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Soil-based assessment of site productivity for southern pine plantations in the coastal plain of the southeastern US: (II) slash pine

Ernest David Dickens [a,*], Dehai Zhao [a,*], David C. Clabo [a], Daniel Markewitz [a], Bronson P. Bullock [a], Dee Cabaniss Pederson [b]

[a] Warnell School of Forestry and Natural Resources, University of Georgia, Athens, GA 30602, USA
[b] Natural Resources Conservation Service, USDA, 355 E. Hancock Ave, Athens, GA 30602, USA

A R T I C L E I N F O

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A B S T R A C T

Non-industrial private forest landowners and foresters often rely on outdated site index models for forest productivity predictions, which hinders accurate assessment. To address this issue, 157 slash pine plots were established in the coastal plain of Georgia, USA, to collect tree and soil data. Using regression tree and linear regression models, we identified modified Cooperative Research in Forest Fertilization soil groups and surface soil extractable phosphorus as significant predictors of site index. The optimal regression tree model ($R^2 = 0.490$, RMSE $= 1.72$ m) outperformed the linear regression model. Updated site index and simulated mean annual increments for slash pine were compared with long-term experimental study data, as well as with previous findings for loblolly pine in the same region (Zhao et al., 2024a). The new predictive models will help non-industrial private forest landowners evaluate slash pine productivity in the Coastal Plain region, applicable across diverse sites.

1. Introduction

Non-industrial private forest landowners own a higher percentage of forestland in the southeastern United States than any other ownership category (Butler et al., 2021). In the state of Georgia, the largest state east of the Mississippi River, there are 9.87 million ha of forests out of a total land area of 15.37 million ha. Non-industrial private forest landowners own approximately 55 % of the total land, which equates to about 8.45 million ha of Georgia's forestland (Lambert et al., 2023). Between 1972 and 2019, there was a dramatic shift in Geogia's pine forests. The area of natural pine stands decreased from approximately 3.76 million ha to 1.70 million ha, while the area of planted pine stands increased about 1.13 million ha to 2.75 million ha (Lambert et al., 2023). This same shift from pine stands being regenerated naturally to being established as pine plantations (728,400 ha in 1952 to 15.78 million ha by 2012) has occurred throughout the southeastern United States (Fox et al., 2007; Huggett et al., 2013). There is an estimate total of 572,000 family forest landowners in six southeastern states (Butler et al., 2021).

Loblolly pine (*Pinus taeda* L.) and slash pine (*P. elliottii* Engelm. var. *elliottii*) are the two most important commercial timber species in the southeastern US (Dicus and Dean, 2008). Industrial forest landowners employ intensive management practices in their pine plantations, including improved site preparation, herbaceous weed and woody control, fertilization, and the use of genetically improved seedlings. These measures have significantly increased plantation productivity (Martin and Jokela, 2004; Fox et al., 2007; Medina Perez et al., 2007; Jokela et al., 2010; Zhao et al., 2009; Zhao et al., 2011). Over the past 60 years, the productivity of pine plantations has tripled compared to natural pine forests due to intensive management (Fox et al., 2007; Jokela et al., 2010).

On non-industrial private forest landowners' properties, pine plantations often undergo less intensive silvicultural treatments (Kittredge, 2004; Butler and Wear, 2013), which necessitates tools for assessing their productivity. Unlike industrial forest landowners who have mapped soil-site productivity relationships over the decades (Homyack et al., 2022), non-industrial private forest landowners rely on publicly available forest productivity data such as site index (SI) and mean annual increment (MAI) from the United States Department of Agriculture (USDA) Natural Resources Conservation Service. These values were derived from outdated SI models based on data collected several decades ago from unmanaged or natural stands composed of trees with

* Corresponding authors.
E-mail addresses: ddickens@uga.edu (E.D. Dickens), zhaod@uga.edu (D. Zhao).

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unimproved genetics, using a SI base age of 50 years. The standard SI values for planted pine stands in the southeastern US have a base age of 25-years (Ashton and Kelty, 2018). With establishment costs ranging from over $500 to $1500 per hectare (Maggard and Natzke, 2023), planted pine stands constitute a significant investment, making reliance on outdated models impractical (Skovsgaard and Vanclay, 2013).

Recognizing the significance of staying pace with advancements in forest management, the Natural Resources Conservation Service has invested in updating information on SI and MAIs for southern pine plantations, known as the NRCS study. Our first paper (Zhao et al., 2024a) focused on developing predictive SI models and updated the SI and MAI data for loblolly pine plantations in Georgia's Coastal Plain based on soil parameters. As the second paper in the NRCS study, we present SI models for slash pine in the same region.

Several studies have compared the growth performance of slash pine and loblolly pines in the southeastern US, under varying cultural intensities (Cole, 1975; Shoulders, 1976; Clason and Cao, 1983; Borders and Harrison, 1989; Shiver et al., 2000; Zhao and Kane, 2012; Zhao et al., 2019). Generally, loblolly pine performs as well as or better than slash pine under low-intensity culture, except on very poorly drained flatwoods sites where slash pine excels. Loblolly pine also shows a stronger response to fertilization compared to slash pine (Haines et al., 1981; Zhao and Kane, 2012), resulting in better performance under intensive management. However, findings on species differences within specific soil groups have been inconsistent across studies, with some studies contradicting others, such as Borders and Harrison (Borders and Harrison, 1989) versus Haines and Gooding (Haines and Gooding, 1983).

In the current research, we analyzed data from 157 slash pine plots, primarily established on non-industrial private forest landowners' properties, to quantify the relationship between SI and soil parameters for slash pine in the Coastal Plain. We utilized the modified Cooperative Research in Forest Fertilization soil groups, available phosphorus (P) in the surface soil layer (0–15 cm), and other soil properties. Subsequently, we simulated stand volume and stem outside-bark green weight MAIs for each soil group. Surface soil available P was identified as a crucial indicator of site fertility, impacting slash pine SI and MAI. During the modeling process, we investigated the hypothesis that the effect of surface soil available P on slash pine SI varies among different soil groups, given its highly variable concentration within and among some soil groups.

We verified the SI and simulated MAIs for slash pine by comparing them with data from a long-term culture/density experimental study conducted across the region. Additionally, we compared the updated SI and MAIs for slash pine with our previous findings for loblolly pine for each modified Cooperative Research in Forest Fertilization F soil group (Zhao et al., 2024a). As a result, we offer species-site recommendations based on our findings.

2. Materials and methods

2.1. Study areas and plot installation

All plots in the NRCS study were established in Georgia, primarily on non-industrial private forest landowners' properties, with some on state and industry-owned lands throughout the Coastal Plain (Fig. 1). Of the

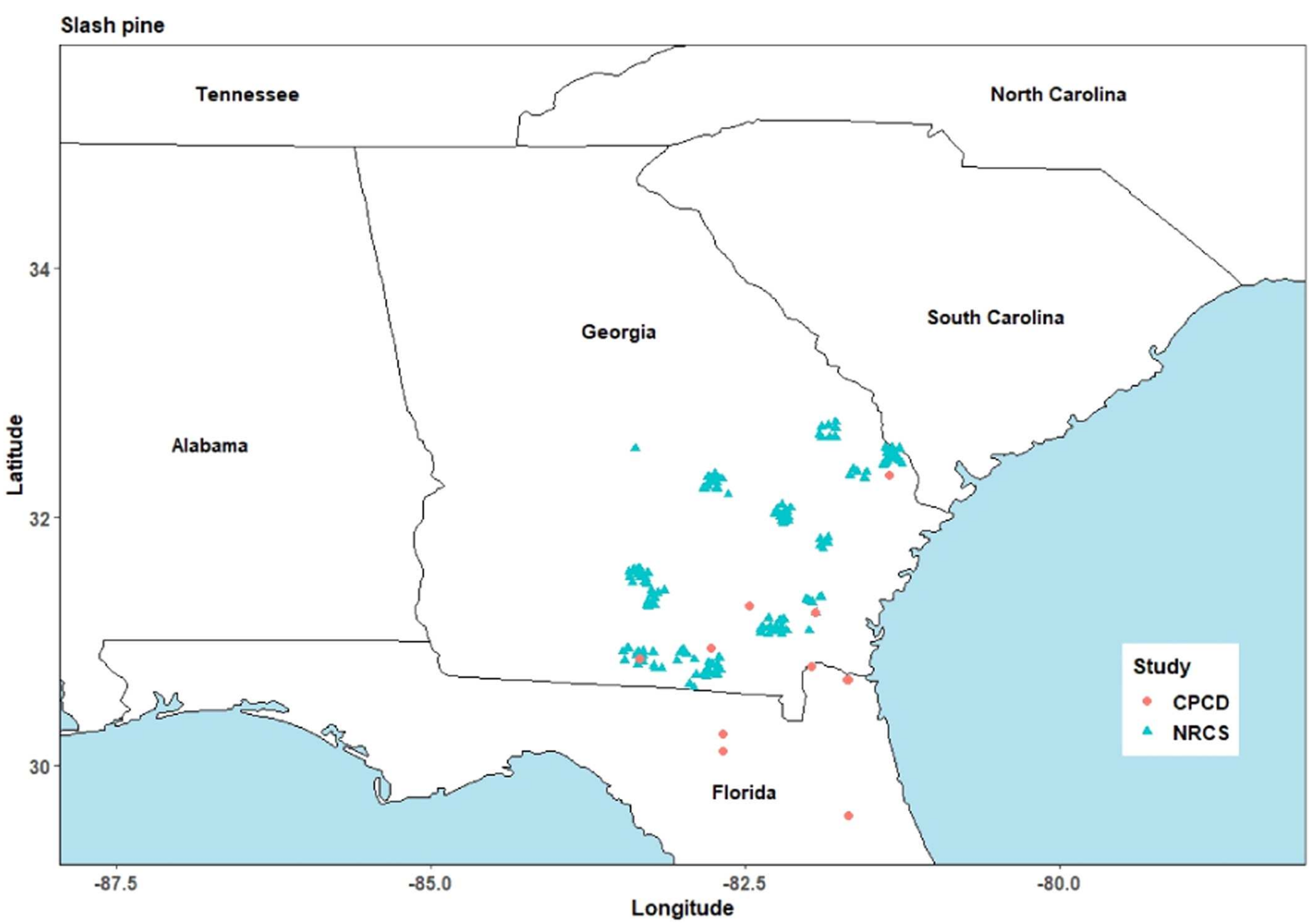

Fig. 1. Locations of the NRCS study slash pine research plots and locations of research installations selected from the Lower Coastal Plain Culture/Density study (CPCD).

157 slash pine plots, 35.1 % were in the Atlantic Southern Loam Plain or Vidalia Upland, characterized by flat to gently rolling terrain with fine textured soils (Griffith et al., 2001). The Sea Island Flatwoods ecoregion contained 24.2 % of plots, known for poorly drained, flat plains with spodosol soils (Griffith et al., 2001). The Tifton Upland had 7.6 % of plots, featuring rolling terrain and well-drained loamy soils. The Okefenokee Plains, with 33.1 % of plots, consists of flat plains and with somewhat-poorly to poorly drained soils and common spodosols. Average July temperature ranged from 24.4°C to 26.2 °C, minimum average January temperature from 11.3°C to 12.4 °C, and annual precipitation from 1178 mm to 1293 mm (NOAA National Centers for Environmental Information, 2024).

Plots received site preparation (mechanical, herbicide or both) and were planted with 1–0 stock open pollinated slash pine seedlings. Circular plots (0.04 ha) were set in forests to capture variability for mapped soil units and stand attributes. Out of the 157 plots, 67 were previously thinned, 14 were in high-fertility and low woody competition progeny test areas, and 143 were on cutover sites with moderate to high competition and varying soil fertility (Table S1). Each plot's latitude, longitude, planting details, and thinned status were documented. Current stand fertilization was either not performed or not known.

2.2. Measurements

Pine planting density within each 0.04-ha measurement plot ranged from 1196 to 2832 trees ha^{-1}. Diameter at breast height (dbh) and total height were measured for all planted slash pines. Two or three 0.004-ha subplots assessed woody competition, recording shrub cover by genus/species, percentage ground cover and height. Hardwoods and volunteer pines (dbh $\geq$ 2.5 cm) were tallied by genus/species, diameter class, height, and number per subplot.

Surface soil (0–15 cm) was sampled at 6–8 random locations within each 0.04-ha plot for pH (Kissel and Vendrell, 2012), concentrations of Mehlich 1 P (M1-P) (Mehlich, 1953), potassium (K), calcium (Ca), magnesium (Mg), boron (B), and copper (Cu). Soil profile (0–2 m) were described using hand augering to record the presence and depth of Bt (argillic) and Bh (spodic) horizons, depth to seasonal high-water table, and soil drainage class. Plots were classified into different soil groups based on these characteristics (Table 1).

To compare, we obtained additional data from the Coastal Plain culture and density study (CPCD) by the Plantation Management Research Cooperative at the University of Georgia. It covered eleven installations in Georgia and Florida's Lower Coastal Plain with slash pine experimental plots. Each installation had six slash pine plots with varying planting densities (741, 2224, and 3706 trees ha^{-1}) and cultural intensity (operational and intensive). The intensive regime included frequent fertilization and complete competition control, while the operational regime had less frequent fertilization and early-stage competition control. The CPCD operational regime was more intensive than typical practices of non-industrial private forest landowners. For more details, refer to Zhao and Kane (Zhao and Kane, 2012) and Zhao et al. (Zhao et al., 2019). Installations were spread across soil groups (3 on B1, 3 on B2 and B3, 3 on C, and 2 on D group soils). In the original CPCD study design, soil group B2 combined both B2 and B3 groups, as is adopted in this current NRCS study. Treatment plots had specific tree counts per plot and a surrounding buffer area. Measurements were taken every two years until age 12, and then every three years until age 24. Tree measurements included dbh for every surviving tree and total height for every other tree. Total height of trees that were not measured was estimated from the model $\ln(H) = b_0 + b_1/dbh$ which was fitted separately for height measured trees in each plot at each measurement age. Stem outside-bark volume and green weight were estimated using updated slash pine equations by Zhao et al. (Zhao et al., 2024b). Stand-level volume and green weight were calculated per hectare basis.

Table 1
Modified Cooperative Research in Forest Fertilization soil groups used in the NRCS study.

Soil Group	Drainage Class[a]	Diagnostic Horizons
A	VP – SP	No spodic, argillic <= 50 cm
B1	VP – SP	No spodic, argillic > 50–100 cm
B2	VP – SP	No spodic, argillic >100–150 cm
B3	VP – SP	No spodic, argillic > 150 cm or not present to 200 cm
C	VP – SP	Spodic with argillic
D	VP – MW	Spodic without argillic
E	MW – W	No spodic, argillic <= 50 cm
F1	MW – W	No spodic, argillic > 50–100 cm
F2	MW – W	No spodic, argillic > 100–150 cm
F3	MW – W	No spodic, argillic > 150–200 cm
G	SE – E	No spodic, no argillic to 200 cm

[a] Soil drainage classes: VP = Very Poorly, P = Poorly, SP = Somewhat Poorly, MW = Moderately Well, W = Well, SE = Somewhat Excessively, E = Excessively drained.

2.3. Site productivity

Site index, defined as the average height of dominant and codominant trees (HD) at 25 years, was determined. Dominant and codominant trees were those with a dbh greater than the stand's average in non-thinned stands (Zhao et al., 2019) or the tallest 80 % in thinned stands. HD values from plot measurement in the NRCS study and the latest remeasurement in the CPCD study were used to calculate site index for slash pine plots, using the proprietary model of the Plantation Management Research Cooperative (Logan, 2005). Summary information, including plot number, stand age ranges and means, M1-P, and SI by soil groups, is presented in Table 2 for NRCS study slash pine plots.

2.4. Soil-based site index model for slash pine – regression trees approach

We employed a regression trees approach, similar to previous work for loblolly pine (Zhao et al., 2024a), to establish the relationship between slash pine SI and soil parameters using NRCS study plot data. This method constructs a decision tree by recursively splitting the data based on soil parameters, aiming to reduce deviance. The SI values are then predicted based on the mean values in terminal nodes (leaves). Explanatory variables included modified Cooperative Research in Forest Fertilization soil groups, M1-P, presence and depth to argillic horizon (Bt_Depth) and spodic horizon (Bh_Depth), and depth to seasonal high-water table (SHWT_Depth). The model was fitted in R (R Core Team, 2023) version 4.2.3, using the rpart package version 4.1.19 (Therneau and Atkinson, 2022).

2.5. Soil-based site index model for slash pine – linear regression model

The dummy variables were set to identify the soil groups:

$$I_A = \begin{cases} 1, \text{Soil A} \\ 0, \text{others} \end{cases}, I_{B1} = \begin{cases} 1, \text{Soil B1} \\ 0, \text{others} \end{cases}, I_{B2} = \begin{cases} 1, \text{Soil B2} \\ 0, \text{others} \end{cases}, I_{B3} = \begin{cases} 1, \text{Soil B3} \\ 0, \text{others} \end{cases},$$

$$I_C = \begin{cases} 1, \text{Soil C} \\ 0, \text{others} \end{cases}, I_D = \begin{cases} 1, \text{Soil D} \\ 0, \text{others} \end{cases}, I_E = \begin{cases} 1, \text{Soil E} \\ 0, \text{others} \end{cases},$$

$$I_{F1} = \begin{cases} 1, \text{Soil F1} \\ 0, \text{others} \end{cases}, I_{F2} = \begin{cases} 1, \text{Soil F2} \\ 0, \text{others} \end{cases}, I_{F3} = \begin{cases} 1, \text{Soil F3} \\ 0, \text{others} \end{cases}, I_G = \begin{cases} 1, \text{Soil G} \\ 0, \text{others} \end{cases}$$

Using NRCS study plot data for slash pine, we conducted regression analysis with observed SI as the dependent variable. This entailed regressing SI against the soil groups (as dummy variables), M1-P, Bt_Depth, Bh_Depth, SHWT_Depth, and interaction terms. Only variables with statistically significant coefficient estimates ($p < 0.05$) were retained in the final model. Variation inflation factors (*VIFs*) were

Table 2
The plot number, the range and mean of stand age, surface soil extractable P (M1-P, mg kg^{-1}), and site index (SI, m) by soil groups for the NRCS study slash pine plots.

Soil Group	Number of plots	Age		M1-P		SI	
		Range	Mean	Range	Mean	Range	Mean
A	10	24–27	25.2	2.34–5.84	3.48	22.2–26.4	23.9
B1	41	6–28	21.0	0.81–5.94	2.13	17.4–25.9	21.5
B2	6	16–26	22.3	1.08–2.30	1.59	16.1–20.4	18.1
B3	6	6–26	22.0	1.99–3.79	2.63	19.9–25.6	23.8
C	19	6–28	17.7	0.37–7.33	1.54	18.7–23.8	20.4
D	9	6–24	13.8	0.90 – 4.97	1.56	19.0–23.6	20.1
E	29	11–26	19.5	1.32–70.16	25.80	18.5–25.7	21.9
F1	19	13–27	20.8	0.39–5.78	2.15	18.9–23.8	21.8
F2	7	13–23	21.1	0.05–2.39	0.85	16.9–22.6	19.0
F3	2	22	22.0	0.08–1.15	0.62	14.9–16.1	15.5
G	9	22–25	24.7	1.19 – 37.99	16.08	14.7–20.3	18.2

computed to identify potential multicollinearity. Model performance was assessed using the coefficient of determination (R^2) and root mean square error (*RMSE*).

2.6. Mean annual increments (MAI) for slash pine

After comparing modeling approaches for slash pine soil-based SI, the superior model was used to estimate SI for each NRCS study plot. These estimated SIs were averaged for each soil group. They were then compared with SI values previously estimated for loblolly pine in the same study (Zhao et al., 2024b), and with operational plots planted at a density of 2224 trees ha^{-1} from the CPCD study. Using these SI values and tree densities of 1236, 1483, 1730, and 2224 trees ha^{-1} at age 5, stand volume and green weight MAIs at ages 10, 15, and 20 were simulated for each soil group using the slash pine growth and yield model system (Logan, 2005). Similarly, MAIs were calculated for operational slash pine plots planted at 2224 trees ha^{-1} from the CPCD study. Finally, observed MAIs from CPCD were compared with simulated MAIs from NRCS based on soil groups.

3. Results

3.1. Regression tree model for slash pine SI

The optimal regression tree model identified two major predictor variables for slash pine SI in the Coastal Plain: a modified Cooperative Research in Forest Fertilization soil group and soil P (Fig. 2 and Table 3).

Table 3
The prediction rules in the optimal regression tree model for slash pine SI (Fig. 2).

Terminal node (leaf)	Soil groups and surface soil P (M1-P)	SI (m)
(1)	(B2, F2, F3, G) & M1-P < 2.3	17.7
(2)	(B2, F2, F3, G) & M1-P ≥ 2.3	19.0
(3)	(B1, C, D, E, F1) & (1.3 ≤ M1-P < 1.6)	19.7
(4)	(C, D) & M1-P ≥ 1.6	20.3
(5)	(C, D) & M1-P < 1.3	20.6
(6)	(B1, F1) & M1-P < 1.3	21.8
(7)	(B1, E, F1) & (1.6 ≤ M1-P < 38.1)	21.9
(8)	(B1, E, F1) & M1-P ≥ 38.1	23.1
(9)	(A, B3)	23.9

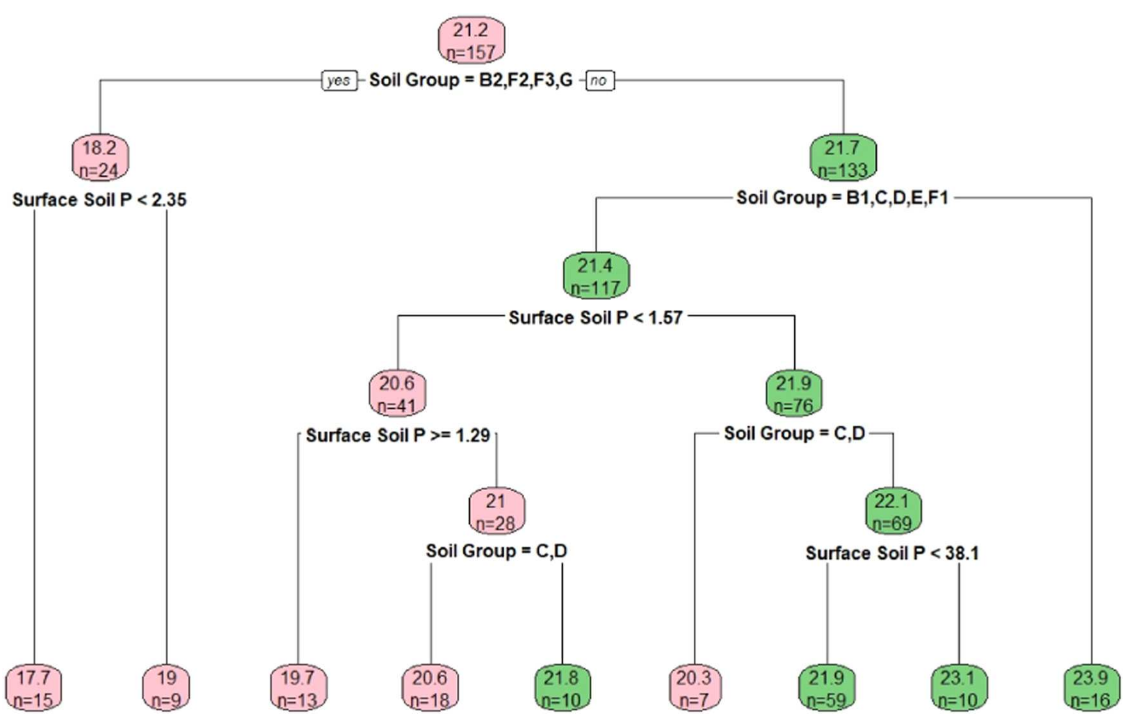

Fig. 2. Tree-based regression model for predicting slash pine SI in the Coastal Plain. Note that the order in which variables are examined depends on the answers to previous questions. The numbers in rounded rectangles indicate the predicted SI and how many cases belong to each node or leaf.

The R^2 of the tree model is 0.490 and *RMSE* is 1.72 m.

Soil groups B2, F2, F3 and G were allocated to the first two leaves of the optimal regression tree (Fig. 2 and Table 3), determined by an M1-P threshold value of 2.35 mg kg^{-1}. All observed M1-P values on B2 and F3 group soils, ranging from 0.08 to 2.30 mg kg^{-1}, were lower than this threshold value. The M1-P values observed on F2 group soils ranged from 0.05 to 2.39 mg kg^{-1}, all below the threshold value except for one observation that was close to the threshold value (Table 2). While the M1-P values observed on G group soils ranged from 1.19 to 37.99 mg kg^{-1}, only one observation was below the threshold value. As a result, the estimation of SI for the first leaf predominantly relied on averaging observed SIs from B2, F2 and F3 soils, while the SI for the second leaf was derived from the average value of most all observations on G group soils.

The observed M1-P values in slash pine plots on soil groups A and B3 ranged from 1.98 to 5.84 mg kg^{-1}. No correlation was found between SI and M1-P on these two group soils. Their average SI was 23.9 m (Fig. 2 and Table 3), the highest among all other soil groups.

Soil groups C and D, characterized by an M1-P range of 0.37 – 7.33 mg kg^{-1}, were assigned to three leaves (3rd, 4th, and 5th) on the optimal regression tree (Fig. 2 and Table 3), based on their M1-P values ($<$ 1.29, 1.29 – 1.57, or $>$ 1.57 mg kg^{-1}). However, the variation in the average SI among these leaves was minimal, with SI increasing from 19.7 m to 20.6 m.

The observed M1-P ranges on B1 and F1 group soils were from 0.81 to 5.94 mg kg^{-1} and from 0.39 to 5.78 mg kg^{-1}, respectively. Plots on these two group soils were categorized into either the 6th leaf (when M1-P $<$ 1.29 mg kg^{-1}), the 3rd leaf (1.29 $\leq$ M1-P $<$ 1.57 mg kg^{-1}), or the 7th leaf (M1-P $\geq$ 1.57 mg kg^{-1}), rather than the 8th leaf, due to all observed M1-P values on these two group soils being below 38.1 mg kg^{-1}. The estimated SI for the 3rd, 6th, and 7th leaves was 19.7, 21.8 and 21.9 m, respectively.

Soil group E exhibited a wide range of M1-P values (1.32 – 70.16 mg kg^{-1}). Plots from soil group E with M1-P $\geq$ 38.1 mg kg^{-1} were assigned to the 8th leaf (SI 23.9 m), while other plots from soil group E were distributed into either the 3rd leaf (SI 19.7 m, when M1-P $<$ 1.57 mg kg^{-1}) or the 7th leaf (SI 21.9 m, 1.57 $\leq$ M1-P $<$ 38.1 mg kg^{-1}). There appeared to be a positive correlation between SI and M1-P for slash pine in soil group E.

3.2. Linear regression model for slash pine SI

The final linear regression model for slash pine SI including only the variables or interaction terms with statistically significant coefficient estimates had an R^2 value of 0.452 and an *RMSE* value of 1.85 m. The estimated parameters, the associated p-values and VIFs for this final model are presented in Table 4. The VIFs ranged from 1.11 to 3.14, all below 4, suggesting that multicollinearity is not a significant concern in the model. Negative coefficients for B1, C, D, F1, F2, F3, and G soil groups indicated that slash pine on these soil groups exhibited significantly smaller SI values compared to those on A group soils. Only two significant interaction terms were identified (Table 4).

Table 4
The estimated parameters, standard errors, p-values, and VIFs for the reduced model that regresses slash pine SI on surface soil extractable P (M1_P) along with dummy variables for the soil groups in the NRCS study.

Variable	Parameter Estimate	Standard Errors	p-value	VIF
Intercept	23.8229	0.4583	< 0.0001	
I_{B1}	-2.2604	0.5419	< 0.0001	2.59
$I_{B2} \times M1\_P$	-3.5659	0.5372	< 0.0001	1.30
I_C	-3.4045	0.6249	< 0.0001	1.90
I_D	-2.8133	0.7688	0.0004	1.46
I_E	-2.8374	0.6750	< 0.0001	3.14
$I_E \times M1\_P$	0.0344	0.0138	0.0141	1.88
I_{F1}	-2.0494	0.6249	0.0013	1.90
I_{F2}	-4.8339	0.8366	< 0.0001	1.37
I_{F3}	-8.3287	1.3872	< 0.0001	1.11
I_G	-5.5970	0.7688	< 0.0001	1.46

Notice: R^2 = 0.452and *RMSE* = 1.85m.

While the coefficient for the interaction term $I_E \times M1\_P$ showed a significantly positive trend, indicating an SI increase with higher M1-P levels on E group soils, its magnitude was relatively small. Even with the highest observed M1-P value of 70.16 mg kg^{-1} on E group soils, the predicted increase is 2.41 m, which falls short of offsetting the negative estimate for I_E. Consequently, on average, the estimated SI of slash pine in soil group E was lower than that in soil group A. This positive SI and M1-P correlation for slash pine in soil group E was also confirmed by the optimal regression tree model.

It's worth noting that the final linear regression model identified a significantly negative coefficient for $I_{B2} \times M1\_P$, suggesting a decrease in SI with higher M1-P levels on B2 group soils, despite their limited range of M1-P (1.08 – 2.30 mg kg^{-1}). However, this negative correlation was not validated by the optimal regression tree model, wherein all slash pine plots in soil group B2 were allocated a constant SI of 17.7 m.

The relationship between slash pine SI and soil parameters (soil classification and M1-P) in the Coastal Plain in the NRCS study was described by:

$$SI = 23.8229 - 2.2604I_{B1} - 3.5659I_{B2}{\cdot}M1\_P - 3.3035I_C - 2.8133I_D - 2.8374I_E + 0.0344I_E{\cdot}M1\_P - 2.0494I_{F1} - 4.8339I_{F2} - 8.3287I_{F3} - 5.5970I_G \quad (1)$$

The optimal regression tree model exhibited superior performance with a higher R^2 value and a smaller *RMSE* value compared to the final linear regression model. Scatterplots, depicting the predicted and observed slash pine SI for both model approaches, further affirmed a more suitable fit for the optimal regression tree model when juxtaposed with the final linear regression model (Fig. 3). Consequently, the optimal regression tree model was chosen for the prediction of slash pine SI in the Coastal Plain (Table 3).

3.3. Comparisons of SI for slash and loblolly pine

Fig. 4 illustrates the average estimated SI values for slash pine by soil groups from the NRCS study, providing a comparison with the average estimated SI values for loblolly pine in the previous study (Zhao et al., 2024a).

Regarding the average estimated slash pine SI, there were no notable differences between the A and B3 soil groups, among the B1, E, and F1 soil groups, between the C and D, and among the B2, F2 and F3 soil groups (Fig. 4). The ordering of soil groups in terms of their SI was as follows: (A, B3) > (B1, E, F1) > (C, D) > G > (B2, F2, F3). Overall, slash pine demonstrated inferior performance in soil groups B2, F2, F3, and G, with a SI range of 17.7 – 18.9 m, while showing better performance in soil groups A, B1, B3, E, and F1, with a SI range of 21.6 – 23.9 m. Conversely, loblolly pine exhibited excellent performance across soil groups A, B1, B2, B3, E, F1, and F2, with an average SI exceeding 24 m.

Both loblolly and slash pines performed worse in soil groups D, F3, and G (Fig. 4). However, slash pine exhibited slightly better performance than loblolly pine in soil groups D and G, whereas loblolly pine showed slightly better performance in soil group F3. In all other soil groups, loblolly pine outperformed slash pine. The largest contrast in SI between loblolly and slash pines was observed in soil groups B2 and F2, with discrepancies of 7.5 m and 7.1 m, respectively.

In the CPCD study, the original soil group "B2" encompassed the B3 group, which was used in the NRCS study. All slash pine plots in the CPCD study were distributed across B1, B2&B3, C and D group soils. The observed SIs of the CPCD operational plots with a planting density of 2224 trees ha^{-1} were averaged for each soil group base, and then

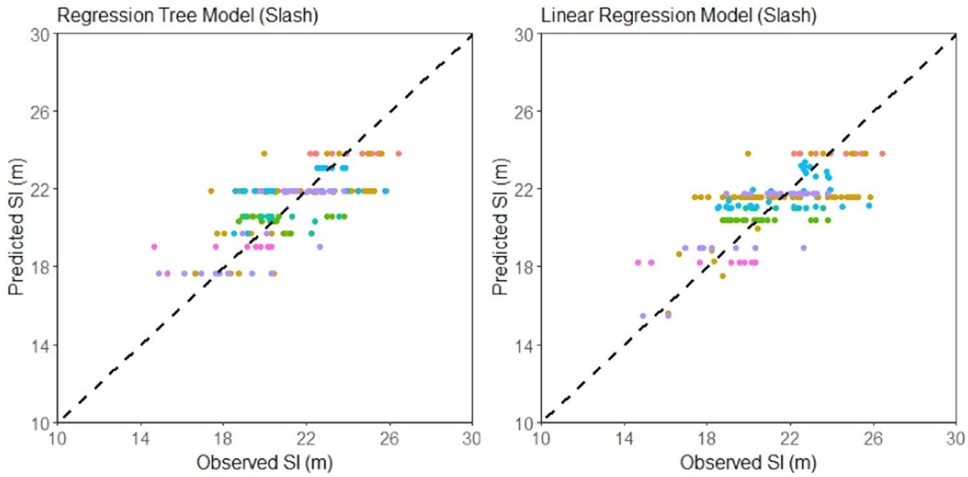

Fig. 3. Predicted vs. observed values of slash pine site index (SI, m) at base age 25 years using the optimal regression tree model (left) and the final linear regression model (right). The dashed line is the one-to-one line.

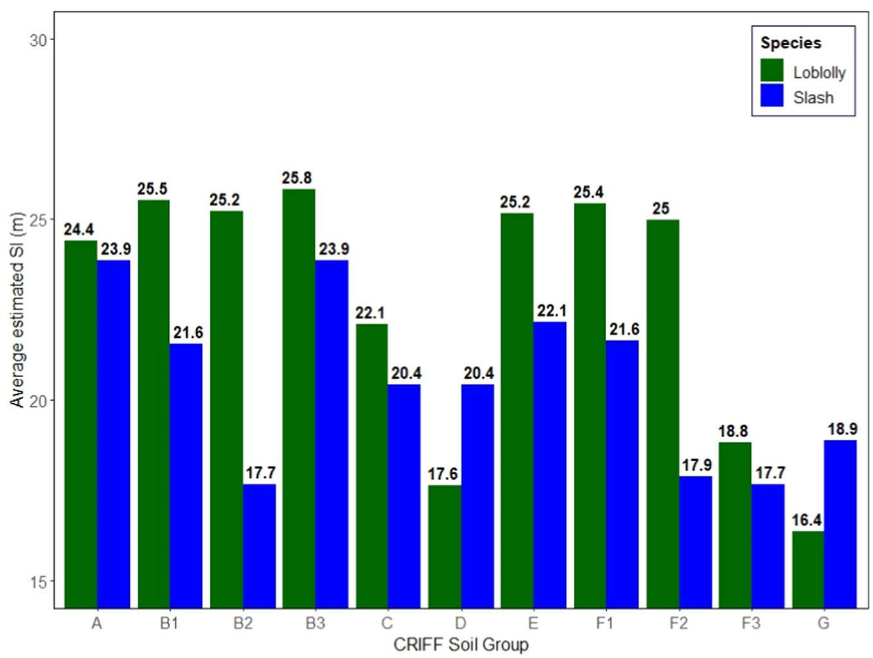

Fig. 4. Comparison of average site index (SI, m) between slash pine and loblolly pine based on the modified Cooperative Research in Forest Fertilization soil groups in the NRCS study. The average SI for loblolly pine was estimated in Zhao et al. (Zhao et al., 2024a a).

compared with the average estimated SI in the NRCS study (Fig. 5).

On B1 group soils, the average slash pine SI was 21.6 m in the NRCS study and 25.1 m in the CPCD study. The average estimated SI for slash pine were 17.7 and 23.9 m, respectively, on the B2 and B3 group soils in the NRCS study. In the CPCD study, without distinguishing between B2 and B3, the average base SI for slash pine was 24.3 m.

The average estimated SI for slash pine on both C and D group soils was 20.4 m in the NRCS study, while the average observed SI on the C and D group soils was 24.5 m and 22.6 m in the CPCD study, respectively. In general, the average estimated SI for slash pine in the NRCS study was lower than the observed slash pine SI in the CPCD study.

3.4. Mean annual increments (MAI)

Using the average estimated SI derived from the optimal regression tree model, we simulated stand volume and stem green weight MAIs for each soil group using the growth and yield model system for slash pine. Figs. 6 and 7 illustrate the MAIs at ages 10, 15, and 20 years for slash pine stands with tree densities of 1236, 1483, and 1730 trees ha^{-1} at age 5 years, representing stand volume and stand green weight respectively. Slash pine performance, as indicated by MAIs, classified the soil groups into five tiers, ranging from well-performing to poor-performing: (A, B3), (B1, E, F1), (C, D), G, (B2, F2, F3).

Using the average estimated SI derived from the optimal regression tree model and slash pine growth and yield model system, we also simulated stand volume and stem green weight MAIs for slash pine stands planted at a density of 2224 trees ha^{-1} on the B1, B2, B3, C and D group soils. We then compared these simulations with the average observed MAIs in “operational” plots with the same panting density of 2224 trees ha^{-1} in the CPCD study.

Compared to plots in the NRCS study, the “operational” plots in the CPCD study are subject to more intensive management. In the CPCD study, the “B2” soil group combined the B2 and B3 groups as defined in the NRCS study. The “operational” regime implemented in the CPCD

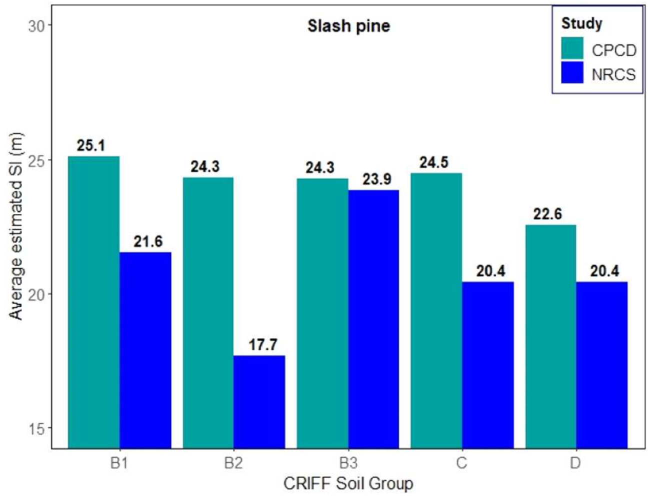

Fig. 5. Comparison average site index (SI, m) for slash pine based on the modified Cooperative Research in Forest Fertilization soil groups between the estimates from the NRCS study and observations from the "operational" plot with 2224 trees ha^{-1} planting density in the CPCD study. In the CPCD study, without distinguishing between B2 and B3, both had the same average base SI of 24.3 m.

study resulted in increased MAIs compared to the NRCS study plots, particularly evident on the B2, C and D group soils (Fig. 8).

4. Discussion and conclusions

In analyzing the relationship between slash pine site index and soil traits, initial variables included surface soil extractable P, depths to argillic and spodic horizons, and depth to seasonal high-water table, excluding soil groups. This initial regression tree model had a higher R^2 (0.529) and lower RMSE (1.66 m) but was biologically unreasonable. Including modified Cooperative Research in Forest Fertilization soil groups, the optimal regression tree model retained soil groups and M1-P, with a slightly lower R^2 (0.490) and higher RMSE (1.72 m). The final linear regression model, also using soil groups and M1-P, had a lower R^2 (0.452) and higher RMSE (1.85 m), showing the regression tree model was better for predicting slash pine site index in the Coastal Plain.

In a previous study (Zhao et al., 2024a), both models predicted loblolly pine site index using soil traits, identifying soil groups and M1-P as significant factors. For loblolly pine, the linear regression model performed better, with a higher R^2 (0.899) and lower RMSE (1.12 m), unlike the current study for slash pine. This performance difference is due to greater variability in slash pine site index across soil groups (Fig. S1). Other environmental factors may also impact slash pine site index. Using topographic and climatic variables, Fiandino et al. (2020) modeled site index for slash pine plantations in central Argentina, achieving a high R^2 (0.83).

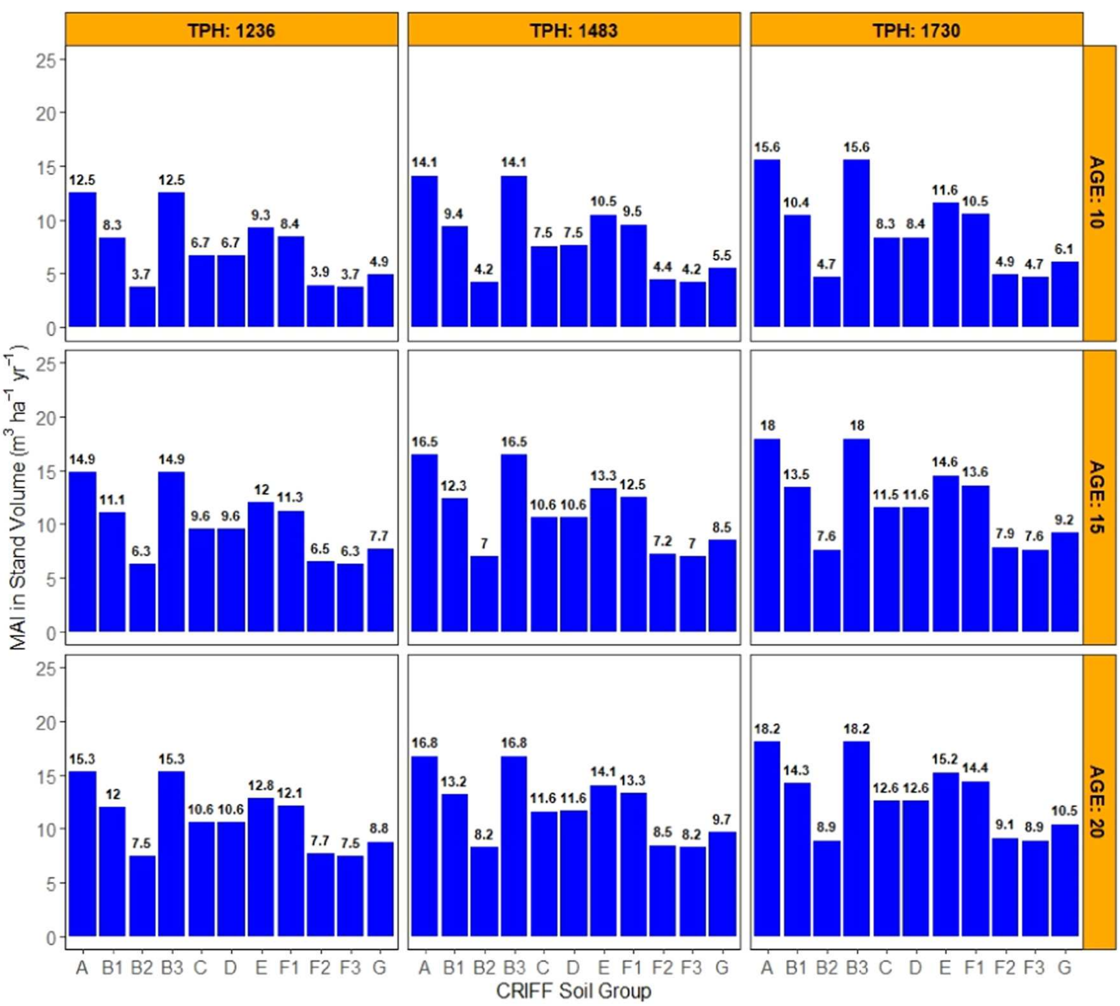

Fig. 6. The mean annual increments (MAI) in stand volume (m^3 ha^{-1}) were simulated using the growth and yield model systems for slash pine plantations based on the average estimated SI from the optimal regression tree model and tree densities of 1236, 1483 and 1730 trees ha^{-1} (TPH) at age 5 years.

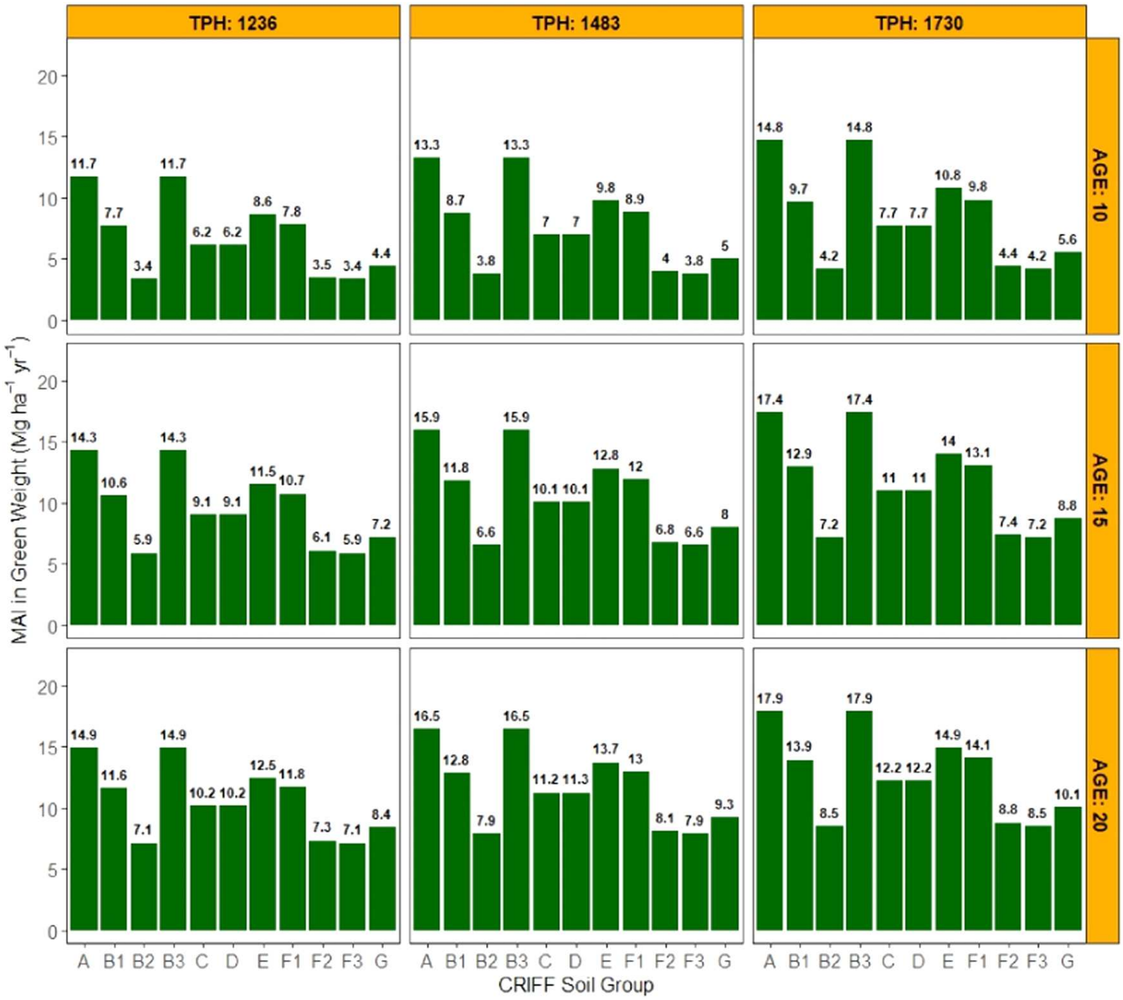

Fig. 7. The mean annual increments (MAI) in stand outside-bark stem green weight (Mg ha^{-1}) that were simulated using the growth and yield model systems for slash pine plantations based on the average estimated SI from the optimal regression tree model and tree densities of 1236, 1483 and 1730 trees ha^{-1} (TPH) at age 5 years.

Soil P significantly influenced both loblolly and slash pine site index, but its impact was stronger and more consistent in loblolly pine. A positive correlation between M1-P and site index was observed for loblolly pine in soil groups B1, B2, E, F1, F2, and G (Zhao et al., 2024a). For slash pine, this correlation was mainly evident in soil group E, which had a wide M1-P range (1.32–70.16 mg kg^{-1}) (Table 2). Most slash pine plots in other soil groups had M1-P below 5 mg kg^{-1}, a threshold level on flatwood very poorly, poorly and somewhat poorly drained soils (Ballard and Prichett, 1975) (Table 2, Fig. S2). In the NRCS study, higher site indices were found in slash pine plots from progeny stands in soil group E and plots with a history of fertilization in soil group G. These plots had lower woody and herbaceous competition and higher M1-P levels (Table S1). Elevated M1-P values in loblolly pine plots in soil groups E, F1 and G indicated prior fertilization, which sustains higher available P levels (Scott and Bliss, 2012).

Soils classified as Group A are typically the most phosphorus-deficient and have excessive moisture in the Southern region, which can limit pine growth (Jokela and Long, 2018). Surprisingly, in the NRCS study, slash pine performed best on soil group A, even with low M1-P levels (< 5 mg kg^{-1}) in 9 out of 10 plots, while loblolly pine performed well across A, B1, B2, B3, E, F1 and F2 soil groups. Loblolly pine consistently outperformed slash pine across B subgroups (Fig. 4 and Fig. S3), though slash pine showed better performance on B3 compared to B1 and B2. The superior performance on B3 soils, typically rich in organic matter, suggests better water and nutrient retention. Lower M1-P values (< 2.3 mg kg^{-1}) in B2 soils likely restricted slash pine growth there.

In the CPCD study, under "operational" management that includes practices such as bedding, chemical site preparation, post-plant herbaceous weed control, and repeated fertilization with NPK and NP, slash pine site index increased significantly, reaching 25.1 m on B1 and 24.3 m on B2 soils, outperforming NRCS predictions (refer to Fig. 5). This "operational" culture led to site index increases of 3.4 m and 6.6 m for slash pine on B1 and B2 soils, respectively (Fig. 5), compared to 1.6 m and 0.8 m for loblolly pine (Zhao et al., 2024a).

Soils classified as Group C and D frequently exhibit deficiencies in nitrogen and phosphorus (Jokela and Long, 2018). Slash pine outperformed loblolly pine on soil group D but underperformed on soil group C, which contrasts with Borders and Harrison (Borders and Harrison, 1989) but aligns with Haines and Gooding (Haines and Gooding, 1983), who recommend planting slash pine for Spodosols that lack an argillic horizon, which includes Group D soils.

Comparing site index values from the NRCS study, the "operational" management in the CPCD study increased slash pine site index by 4.1 m on Group C soils and 2.2 m on Group D soils, resulting in 24.5 m and 22.6 m, respectively (Fig. 5). For loblolly pine, the site index increased by 5.4 m on C soils and 4.8 m on D soils, reaching 27.5 m and 22.4 m, respectively (Zhao et al., 2024a). Intensive management showed loblolly and slash pines performed comparably on D soils, but loblolly pine outperformed slash pine on C soils. Loblolly pine showed a strong

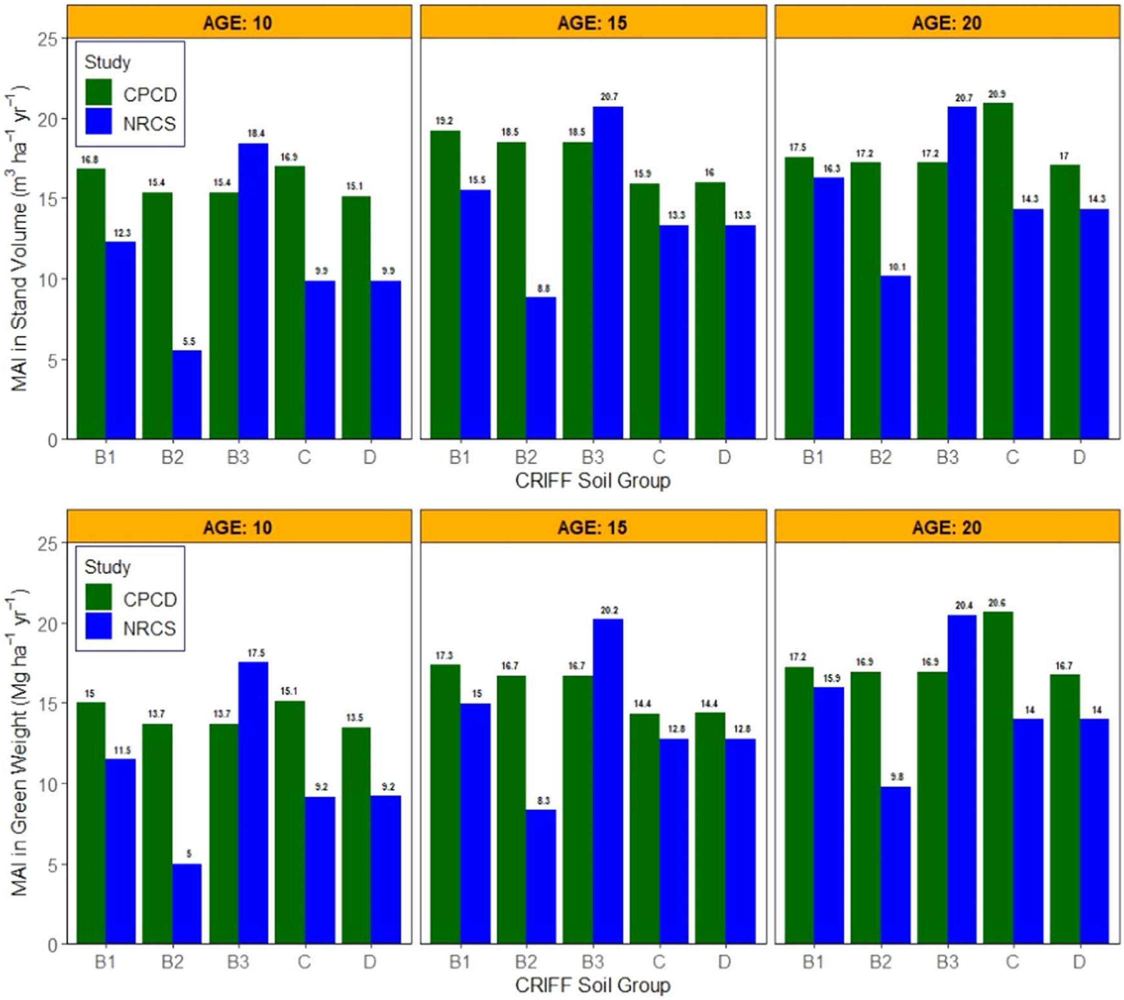

Fig. 8. Comparisons of slash pine stand volume and green weight MAIs between the NRCS and CPCD studies. The values were simulated with the average estimated site index and initial density of 2224 trees ha^{-1} in the NRCS study, while the values were observed in the "operational" plot with 2224 trees ha^{-1} planting density in the CPCD study. In the CPCD study, without distinguishing between B2 and B3 soil groups, both had the same value.

response to fertilizer and weed control treatments on Group C and D soils (Jokela and Long, 2018).

In the NRCS study, loblolly pine consistently outperformed slash pine on E, F1, and F2 soils (Fig. 4 and Fig. S3). Slash pine performed well on E and F1 soils but poorly on F2 soils with low M1-P levels (0.05 – 2.39 mg kg^{-1}). Both pines underperformed on F3 soils, with loblolly slightly better. The good performance on E soils is likely due to past fertilization in progeny test stands, and on F1 soils, due to former forest industry research sites' fertilization.

Both pines in soil group G had high surface soil P (Fig. S2), due to past forest management or old-field sites, but still showed poor performance, with slash pine outperforming loblolly (Fig. 4). This contrasts with Borders and Harrison (Borders and Harrison, 1989), who recommended loblolly for G soils. These soils are deep, coarse-textured, prone to drought, and low in water and nutrient retention, limiting fertilizer effectiveness (Jokela and Long, 2018). Thus, sand pine (*P. clausa*) and longleaf pine (*P. palustris*) are preferred for reforestation on such soils (Jokela and Long, 2018).

Pine growth response of pines to silvicultural management is inversely related to base site quality (Zhao et al., 2016). In the NRCS study, most loblolly and slash pine plots had minimal or no fertilization history. Loblolly pine plots showed higher site index in soil group B compared to A. However, in the CPCD study, loblolly pines on soil groups B1, B2 and B3 were less responsive to intensive management than those on soil group A, consistent with Ballard and Prichett (1975) and Jokela and Long (Jokela and Long, 2018). Slash pine, however, responded more to intensive management on B1 and B2 soils, likely due to lower M1-P levels. Surface soil P were below 5 mg kg^{-1} in almost all slash pine plots and most loblolly plots. Both species responded well to fertilizer and weed control treatment on soil groups C and D (also see Jokela and Long, 2018). This contrasts with Pritchett and Comerford (Pritchett and Comerford, 1982), who found the most significant growth response to phosphorus fertilization in slash pine on poorly drained Group A and B soils, but not on Group C, D, or excessively drained G soils.

Ballard and Pritchett (Ballard and Pritchett, 1975) found significant growth response to phosphorus fertilization for slash pine on soils with surface soil P concentration below 5 mg kg^{-1}, primarily on Group A and B soils. No pronounced growth response was observed when M1-P exceeded 5 mg kg^{-1}. In the NRCS study, most slash pine plots (116 out of 157) had M1-P levels below 5 mg kg^{-1}, except for soil groups E and G. This indicates potential to enhance slash pine productivity on non-industrial private forest landowners' properties through fertilization with P, N+P, and/or N+P+K, except on Group G soils, where longleaf or sand pine are preferable.

In summary, the optimal regression tree model for predicting slash pine site index provides non-industrial private forest landowners with valuable tools to assess site productivity for slash pine in the Coastal Plain, especially where forest stands are not yet established. The revised site index and mean annual increments for each soil group aid strategic planning for planting or replanting. The modified Cooperative Research in Forest Fertilization soil grouping serves as a useful base for evaluating site productivity and making species-site recommendations. Loblolly pine is the preferred choice for soil groups B, E, F1 and F2. Either loblolly or slash pine is suitable for soil groups A, C, and F3. Slash pine is recommended for soil groups D and G, while longleaf and sand pine are better suited for Group G soils.

CRediT authorship contribution statement

Ernest David Dickens: Writing – review & editing, Supervision, Project administration, Investigation, Funding acquisition, Conceptualization. **Dehai Zhao:** Writing – original draft, Visualization, Validation, Methodology, Investigation, Formal analysis, Conceptualization. **Bronson P. Bullock:** Writing – review & editing. **Daniel Markewitz:** Writing – review & editing. **David C. Clabo:** Writing – review & editing, Investigation. **Dee Cabaniss Pederson:** Writing – review & editing, Investigation, Funding acquisition.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data Availability

Data will be made available on request.

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Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.foreco.2024.122093.

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