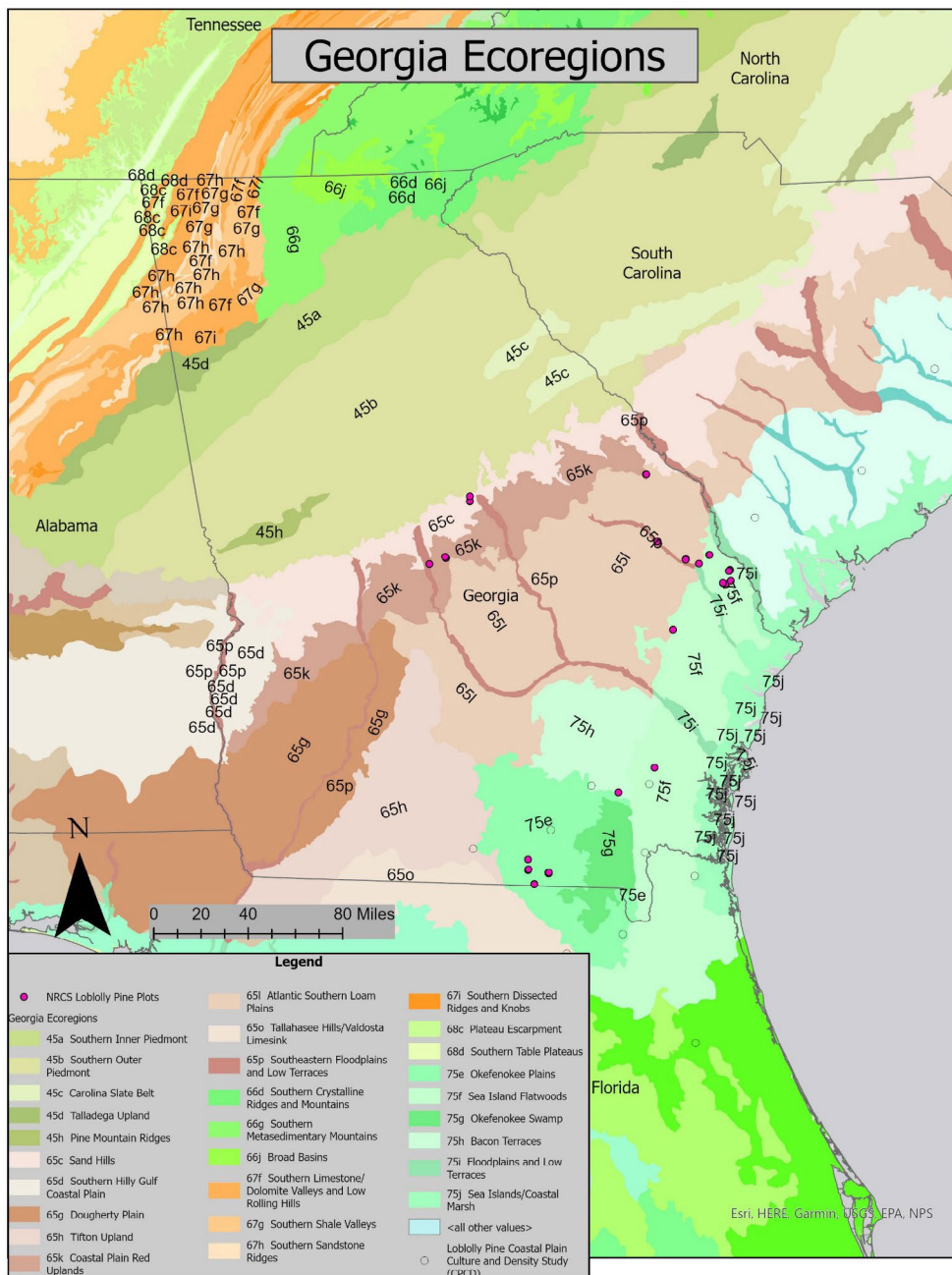


Figure 4: Plots included in the Natural Resource Conservation Service (NRCS) and Coastal Plain culture and density (CPCD) study locations in Georgia, Florida, and South Carolina. This paper is focused on the NRCS study which had plots located only in Georgia; NRCS plots are symbolized by pink circles and loblolly pine CPCD installations by hollow circles. Georgia Ecoregions are overlaid with loblolly and slash pine NRCS/ CPCD plots and installations (Griffith and others, 2001).

Plain in South Carolina, Georgia, and Florida. All locations had one of five CRIFF soil groups (A, B1, B2, C, and D). Unlike the NRCS study, the CPCD study combined soil groups B2 and B3 into B2. There were two levels of treatment (intensive and operational). The intensive management regime was not used for comparison purposes with the NRCS plots. The operational management included adding bedding, banded chemical site preparation, herbaceous weed control treatment at the beginning of the first growing season, fertilization at planting (500 lb/ac 10-10-10, i.e., 50 lb/ac N + 21 lb/ac P + 41 lb/ac K), and N+P fertilization (200 lb/ac N + 25 lb/ac P) during the 8th, 12th, and 20th growing seasons. Productivity results (SI and MAI) from CPCD operational management stands were used for comparison to the NRCS study results, as the management practices to approximate the upper limits for loblolly pine productivity given the multiple fertilization treatments. The CPCD stands had been measured biennially for 24 years. With high fertilizer prices since 2022 and static stumpage prices, most NIPFLs cannot cost justify multiple fertilizer applications but the UGA CPCD study illustrates that multiple fertilizer applications can significantly improve loblolly pine growth. Comparing NRCS results to CPCD operational results allowed researchers to verify the accuracy of NRCS findings by comparing them to a longer-term loblolly pine experimental study in the same region.

The climate type of southeastern Georgia is considered humid subtropical, with short winters and long hot summers. Across the state on average, temperatures exceed 95°F between 1 and 20 days per year depending on location. Average annual precipitation ranges from ~45 inches to ~70 inches across the state (Frankson et al., 2022). Stands used in the study were located in two Major Land Resource Areas (MLRAs), which are characterized by a particular combination of soil, water, climate, vegetation, and land use (United States Department of Agriculture 2022). The two MLRAs are the Southern Coastal Plain and Atlantic Coast Flatwoods. These MLRAs covered five recognized ecoregions: Southeastern Plains Sand Hills, Coastal Plain Red Uplands, Atlantic Southern Loam Plain/ Vidalia Upland, Sea Island Flatwoods, and Okefenokee Plains. Each ecoregion has specific soil and environmental conditions, which are described in Table 1.

Table 1: The ecoregions in which loblolly pine site index and mean annual increment study stands were located, the landform characteristics of the ecoregions, and the percentage of plots that are within the ecoregion.

Ecoregion	Landform characteristics	Percent of stands in ecoregion
Southern Coastal Plains Sand Hills	Dissected landscape consisting primarily of low-nutrient sandy soil with some loam or clay soil layers (E, F1, F2, F3, and G soil groups primarily)	7.4%
Coastal Plain Red Uplands	Well-drained loamy/sandy surface layer soils with red subsoils (E, F1, F2, F3, and G soil groups primarily)	15.7%
Atlantic Southern Loam Plain	Flat to gently rolling topography with fine textured soils	20.7%
Sea Island Flatwoods	Flat plains with mostly poorly drained Spodosol soils (C and D soil groups), but some better drained Ultisols soils occur (E, F1, F2, and F3 soil groups)	33.9%
Okefenokee Plains	Flat plains and low terraces with somewhat-poorly to poorly drained soils (A, B1, B2, and B3 soil groups); spodosols (C and D soil groups) are common.	22.3%

PLOT CHARACTERISTICS

This study consisted of 126, 1/10th ac circular plots. Plot centers were typically arranged in sets of three to nine plots (usually no more than 132 ft apart) per stand, depending on the similarity of soil and competing vegetation conditions across stands. There were six plots which had been progeny test areas (afforested old-field sites), nine plots that were believed to be former old-fields (in annual agricultural crops) due to high (> 5 to 10 parts per million; ppm, with most ≥ 10 ppm) surface soil Mehlich 1 phosphorus (P), and the rest were cutover sites (previously forested for one or more rotations). Stands with inventoried plots received site preparation, in the form of chemical, mechanical, or both. Stands ranged between 7 and 29 years old. Most of the plots were unthinned (93), and the remaining plots were thinned (25) (Figure 5). Stand density ranged from 469 to 1,489 tpa. Within the 1/10th acre plots, two or three randomly located 1/100th acre circular plots were sampled to assess woody competition (hardwood trees, shrubs, and wilding pines).



Figure 5: *Example of a 13-year-old, unthinned loblolly pine stand plot in Effingham County, GA, used to estimate site index and mean annual increment. This plot occurred on the B2 modified Cooperative Research in Forest Fertilization (CRIFF) soil group.*

FIELD MEASUREMENT

The following information was collected for each plot:

- Location (latitude and longitude coordinates)
- Planting date (mo, yr)
- Bedding status (binary; Y, N)
- Thinning status (binary; Y, N)
- Between and within row spacing recorded to determine initial planting density
- Diameter at breast height (dbh) and total height for planted pines
- Stem densities and heights for woody competition (stems greater than 1" dbh) and percent cover (stems less than 1" dbh) were documented in two or three 1/100th ac circular plots nested within the 1/10th ac inventory plot to obtain a plot average as woody vegetation density often varied within plots.
- Surface soil (0-6") was sampled at six to eight spots within the 1/10th ac plot for one composite soil sample.
 - Testing for pH was completed using the CaCl₂ test and Mehlich I extraction method for P, K, Ca, Mg, Mn, and Z.
- Soil profile data collected by NRCS soil scientists
 - Presence and depth to Bt horizon (≥ 1.2 times as much clay as overlying horizons or 3% more clay than the eluvial layer if <15% clay), Bh horizon, depth to seasonal high-water table, chroma ≤ 2 , and soil series description reported drainage class (Figure 6)
 - Data used to group soils into modified CRIFF groups



Figure 6: Example of a Cooperative Research in Forest Fertilization (CRIFF) C soil profile with a spodic (Bh) horizon and an underlying argillic (Bt) horizon. Hole was augered to a depth of 80".

Table 2: Summary information for variables collected at inventoried plots, including Cooperative Research in Forest Fertilization (CRIFF) soil group, number of plots, age range, mean age, soil phosphorus (M1-P) range, and soil phosphorus (M1-P) average. Plots with a M1-P value >10 ppm were considered old-field sites.

Species	Modified CRIFF soil group	Number of plots	Age (years)		M1-P (mg kg ⁻¹) ^{1, 2, 3}	
			Range	Mean	Range	Mean
Loblolly pine (n=118)	A	12	8 - 27	21.0	1.7 - 5.8	3.4
	B1	13	9 - 28	20.6	1.6 - 8.6	3.6
	B2	2	9 - 28	18.5	2.2 - 3.1	2.6
	B3	10	9 - 25	17.2	2.4 - 48.5	11.0
	C	20	13 - 28	22.0	1.2 - 3.2	2.0
	D	4	13	13.0	0.8 - 1.3	1.1
	E	19	7 - 21	11.5	2.5 - 86.5	31.5
	F1	15	7 - 21	12.5	2.4 - 48.7	20.0
	F2	5	7 - 20	14.8	3.5 - 24.5	11.2
	F3	6	20 - 23	21.5	4.0 - 15.6	8.4
	G	12	20 - 29	25.1	8.4 - 54.5	30.1

¹Multiply mg kg⁻¹ by two to get lb/ac at a 6.67 in soil depth (acre-furrow-slice).

² Surface soil M1-P levels below 5 mg/kg which is approximately equal to parts per million; ppm (10 lb/ac assuming a furrow acre slice of soil weighs 2 million lbs) are critical for CRIFF soil groups A, B, and C, and have a high probability of response with the addition of P, preferably at planting.

³ Soil M1-P is used as an indicator of site fertility on the remaining CRIFF soil groups.

SITE PRODUCTIVITY

Site index (SI) was estimated using the average height of dominant and co-dominant trees at base age 25 years old. For this analysis, dominant and codominant trees were defined as those with a DBH greater than the average DBH of trees in an unthinned stand, or the tallest 80% of trees in thinned stands. Mean (real from the measured tree data, not predicted) loblolly pine SI values as well as CPCD estimated (predicted) SI values are found in Figure 7.

This study utilized the proprietary UGA PMRC loblolly pine site index model (Borders and others, 2014). The following variables were used to explain loblolly pine site index estimates: modified CRIFF soil group (as dummy variable), concentrations of Mehlich I P (MI-P milligrams/kilogram; mg/kg = ppm), presence/depth to an argillic horizon, presence/depth to a spodic horizon, presence/depth to a seasonal high-water table, presence/depth to chroma ≤ 2 (a gray soil color from iron being reduced due to wet conditions). The dependent variable (SI values) was regressed against these variables.

Predicted (using the predicted NRCS and base CPCD SI values) mean annual increment of green weight starting at stand age five years and estimated at five-year increments prior to the first thinning was calculated by soil group and different planting spacings. The PMRC loblolly pine growth and yield simulator was used to estimate green weight ($t\ ac^{-1}$) MAIs at ages 10, 15, and 20 years by CRIFF soil group for three different planting densities (500, 600, and 700 surviving tpa at age 5-years) (Borders and others, 2004, 2014). The loblolly pine 'operational management' CPCD study inventories through stand age 24 years and 600 tpa (closest CPCD study planting density to most operational plantings) was used to simulate NRCS plot data MAI estimates. Individual tree outside-bark stem green weight was calculated using equations updated by Zhao and others, (2024b):

$$Loblolly\ GW\ (lb)\ outside\ bark = 0.0872 * DBH^{1.8956} HT^{1.1692}$$

RESULTS

The regression analysis found that two of the tested variables were significant predictors of SI: the modified CRIFF soil group and the surface soil Mehlich I P (M1-P) value in mg/kg (an estimate of soil available P). Modified CRIFF soil groups and soil P accounted for 89.9% of variation in loblolly pine SI estimates. There was an interaction detected between the soil groups and M1-P. This was most evident on B3, E, F1 and F2 soils where there were large surface soil M1-P differences. On these soils, with an M1-P value < 6.2 mg/kg, the mean SI was 81.4 ft. When M1-P was 6.2 mg/kg or greater, the same soil groups had average heights of 85.3 ft at age 25 years. This means that surface soil M1-P, used as an indicator of site (in these cases the plots) fertility, correlated well with improved growth when above a specific threshold concentration for loblolly pine growth on some Coastal Plain soils.

Loblolly pine had varying SI depending on the soil type. The average SI (in feet) by modified CRIFF soil group is shown, and the operational CPCD study results are indicated by orange bars for soil types A-D for comparison in Figure 7. The most productive soil types for loblolly were B3, B1, F1, E and B2 (in decreasing order of average site index). The least productive soil types were C, F3, D, and G, from highest to lowest average site index. CRIFF soil types A and F2 were intermediately productive.

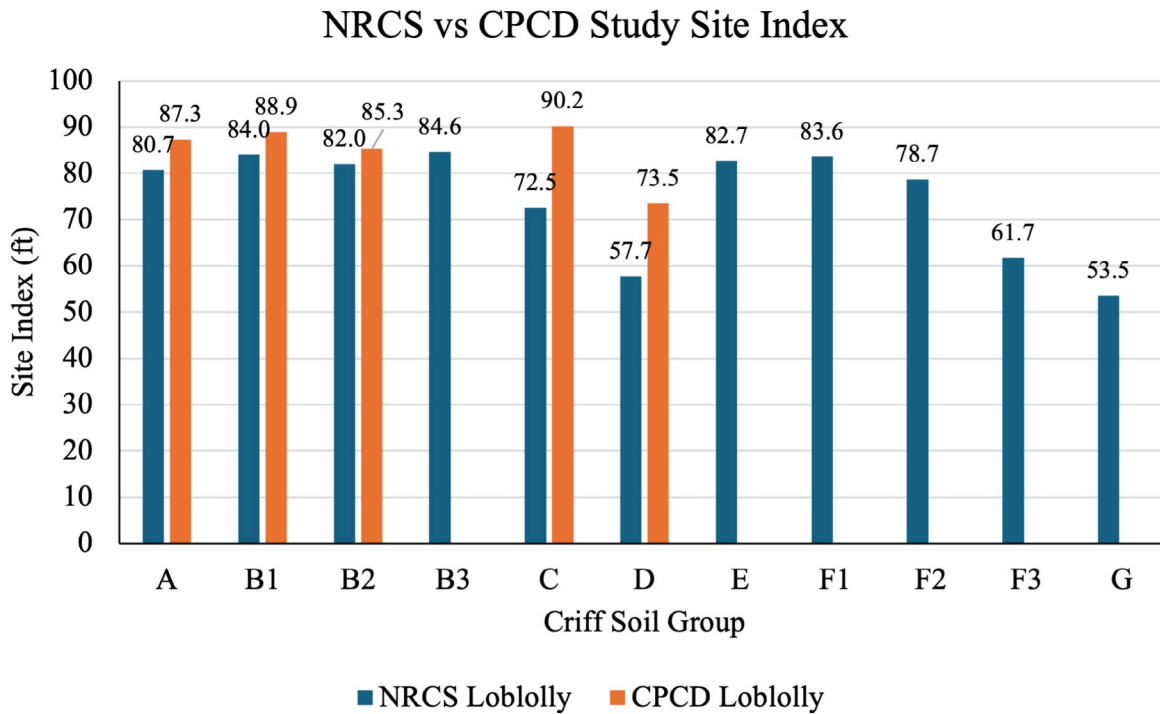


Figure 7: Mean site index values in feet for loblolly pine stands on different modified Cooperative Research in Forest Fertility (CRIFF) soil groups. Natural Resources Conservation Services (NRCS) study estimates are blue bars, and Coastal Plain culture and density (CPCD) study estimates are orange bars for comparison, where data were available for specific soil groups.

The NRCS and CPCD study estimated (predicted) SI values were used to simulate (model) estimated green stem weight MAI by soil group. The PMRC loblolly pine growth and yield simulator was used. CRIFF soil groups by average green weight MAI are listed from highest to lowest:

$$B3 > [B1, F1] > [B2, E] > F2 > A > C > F3 > D > G$$

The estimated MAIs were projected at stand ages 10-, 15-, and 20-years for three different surviving trees per acre at age 5-years (500, 600, and 700 trees per acre). The projected results are depicted in Figure 8.

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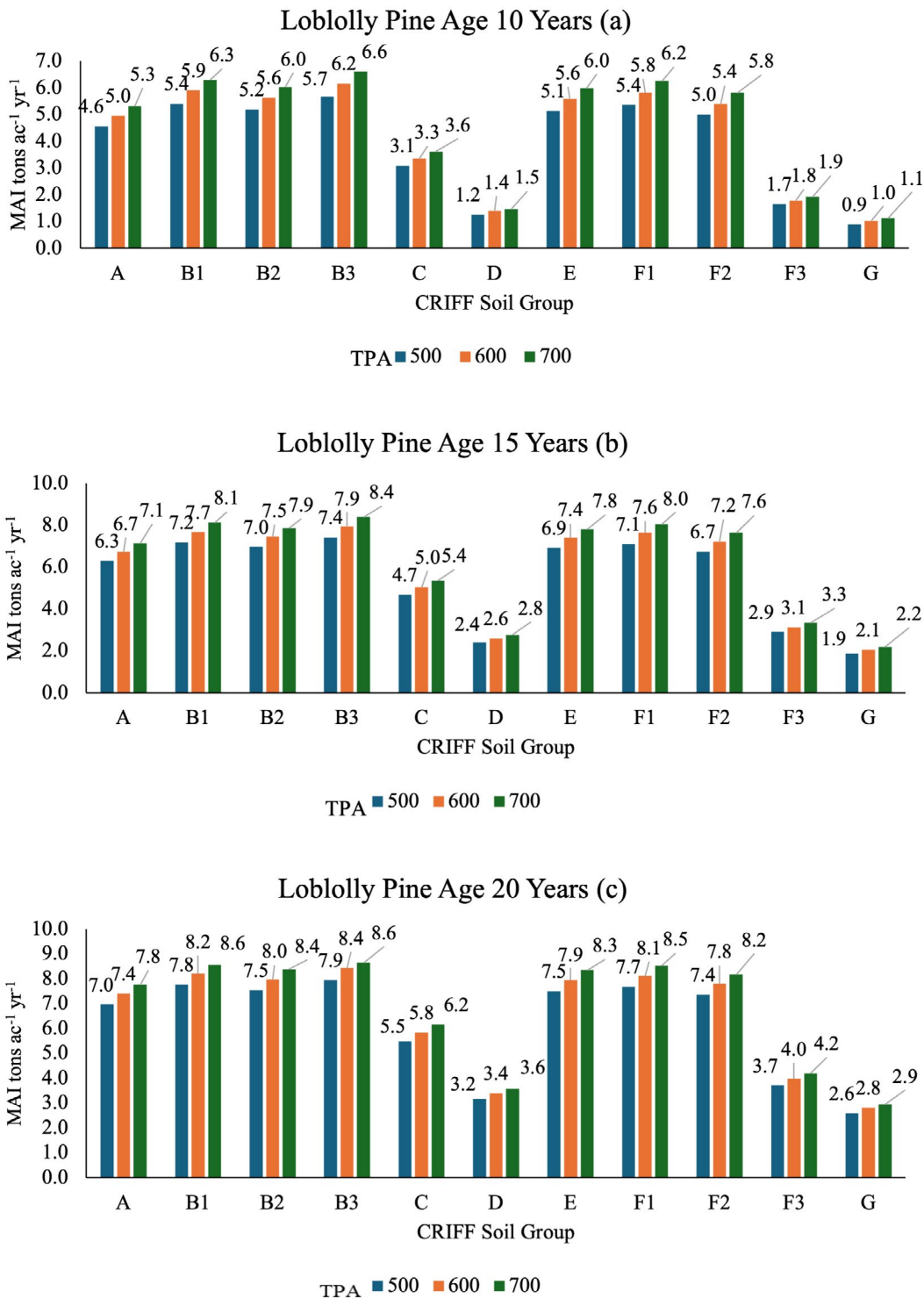


Figure 8: The modeled mean annual increment (MAI) in tons/acre/year by Cooperative Research in Forest Fertilization (CRIFF) soil group. Results are projected from age five years using the estimated Natural Resources Conservation Service (NRCS) study and base Coastal Plain Culture Density (CPCD) study site index values for stands at stand ages 10 (a), 15 (b), and 20 years (c). The bar colors represent different densities of 500 (blue), 600 (orange), and 700 (green) trees per acre surviving at age 3-years.

Woody vegetation competition was assessed on each plot, and analysis revealed significant differences by soil group. CRIFF groups A, B2, C, D, E, F1, and F2 had low hardwood competition, while soil groups B1, B3, F3, and G had high woody competition. High woody competition was correlated with a decrease in SI, although low woody competition did not ensure a higher SI value.

CONCLUSION

Overall, CRIFF groups B (B1, B2 and B3), E, F1, and F2 consistently rank as the most productive soil types for loblolly pine. Alternatively, groups C, D, F3, and G were the least productive, and group A was intermediate, most likely due to low surface soil M1-P. The most likely reason why soil group A SI was intermediate was only one of the 12 plots in this group had a surface soil M1-P level greater than 5 mg/kg (5.88 mg/kg), while the remainder were below the critical threshold of 5 mg/kg (Ballard and Pritchett, 1975). When CRIFF soil group A surface soil M1-P levels are less than 5 ppm, the addition of P at planting significantly improves loblolly and slash pine growth (Ballard and Pritchett, 1975; Pritchett and Comerford, 1982; Gent and others, 1986). For F-type soil groups, an increase in depth to top of the Bt horizon corresponded to a decrease in SI for loblolly pine. Soil type B was inconclusive in this trend. Analyses revealed that site index and soil P were not correlated for CRIFF groups A, B3, C, D and F3 (with A, C, and D, 35 of 36 plot's soil M1-P levels were below the critical threshold of 5.0 mg/kg). Available soil P and SI had strong positive correlations for soil types B1, B2, E, F1, F2, and G, meaning that increases in soil P (used as a critical threshold value for B1 and B2 and as an indicator of site fertility for the upland soils; E, F1, F2, and G) led to increased SI.

Even on less productive soils, SI can be improved. Loblolly pine is very responsive to fertilization on C and D soils, according to the CPCD study. In that study, SI increased by 17.7 (C) and 15.8 ft (D), respectively. There were 6.6, 4.9, and 2.6 ft increases in SI on CRFF A, B1, and B2, respectively, due to intensive management practices that included multiple fertilizer treatments. MAI was increased on B1 and D soils prior to stand age 15 years with intensive management, but values tended to flatten after stand age 15 years likely due to density dependent mortality. Research has shown that MAI on CRIFF A and C could be sustained throughout the rotation with intensive management. Although improved management techniques can increase productivity, loblolly pine should not be the favored pine species on CRIFF D (without fertilization), F3 (longleaf pine sites; where Bt >60"), and G (longleaf pine sites) soils.

The observed SI values for this study (NRCS) differed from those observed in the CPCD study. The NRCS SI estimates were markedly (on CRIFF C, 17.5 ft; CRIFF D, 15.8 ft) to modestly lower (on CRIFF A, 6.6 ft; B1, 4.9 ft; and B2, 2.6 ft) than those observed in the CPCD study, but the values for this study more so reflect what might be observed with operational management on NIPFL property. Due to the high price points, these vegetation management (to a lesser extent) and especially multiple fertilization treatments may be unrealistic for private landowners along with containerized, higher-cost seedling genetics such as closed-pollinated (full-sib) families. The NRCS SI values may be more reasonable to expect for private and family forest owners under the management and seedling genetics scenarios often used on these lands. These updated estimates should provide better estimates for landowners to project SI and MAI for loblolly pine on their specific soil types and to correctly match loblolly pine to soil groups.



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