



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

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SUMMARY

Timber producers and private forest owners have used site index estimates for decades to predict tree growth rates for specific tree species or genera and, occasionally by soil types. Slash pine (*Pinus elliottii*) estimates were originally described for natural stands in the Georgia Coastal Plain by U.S. Department of Agriculture (1929), Bennett and others, (1959), and McGee (1961). There have been significant changes in forestry over the past 65+ years, making these estimates no longer accurate. This study, funded through a cooperative agreement by and with the Natural Resources Conservation Service (NRCS), the UGA Research Foundation and the Warnell School of Forestry and Natural Resources aimed to update soil productivity estimates for slash pine in the southeastern Coastal Plain. At each of 157 inventory plots, this project recorded important soil parameters that relate to soil water and nutrient relations, two of the three essential requirements of trees (the third essential requirement being sunlight). Publicly available soil productivity estimates are used mainly by private forest owners, who are the primary owners of forest land in the southeastern U.S and consulting foresters. More accurate tree species site index estimates provide forest owners and managers with the best possible information for decision making.

INTRODUCTION

The Southeast is commonly referred to as the timber basket of the U.S. Approximately 51% of U.S. timber is produced in the Southeast as of 2017 (Howard & Liang, 2019). Based on the 2005 Resources Planning Act Timber Assessment, 66% of all timber harvested in the Southeast in 2002 was from non-industrial private forest landowners (NIPFLs). This is expected to remain the same in their 2030 projection (Haynes and others, 2007). As of 2013, 86% of forest land in the region is privately owned, and two-thirds of this is owned by NIPFLs (Butler & Wear, 2013). Because of this, the individual land management practices of private forest owners shape forest sustainability and productivity for the entire region.

Slash pine (*Pinus elliottii*) is an important timber species in the Coastal Plain, and it is the dominant species on about 4.5 million acres in the South (McConnell, 2023). It is valued due to its fast growth, tolerance to drought, fire, and shade, and use for specific timber products including lumber, poles, gum naval stores, and fiber. Slash pine is naturally found in poorly drained flatwoods and along streams. The species can perform well in seasonally flooded areas (Barnett & Sheffield 2004). The natural range of slash pine extends from South Carolina southward to central Florida and westward to Louisiana, with some sparse populations in Texas (Figure 1). The range of slash pine has been extended due to tree improvement programs and planting outside of its native range. Today, it can be found from South Carolina to Texas and along the Gulf Coast of the U.S.

Non-industrial private forest landowners utilize many sources of publicly available data to make informed management decisions on their land. Important information includes soil profile data, hydrology and weather patterns, and species productivity estimates. The latter is particularly useful, as productivity estimates by soil type and species can give forest owners a realistic expectation of stand growth and productivity over a certain period of time (most often 25 years for planted stands and 50 years for natural stands) and pine species selection. Stand productivity is commonly assessed using site index (SI), which is defined as “a measure of actual or potential productivity for a single species or a group of similar species expressed in terms of average height of a certain number of codominant and dominant trees in the stand at an index age” (Geyer & Lynch, 1987). Site index is expressed as the average height (a measure of productivity) of a certain number of dominant and codominant crown class trees at an index age (e.g., 25 years for pine plantations). Site index is based on tree height instead of diameter because diameter growth is heavily influenced by competing vegetation and stand stocking. Site index alone is not a perfect estimation, as it does not include the natural variation in stand productivity over time. Mean annual increment (MAI) is the total weight or volume (often expressed as green tons or cubic feet volume per acre) increment of a stand up to a given age, divided by that age. It is valid for unthinned stands and is affected by stand density, measured in trees per acre (tpa).

Estimates of SI for slash pine by soil type were first produced in 1929 by the U.S. Forest Service and were later updated for Georgia during the late 1950s and early 1960s by the U.S. Forest Service Southeastern Forest Experiment Station (U.S. Department of Agriculture, 1929; Bennett and others. 1959; McGee, 1961). The Natural Resources Conservation Service’s (NRCS) Web Soil Survey website has the most easily accessible forest productivity data (NRCS, 2019). The NRCS productivity table footnotes for slash pine state that estimates are from even-age, fully stocked, unmanaged stands. However, there have been significant changes in forest management practices and technologies, meaning that estimates from 65 years ago are no longer accurate. Site-specific mechanical and chemical site preparation, forest fertilization, genetically improved seedlings, and midrotation tending have led to reduced stand rotation ages and greater productivity (wood volume growth). Environmental factors such as increased temperature, atmospheric CO₂, and N deposition have likely contributed to productivity increases. For the most realistic estimates, NIPFLs need new, updated SI estimates, which account for improved practices and increases in productivity.



Figure 1: The native distribution of slash pine (*Pinus elliottii*). Maps courtesy of the *Silvics of North America* (Lohrey & Kossuth, 1990).

One of the most important factors in determining stand productivity is soil characteristics. Soil provides water and nutrients to the tree, both of which are variable depending on soil type. One method to organize and group soils in the Coastal Plain for management decisions, including species selection and fertilization decisions, was developed by the University of Florida and called Cooperative Research in Forest Fertilization (CRIFF) (Jokela and Long, 2018). This classification system uses the soil drainage class, the presence/depth to the argillic (Bt) horizon, and the presence/ depth to the spodic (Bh) horizon. The CRIFF soil groups are H, A, B, C, D, E, F, and G. Pines are not planted on CRIFF H soils. The different soil groups and their qualities are displayed in Figure 2.

CRIFF Forest Soil Classification

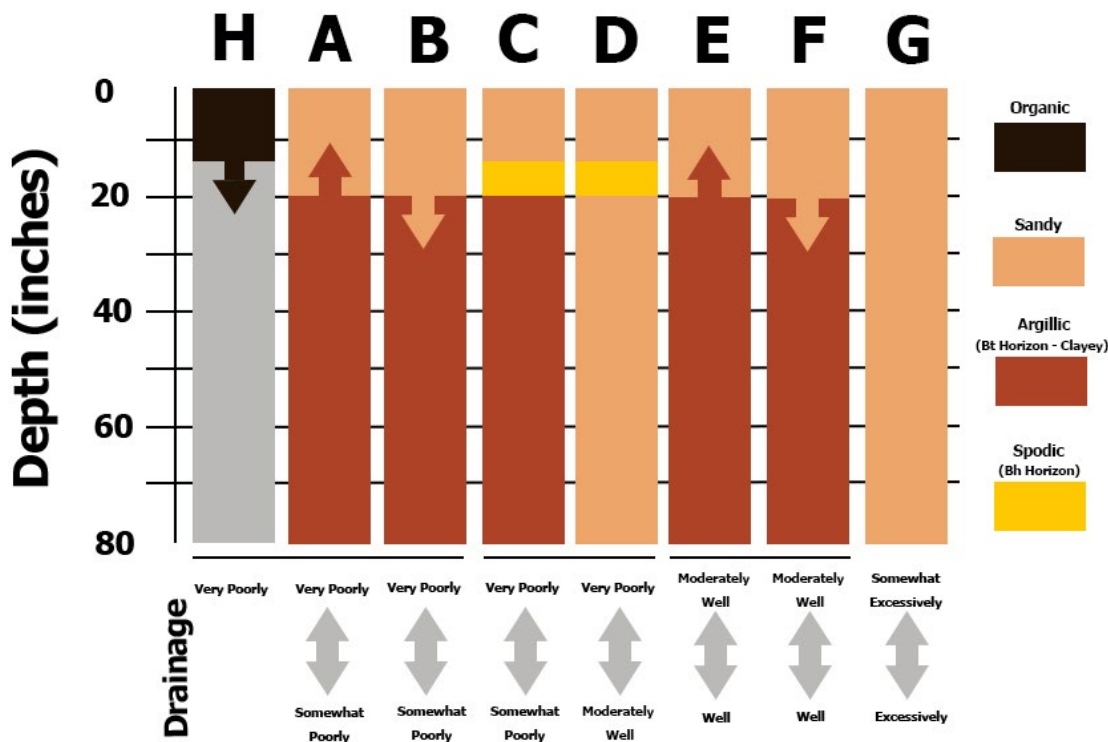


Figure 2: The Cooperative Research in Forest Fertilization (CRIFF) soil classification system, developed by the University of Florida specifically for the Coastal Plain region of southern Georgia and northern Florida. Figure redrawn from Jokela and Long (2018).

METHODS

This study used a modified version of the CRIFF soil classification system, which split groups “B” and “F” into three subgroups each. The subgroups were categorized based on the depth to the Bt horizon (with B3 including no Bt past 80”; Typic Fluvaquents were examples of these B3 soils). If the Bt horizon was >20-40”, it was grouped as B1 or F1, >40-60” classified as B2 or F2, and >60-80” to the Bt horizon was either B3 (or no Bt to 80” as stated above) or F3. This was incorporated into the CRIFF soil classification system because the depth to the Bt horizon or increase in clay is a significant factor in tree growth, as this horizon slows water infiltration and is more nutrient-dense than overlying sandy textured E soils or thin A horizons. 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. Soil data were collected by NRCS soil mappers. The modified CRIFF soil groups are visualized in Figure 3. Soil profile delineation was conducted by NRCS soil scientists and to a lesser extent by UGA personnel.

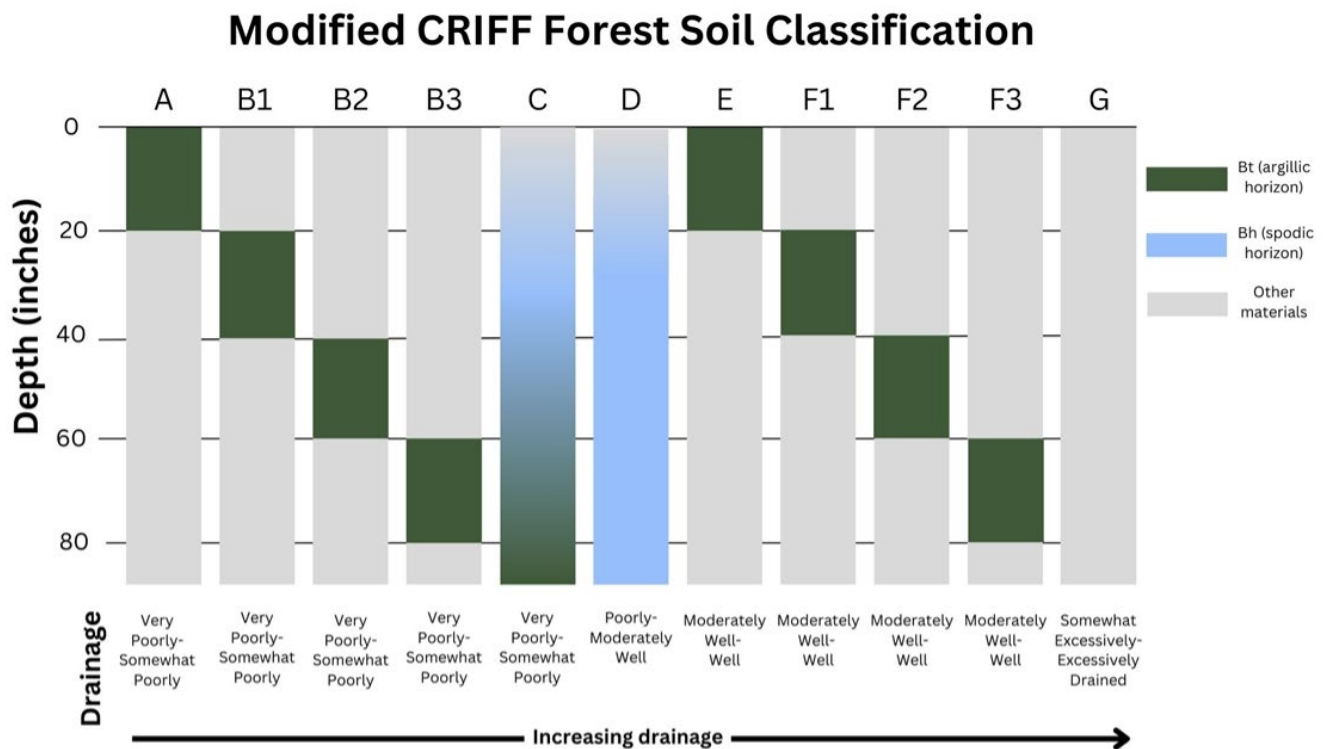


Figure 3: Diagram of the modified University of Florida Cooperative Research in Forest Fertilization (CRIFF) soil classification system (excluding group H) used for site index and mean annual increment analyses in this study. The argillic (Bt) and spodic (Bh) horizons are depicted in green and blue, respectively.

STUDY AREAS

For this study, 157 planted slash pine plots were inventoried. Most plots were in stands located on private lands, but some were on land owned by industry or the Georgia Department of Natural Resources. All plots were located within the state of Georgia. Study sites are located primarily in southeastern Georgia. Figure 4 shows the distribution of stands inventoried for this study (blue) and the Coastal Plain culture and density (CPCD) study (red), which was included as a comparison for SI and MAI estimates by CRIFF soil groups. The CPCD study was established by the University of Georgia's Plantation Management Research Cooperative (PMRC) and cooperative members in Georgia and Florida with 11 experimental slash pine stands. Management conducted on CPCD sites was considered 'operational' but more intensive than what most landowners would undergo. While the studies are not identical, the CPCD results provide a useful benchmark by which to compare the NRCS study SI and MAI estimates.

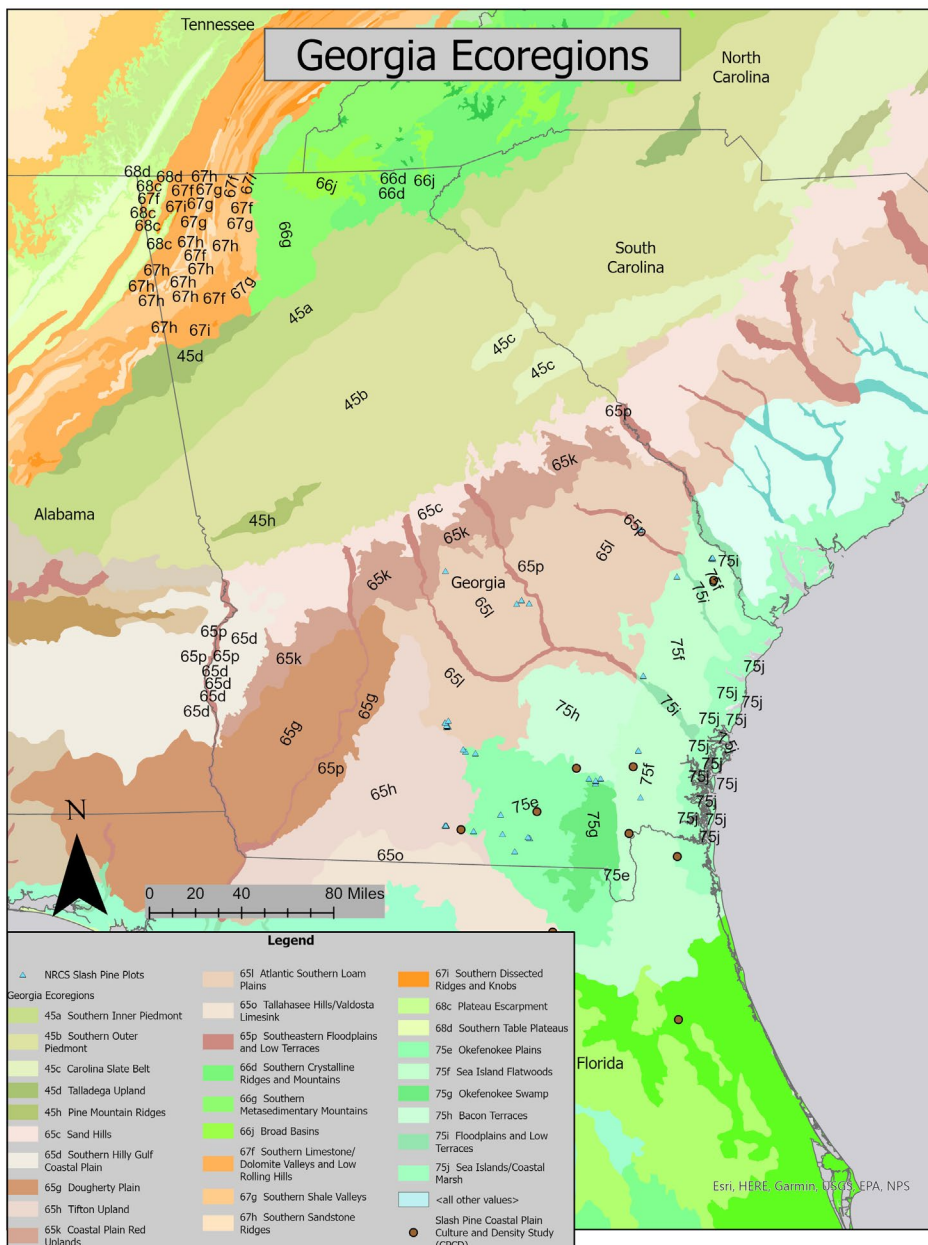


Figure 4: *Slash pine stands included in the Natural Resources Conservation Service (NRCS) study, as well as Coastal Plain culture and density (CPCD) study sites. NRCS sites are depicted in blue triangles and are only in southeastern Georgia, while CPCD sites are brown circles and spread from the Georgia/South Carolina border to upstate Florida within the Atlantic Coastal Plain region. Georgia Ecoregions are overlaid with loblolly and slash pine NRCS/CPCD plots and installations (Griffith and others, 2001).*

All CPCD study locations were in the Lower Coastal Plains and on five CRIFF soil groups. These soil groups were B1, B2, B3, C, and D. The CPCD study has one soil group named B2, while B2 is split into B2 and B3 in the NRCS study. The CPCD slash pine sites were planted with 900 trees per acre and had two levels of treatment (operational and intensive). The intensive management option will not be used for comparison here. Operational management practices consisted of bedding and chemical site preparation, herbaceous and woody control in the first year, fertilization at planting (500 lb/ac 10-10-10, i.e., 50 lb/ac N + 21 lb/ac P + 41 lb/ac K) and fertilization at ages 8, 12, and 20 years with 200 lb nitrogen (N) and 25 lb/ac phosphorus (P). The productivity results from operational methods were used to compare with the NRCS study, as these methods are more closely related (compared to the “intensive” CPCD treatment sequence) to the management activities of private, non-industrial forest owners (NIPFLs). Comparing NRCS results to CPCD operational results allowed researchers to verify the accuracy of NRCS findings by comparing them to a long-term slash pine experimental study in the same region, although operational management in the UGA CPCD study is still more intensive than the management practices of most private forest owners. 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 slash pine growth.

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). Forest research plots for 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 MLRAs are: Southern Coastal Plain and Atlantic Coast Flatwoods. These MLRAs covered four recognized ecoregions: Atlantic Southern Loam Plain, Sea Island Flatwoods, Tifton Upland, and Okefenokee Plains. Each ecoregion has specific soil and environmental conditions, which are described in Table 1.

Table 1: Georgia ecoregions in which site index and mean annual increment slash pine study stands are located. Landform characteristics of the ecoregions are included along with the percentage of plots that are located within the ecoregion.

Ecoregion	Landform characteristics	Percent of plots in ecoregion
Atlantic Southern Loam Plain	Flat to gently rolling topography with fine textured soils (all groups excluding A, C and D)	35.1%
Sea Island Flatwoods	Flat plains with mostly poorly drained Spodosol soils (C and D soil groups), but some better drained Ultisols soils (E, F1, F2, and F3) occur	24.2%
Tifton Upland	Rolling terrain and well-drained loamy soils (E, F1, F2, F3, and occasionally G soils)	7.6%
Okefenokee Plains	Flat plains and low terraces with somewhat-poorly to poorly drained soils (A, B1, B2, and B3 soils); spodosols (C and D soils) are common.	33.1%

PLOT CHARACTERISTICS

Inventory plots were circular 1/10th ac and typically arranged in sets of three to nine plots per stand, depending on the similarity of soil and competing vegetation conditions across stands. Plot centers within a stand typically were not located more than 132 ft from each other. The stands had a variety of management conditions prior to the study. Of the 157 plots, 67 of them had been thinned (90 unthinned) (Figure 5), 14 were in high-fertility and low woody competition progeny test areas, and 143 of the 157 plots were stands on cutover sites (previously forested for one or more rotations) with moderate to high woody competition levels and a wide range of soil fertility levels. Two 1/100th ac plots were nested inside the 1/10th ac plot to assess competing woody vegetation. The total woody competition (hardwood trees and shrubs and wilding pines) across all inventoried plots ranged from 165 to 1,758 tpa, greater than or equal to 1" diameter at breast height (dbh; 4.5 ft above groundline). Stands ranged from 6 to 28 years old. Planting densities ranged from 484 to 1,146 tpa. All plots received some form of site preparation and were planted with open-pollinated slash pine seedlings. Site preparation included mechanical, chemical, prescribed fire or combinations of methods. Based on Mehlich 1 soil P analyses (MI-P < 5 to 10 parts per million; ppm), most sites indicated no recent history of fertilization.



Figure 5: Example of an unthinned, 20-year-old slash pine stand plot in Ware County, Georgia 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 MEASUREMENTS

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)
- Diameter (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 randomly located 1/100th acre circular plots nested within the 1/10th ac inventory plot
- Surface soil (0-6") sampled at six to eight spots within the inventory plot for one composite soil sample per plot
 - 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 were used to group soils into modified CRIFF groups

Table 2: Summary statistics for variables collected at each inventoried plot. The summary information includes Cooperative Research in Forest Fertilization (CRIFF) soil group, stand age range, mean stand age, surface (0-6") soil Mehlich I-P range, and Mehlich I-P average. Plots with a M1-P value > 10 mg kg⁻¹ were considered to have a relatively recent history of fertilization (former pastures, hay, old-field sites or previous owner fertilization).

Species	CRIFF soil group	Number of plots	Age (years)		M1-P (mg kg ⁻¹) ^{1, 2, 3}	
			Range	Mean	Range	Mean
Slash pine (n=157)	A	10	24-27	25.2	2.34-5.84	3.48
	B1	41	6-28	21.0	0.81-5.94	2.13
	B2	6	16-26	22.3	1.08-2.30	1.59
	B3	6	6-26	22.0	1.99-3.79	2.63
	C	19	6-28	17.7	0.37-7.33	1.54
	D	9	6-24	13.8	0.90-4.97	1.56
	E	29	11-26	19.5	1.32-70.16	25.8
	F1	19	13-27	20.8	0.39-5.78	2.15
	F2	7	13-23	21.1	0.05-2.39	0.85
	F3	2	22	22.0	0.08-1.15	0.62
	G	9	22-25	24.7	1.19-37.99	16.08

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

² Surface soil M1-P levels below 5 mg kg⁻¹ which is approximately equal to parts per million; ppm (10 lb ac⁻¹ 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.

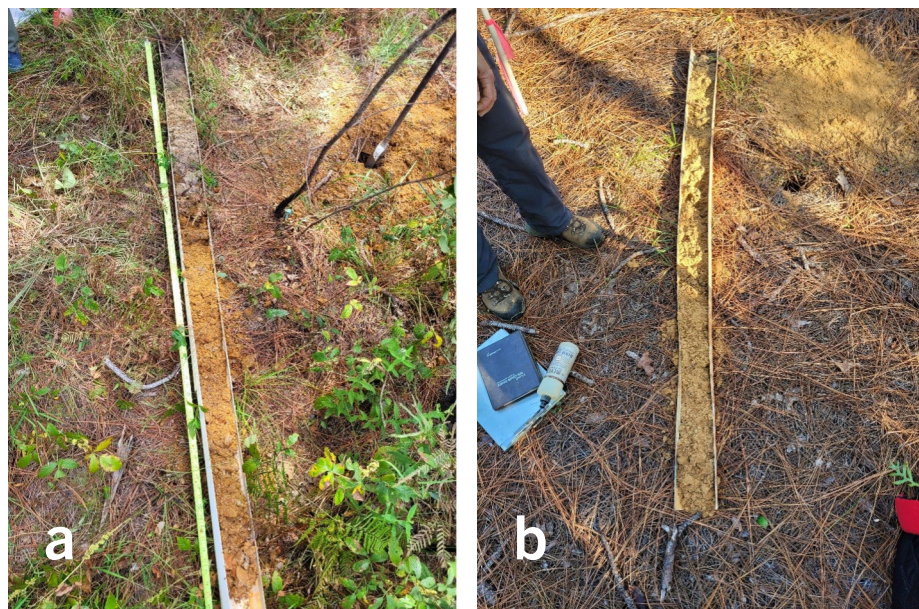


Figure 6: Examples of (a) modified Cooperative Research in Forest Fertilization (CRIFF) B1 soil with an argillic (Bt) horizon between 20 and 40" with somewhat to very poorly drained soil drainage, and (b) a very well drained CRIFF G soil profile. Holes were augered to a depth of 80".

SITE PRODUCTIVITY

The SI was defined using the average height of dominant and co-dominant trees at stand age 25 years old. Dominant and codominant trees were classified as those with a DBH greater than the average DBH of an unthinned stand, or the tallest 80% of stems in thinned stands. Figure 7 illustrates the mean (real, not predicted) NRCS and the base CPCD SI values for each modified CRIFF soil group.

This study utilized the proprietary UGA PMRC slash pine site index model to develop estimates (Logan, 2005). The following explanatory variables were used to explain slash pine site index estimates: modified CRIFF soil group (as dummy variables), concentrations of Mehlich 1 P (M1-P mg kg⁻¹; ppm), presence/depth to an argillic horizon, presence/depth to a spodic horizon, presence/depth to a seasonal high-water table, and presence/depth to chroma ≤ 2 (light gray soil color indicating reduced iron, wet soil conditions). The dependent variable (SI values) was regressed against these variables.

The MAI of plots expressed as green weight increment (t ac⁻¹ yr⁻¹) at certain ages was calculated at various planting densities (Dickens and others, 2024) using predicted NRCS and base CPCD site index values. A PMRC slash pine growth and yield simulator was used to estimate green weight MAIs at ages 10, 15, and 20 years, starting at stand age five years by CRIFF soil group for 500, 600, and 700 surviving tpa at stand age 5-years (Logan, 2005). Actual measurements from the CPCD study through stand age 20 years (operational management and 900 tpa as 600 tpa was not an option for the slash pine CPCD study) and simulated NRCS plot data were used to derive MAI estimates. Green weight was calculated using equations updated by Zhao and others, (2024):

$$\text{Slash GW (lb) outside bark} = 0.1648 * \text{DBH}^{1.9416} \text{HT}^{0.9755}$$

RESULTS

The regression model found two variables that had significant correlations with SI. The modified CRIFF soil group and surface (0 to 6") soil phosphorus (MI-P) levels were both major predictor variables for slash pine SI. Different CRIFF soil groups showed variation in the threshold value for M1-P available in the soil. Soil groups B2, F2, F3, and G had a M1-P threshold of 2.4 ppm. Site index values averaged 58.1 ft when M1-P was less than 2.35 ppm and 62.3 ft when M1-P was greater than or equal to 2.4 ppm. For soil groups B1, E, and F1, MI P < 1.6 ppm resulted in a SI of 71.5 ft, between 1.6 and 38.1 ppm resulted in a SI of 71.9 ft, and ≥ 75.7 ft for M1 P > 38.1 ppm.

CRIFF Soil Groups in order of SI Productivity

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

*due to a history of fertilization as indicated by soil M1-P

Slash pine had poor performance on B2, F2, F3, and G soils with an average SI between 50.9 (F3) and 62.3 ft (F2). The average SI increased for soil groups A, B1, B3, and F1 and ranged from 70.9 to 78.4 ft. Average SI by soil type for this study and the CPCD study are depicted in Figure 7. The CPCD results for every category are greater than the results for this study (NRCS). This is due to the more intensive and expensive management (primarily multiple fertilizer treatments) that was conducted in the CPCD study, and estimates are not realistic for typical management done by NIPFLs. The B3 group productivity level was high for slash pine and likely due to plot locations at toe or foot slope positions and in very close proximity to bodies of water (many alluvial soils such as Typic Fluvaquents have black, organic matter-rich soil to 12-30 inches).

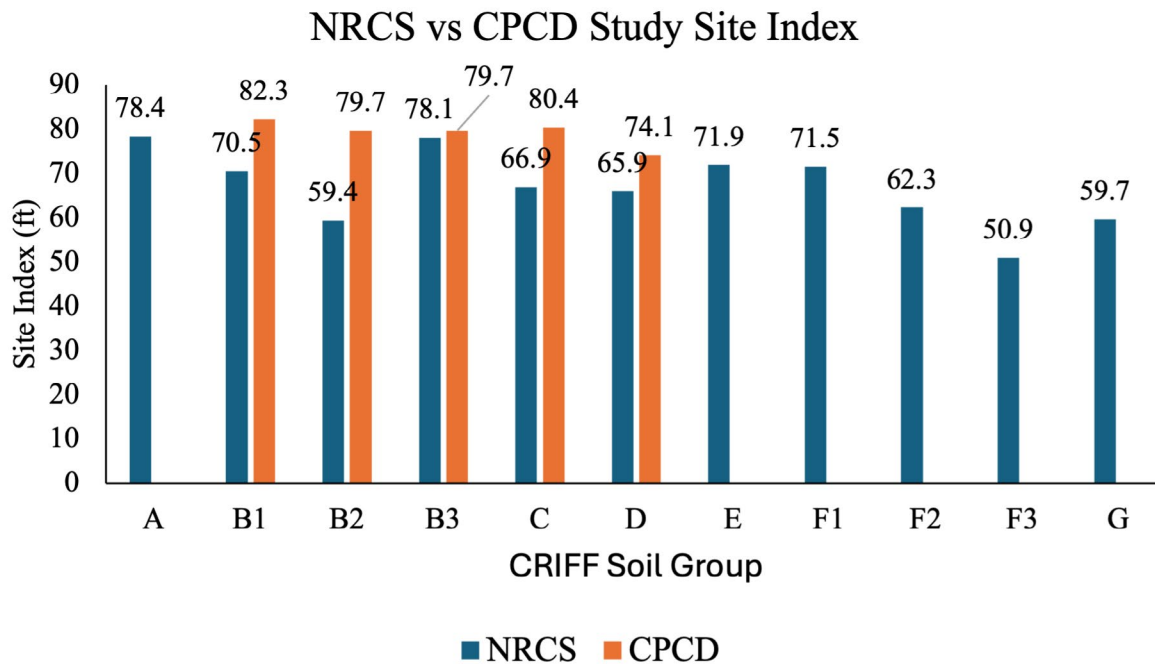


Figure 7: The estimated average site index in feet by Cooperative Research in Forest Fertilization (CRIFF) soil group for slash pine. This study (Natural Resources Conservation Service or NRCS) is shown in blue, and the Coastal Plain culture and density (CPCD) study estimates are shown in orange where data were available.

The green weight MAIs for each soil type were estimated using the average estimated SI and the PMRC growth and yield system. The MAI estimates for slash pine at 10, 15, and 20 years are shown in Figure 8.). The 10-year MAI by tree density ranged from 1.5 to 5.2 tons ac⁻¹ yr⁻¹ for 500 tpa, 1.7-5.9 tons ac⁻¹ yr⁻¹ at 600 tpa, and 1.9-6.6 tons ac⁻¹ yr⁻¹ when tree density was 700 tpa. At 15 years, these ranges shifted to 2.6-6.4-, 2.9-7.1-, and 3.2-7.8-tons ac⁻¹ yr⁻¹ for 500, 600, and 700 tpa, respectively. Stands aged 20 years had ranges of 3.2-6.6-, 3.5-7.4-, and 3.8-8.0-tons ac⁻¹ yr⁻¹ when tpa were 500, 600, and 700, respectively. The two soil groups with the lowest MAIs for all ages and tpa were B2 and F2 followed closely by F3 and G. The two soil groups with the highest MAIs for all ages and tpas were A and B3. The CRIFF soil groups sorted by MAI stand volume or green weight are listed below, from lowest to highest productivity. Soil groups A and B3 are tied for the highest MAI volume.

$$A/B3 > E > F1 > B1 > C > D > G > F2 > B2/F3$$

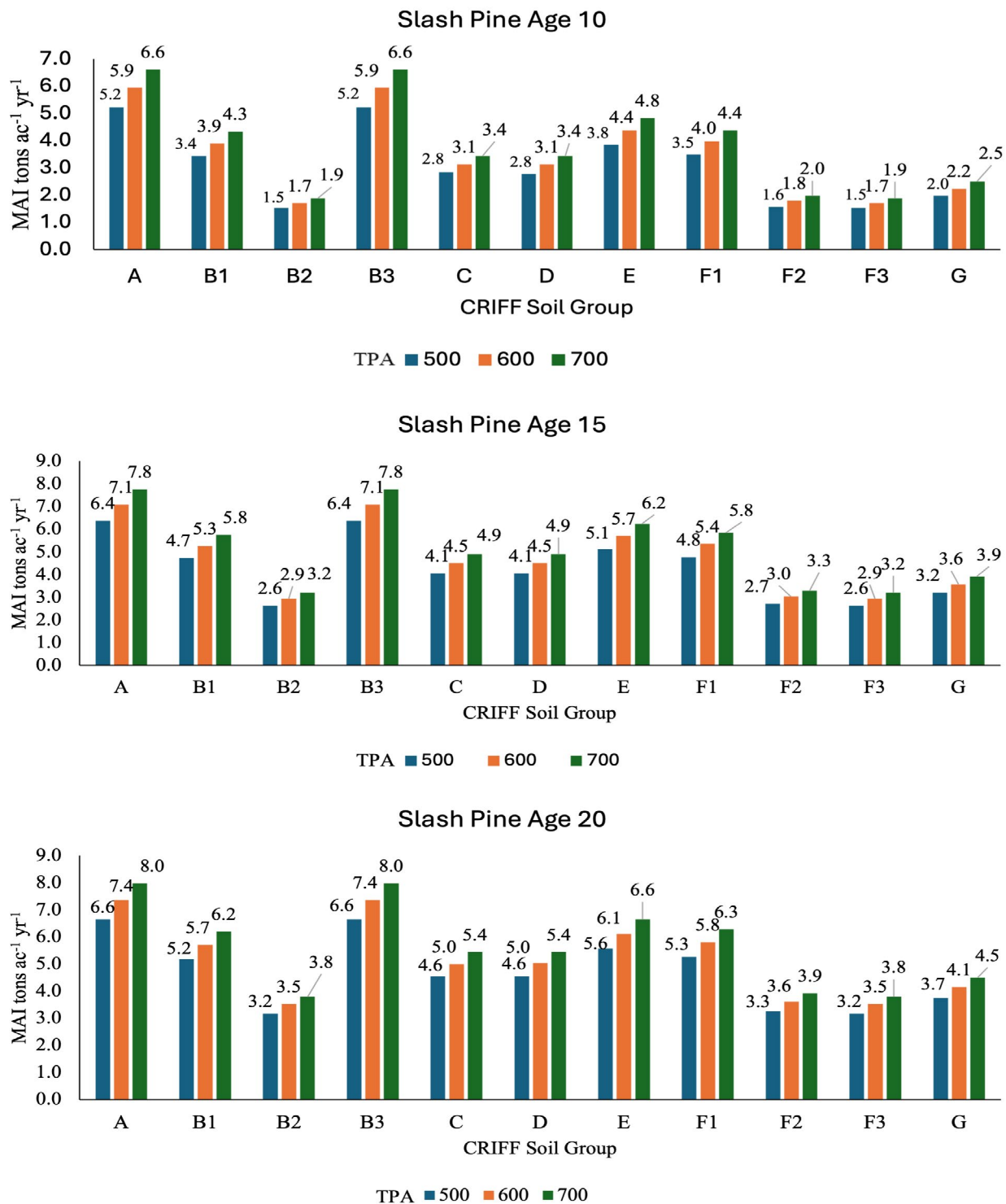


Figure 8: Slash pine average (predicted) mean annual increment (MAI) in tons per acre per year by Cooperative Research in Forest Fertilization (CRIFF) soil group. Results are projected from age five years using the Natural Resources Conservation Service (NRCS) study estimated site index values for stands at 10 (a), 15 (b), and 20 years (c) old by three different surviving trees per acre rates at age 3-years. Blue represents 500, orange is 600, and green is 700 trees per acre.



The NRCS plots showed higher SI values when plots were located on progeny test area stands in soil group E, or with plots that had a history of fertilization on soil group G. Plots with these soil and competition conditions had lower woody and herbaceous competition (70 to 80% fewer 1" dbh stems per acre than other CRIFF E and G soil group plots), and higher M1-P levels. This indicates that the presence of M1-P can be used as an indicator of site productivity, and the lack of woody and herbaceous competition allows slash pine to have a greater SI value on average.

CONCLUSION

Data from this study showed clear trends in estimated slash pine SI on various soil groups. Average site index values for slash pine depend on the CRIFF soil group. From highest SI to lowest, the CRIFF soil groups are A/ B3, B1/E/F1, C/D, and B2/F2/G, F3 though this grouping could have been impacted by limited sample size and the high surface soil M1-P levels in the G plots.

According to the results of the study, an increase in depth to the top of the argillic (Bt) horizon correlated with a decrease in SI for slash pine on soil groups B and F except for soil group B3 (due to the majority of B3 plots being on Fluvaquents; toe and footslope positions). Some soil groups had important SI interactions with M1-P levels. Soil types B2, F2, F3, and G had a threshold of 2.35 ppm M1-P. When M1-P was less than 2.35ppm, SI was less than 58.1 ft, whereas if M1-P exceeded 2.35 ppm, SI was greater than or equal to 62.3 ft.

Mean annual increment values hierarchy were the same as SI among CRIFF soil groups (because MAI is calculated from SI). The average MAI varied between this study and the CPCD study, with CPCD values higher for every comparable soil type. This is likely due to the increased intensity of management, both with woody and herbaceous weed control and with multiple fertilizer treatments. Although those management practices are not often realistic for private landowners, it does show that slash pine is capable of significantly greater productivity if more intensively managed. This was especially true for soil groups B2, C, and D.

The updated SI and MAI estimates for slash pine created through this research provide non-industrial private landowners with more accurate and current information to make species selection decisions by soil group. This information also allows forest owners and managers to have reasonable expectations of slash pine productivity with operational management (limited or no fertilization) and provides insight into improving growth depending on soil type.

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