Forest Ecology and Management 565 (2024) 122054

Contents lists available at ScienceDirect

Forest Ecology and Management

journal homepage: www.elsevier.com/locate/foreco

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

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ARTICLE INFO

Keywords:
Southern pine
Soil properties
Site index
Mean annual increment
Surface soil extractable P
CRIFF

ABSTRACT

Site productivity and forest management strategies hinge on intrinsic site resources such as soil water and nutrient availability. In this study, regression tree model and linear regression model approaches were employed to quantify the relationship between site index and soil parameters for loblolly pine plantations in the Coastal Plain. Both the optimal regression tree model and the final linear regression model identified modified CRIFF (Cooperative Research in Forest Fertilization) soil groups and surface soil extractable phosphorus (Mehlich 1 P) as significant variables for predicting site index. The final linear regression model, with a R^2 of 0.899 and an *RMSE* of 1.12 m, exhibited superior performance compared to the optimal regression tree model. Additionally, mean annual increments in stand volume and green weight for each soil group were simulated and compared with data from a long-term loblolly pine culture/density experimental study in the same region. These resulting predictive models offer applicability across diverse sites and are particularly well-suited for areas where forest stands are not currently established.

1. Introduction

In the southern United States, there are about 14.5 million hectares of natural pine forests and 16.8 million hectares of pine plantations (Oswalt et al., 2019). Loblolly pine (*Pinus taeda* L.) and slash pine (*P. elliottii* Engelm. var. *elliottii*) are the two most important commercial timber species in this region (Dicus and Dean, 2008). Over 50 % of industrially owned lands have been developed into intensively managed plantations, characterized by substantial inputs including mechanical and chemical site preparation, post-planting woody and herbaceous competition control, fertilization, and the adoption of genetically improved seedlings (Martin and Jokela, 2004; Fox et al., 2007; Zhao et al., 2016). Non-industrial private forest landowners (NIPFLs) have also intensified their approaches to plantation establishment and management, using it as a primary or secondary source of income through timber and pine straw (Jokela and Long, 2018). However, in general, NIPFLs tend to implement either extensive or less-intensive management strategies.

Site productivity assessment enables forest managers to determine the optimal rotation age, thinning, sustainable yield, and regeneration cutting strategies (Pretzsch, 2009), and aids in the selection of appropriate tree species for reforestation (Zhao and Kane, 2012; Zhao et al., 2019). Site productivity is usually quantified through site index (SI), which represents the average dominant height of a stand at a reference age (Carmean, 1975; Skovsgaard and Vanclay, 2008). This measure assumes that dominant height remains relatively unaffected by a specific range of stand density. Site index serves as a widely used indicator of site quality for even-aged, single-species forest stands, such as pine plantations in the southern US.

However, observations in plantation stands suggested that stand dominant height might be influenced by extremely low or high initial planting densities (Zhao et al., 2008, 2012; MacFarlane et al., 2000). When site productivity is defined as site production achievable at a specific site with a given genotype and under a specified management regime (Skovsgaard and Vanclay, 2013), the correlation between site index and volume (or weight) growth may be weak. This can result in considerable site-dependent variations in total volume (or weight) production at a given height, within a specified growth region, and even for a well-designed silviculture (Assmann, 1970; Skovsgaard and Vanclay, 2013). Furthermore, site productivity is subject to temporal

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https://doi.org/10.1016/j.foreco.2024.122054
Received 15 April 2024; Received in revised form 30 May 2024; Accepted 2 June 2024
Available online 8 June 2024
0378-1127/

variation (Skovsgaard and Vanclay, 2013; Zhao et al., 2023), which can be measured using mean annual increment (MAI). Mean annual increment is calculated by dividing the total volume (or weight) by the stand age.

NIPFLs and practicing foresters have been seeking updated estimates of SI and MAI from the United States Department of Agriculture (USDA) Natural Resources Conservation Service (NRCS) for more than four decades. Although the NRCS provides SI values for various soil series categorized by pine species, a significant challenge arises from the utilization of outdated SI models. These models were developed based on data from unmanaged stands composed of trees with unimproved genetics, where the data were collected several decades ago, and the SI base age was 50 years. For instance, the SI models for natural stands of southern pines, originally developed by Schumacher and Coile (1960), are still being employed by the Forest Inventory and Analysis (FIA), NRCS, NIPFLs, and some consulting foresters regardless of the origins of the stands. Reliance on outdated models poses a challenge in accurately assessing site productivity in contemporary forest management contexts.

Over the past six decades, the productivity of pine plantations has substantially improved, leading to shortened rotations compared to natural pine forests. This improvement can be attributed to various silvicultural practices such as site preparation, control of understory competition, fertilization, and the use of genetically improved seedlings (Martin and Jokela, 2004; Jokela et al., 2010; White and Duryea, 1997; Zhao et al., 2019). While the SI values are traditionally calculated based on a 50-year base age for naturally regenerated stands, planted pine stands typically use a base age of 25 years for SI calculations. Recognizing the importance of keeping pace with advancements in forest management practices, the NRCS acknowledges the necessity of updating information related to SI and MAI culmination for southern pines.

Soils provide two essential resources for trees: water and nutrients. The University of Florida Cooperative Research in Forest Fertilization (CRIFF) soil grouping scheme utilizes soil drainage classes and the presence/depth to an argillic horizon, as well as the presence/depth to a spodic horizon to classify Coastal Plain soils into eight groups (Fig. 1). The CRIFF system is widely used to inform fertilizer recommendations for southern pines and aid pine species selection for specific sites (Jokela and Long, 2018). Numerous studies in the Coastal Plain have demonstrated a strong correlation between surface soil extractable phosphorus (P) and P fertilization and the growth of loblolly and slash pines, including height, basal area, and volume growth on various soil series (i.e., CRIFF A and B group soils). However, there is less observed correlation on CRIFF C and D soils (Ballard and Pritchett, 1975; Pritchett and Comerford, 1982; Wells et al., 1973; Gent et al., 1986; Hynynen et al., 1998). Surface soil P tends to be less mobile than N and K in most soils (Ballard, 1980). Its concentration may be correlated to previous land management, land use history, and the growth of southern pines on CRIFF E, F and G group soils.

The aim of our research, carried out under a Cooperative Agreement with the NRCS, was to establish updated estimates for SI and MAI for loblolly and slash pines based on soil parameters. This paper, serving as the initial publication of our project, focuses on development of predictive models for loblolly pine SI in the Coastal Plain. We utilized modified CRIFF soil groups and soil nutrient status, particularly focusing on available P in the surface soil layer (0–15 cm). Subsequently, stand volume and stem outside-bark green weight MAIs were simulated for each soil group.

We evaluated the accuracy of our findings by comparing and verifying them against data from a long-term loblolly pine experimental study conducted across the region. Surface soil available P could serve as a crucial indicator of site fertility, exerting a significant impact on loblolly pine SI and MAI. During the modeling process, we investigated the hypothesis of varying effects of surface soil available P on loblolly pine SI among different soil groups, considering its highly variable concentration within and among some soil groups. The resulting models are applicable across diverse sites and are particularly suitable for areas where forest stands have not yet been established.

2. Materials and methods

2.1. Study areas and field measurement

All plots in the NRCS study were established in Georgia on primarily NIPFLs' properties, with some plots located on state and forest industry owned lands. Plots were located throughout the Coastal Plain of Georgia (Fig. 2) across two Major Land Resource Areas (MLRAs): Southern

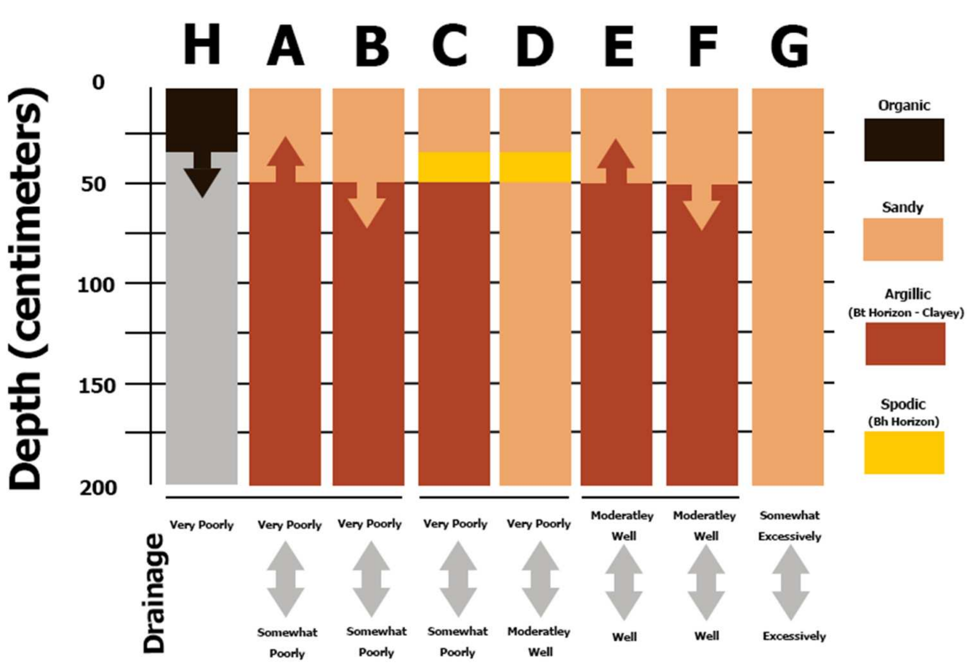

Fig. 1. A soil classification system developed by the University of Florida's Cooperative Research in Forest Fertilization program (CRIFF) employed to guide forest management strategies in the Coastal Plain region. Redrawn from Jokela and Long (2018).

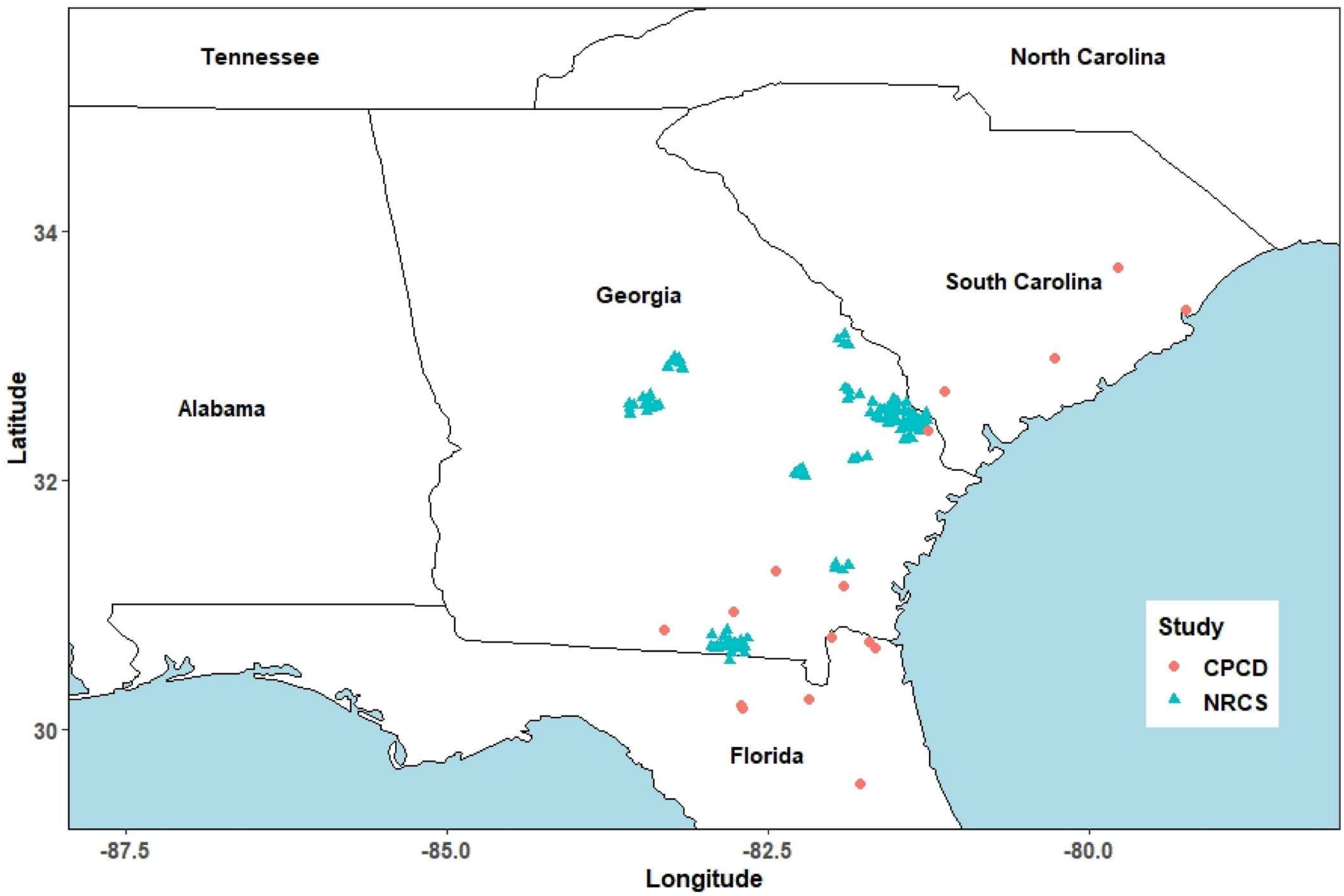

Fig. 2. Locations of the NRCS loblolly pine research plots and locations of research installations selected from the Lower Coastal Plain Culture/Density study (CPCD).

Coastal Plain (MLRA 133 A) and Atlantic Coast Flatwoods (MLRA 153 A) (USDA Natural Resources Conservation Service, 2022). Of the 118 inventoried stands for the study, 7.4 % were in the Southeastern Plains Sand Hills ecoregion of Georgia (Griffith et al., 2001). This ecoregion is a rolling, highly dissected landscape with low nutrient soils formed in thick beds of sand, though some soils with high loam or clay content do exist. Moving north to south, 15.7 % of plots were in the Coastal Plain Red Uplands ecoregion (Griffith et al., 2001). Soils in this ecoregion are mostly well-drained with a brown or reddish-brown loamy or sandy surface layer and red subsoils. The Atlantic Southern Loam Plain or Vidalia Upland contained 20.7 % of plots used in the study. This area is characterized by flat to gently rolling topography often with fine textured soils (Griffith et al. 2001). Continuing south, 33.9 % of plots were in the Sea Island Flatwoods ecoregion. The ecoregion is characterized by poorly drained, flat plains common to the Spodosol soil Order, though a few areas of better drained soils in the Ultisols soil Order do occur (Griffith et al. 2001). The most southern ecoregion where plots were located was the Okefenokee Plains, which had 22.3 % of plots. This area consists of flat plains and low terraces with somewhat-poorly to poorly drained soils. Spodosols are common in this ecoregion. Climate across these ecoregions over the 100-year period from 1901 to 2000 varied from north to south across the study region. Maximum average temperature ranged from 24.2 °C in Baldwin County to 26.2 °C in Echols County, minimum average temperature ranged from 10.7 °C in Baldwin County to 12.4 °C in Echols County. Average annual precipitation ranged from 1,155 mm in Burke County (northern limit of study area) to 1,293 mm in Echols County, the most southern county in the study (NOAA National Centers for Environmental Information, 2024).

Stands where plots were installed received site preparation (mechanical, herbicide or both) and were planted primarily with 1–0 stock open pollinated loblolly pine families though some sites (3 plots) were planted with closed pollinated seedlings. Plots were circular and 0.04 ha. Plots were installed mostly in sets of three, with plot sets in a stand established relatively close together to reduce variability for a given soil map unit and stand attributes. Of the 118 plots installed, nine were on former old-field sites, six were on a former progeny test area that had been an old field for a couple of decades prior, and the remaining 103 plots on cutover sites.

The latitude and longitude, along with silvicultural details such as planting month and year, planting spacing, bedding status (yes or no), and thinned status (yes or no) were documented for each plot. Pine planting spacing was measured and tallied within each 0.04-ha measurement plot and ranged from 1,160 trees ha^{-1} to 3,680 trees ha^{-1}. Diameter at breast height (dbh) and total height were measured for all loblolly pine trees in the measurement plots. Additionally, two or three 0.004-ha circular plots within the 0.04-ha plot were sampled to assess woody competition. Shrub cover was recorded by genus or species, including percentage ground cover (ocular assessment) and height. Hardwoods and volunteer pines with a dbh $\geq$ 2.5 cm were tallied by genus or species, considering diameter class, total height, and number per 0.004-ha plot.

Surface (0–15 cm) mineral soil was sampled at 6–8 randomly chosen locations within each circular 0.04-ha plot using a stainless-steel soil probe. Samples were then analyzed for pH (Kissel and Vendrell, 2012), as well as concentrations of Mehlich 1 P (M1-P) (Mehlich, 1953), potassium (K), calcium (Ca), magnesium (Mg), manganese (Mn), and zinc (Zn). Soil profile data (0–2 m) included the presence and depth of Bt (argillic horizon), presence and depth to Bh (spodic horizon), depth to seasonal high-water table, and drainage class. Based on soil drainage class and the presence/depth to Bt and Bh horizons, plots were classified into modified CRIFF soil groups (Tables 1 and 2).

For comparison purposes, two additional datasets from experimental studies on loblolly pine conducted by the UGA Warnell School of Forestry and Natural Resources were employed. The first dataset was derived from the Coastal Plain culture and density study (CPCD) conducted by the Plantation Management Research Cooperative (PMRC) at 15 installations (or locations) in the Lower Coastal Plain of Georgia, Florida, and South Carolina, across five soil groups (3 locations in CRIFF A, B1, B2, C and D soil groups) (Fig. 2). Soil group B2 in the CPCD study combined both B2 and B3 groups, as adopted in our NRCS study. At each location, there were six levels of planting densities (741, 1,483, 2,224, 2,965, 3,706 and 4,448 trees ha^{-1}) and two levels of cultural treatment (intensive and operational). At each installation, there was a random assignment of cultural intensities to main plots, and within a cultural intensity level the planting densities were randomly assigned to subplots. The operational treatment consisted of bedding in the spring followed by a fall banded chemical site preparation and a first-year spring herbaceous weed control (HWC) treatment. The intensive cultural treatment included bedding in the spring followed by a fall broadcast chemical site preparation, tip moth control through the first two growing seasons and repeated herbicide applications to achieve complete vegetation control throughout the rotation. At planting, 561 kg ha^{-1} of 10–10–10 fertilizer was applied on all plots. The operational treatment plots were fertilized with the equivalent of 224 kg N ha^{-1} and 28 kg P ha^{-1} before the 8th, 12th, and 20th growing seasons. The intensive cultural treatment plots also received 673 kg ha^{-1} of 10–10–10 plus micronutrients and 131 kg ha^{-1} of NH_4NO_3 in the spring of the 3rd growing season, 131 kg ha^{-1} NH_4NO_3 in the spring of the 4th growing season, 336 kg ha^{-1} NH_4NO_3 in the spring of the 6th growing season, and 224 kg N ha^{-1} and 28 kg P ha^{-1} in the spring of the 8th, 10th, 12th, 14th, 16th, 18th, 20th, and 22nd growing seasons.

In the CPCD study, an interior measurement plot within each treatment plot was established for data collections. All trees in measurement plots were tagged and measured in the dormant season for dbh, and every other tree was measured for total height after the fourth growing season. Measurements were repeated every two years until age 12 years and then every-three years until age 24 years. Total height of trees not measured for height was estimated from the model $\ln(H) = b_0 + b_1/dbh$ fitted separately for height measured trees in each plot at each measurement age. For more information about the experimental design and treatment regimes in the CPCD, please refer to Zhao et al. (2019).

The second dataset originated from the UGA Warnell School site preparation and herbaceous weed control (HWC) study conducted on the Orsino soil series, specifically a CRIFF D soil. This study had eight plots: four plots with HWC and four plots without HWC (Clabo and Dickens, 2023). Dbh and total height were measured for all trees in each plot. While neither this study nor the CPCD study involved sampling surface soil for available P determination, comprehensive information regarding site preparation, HWC, and fertilization history is available for both studies.

Table 1
Modified CRIFF soil groups used in the study.

Soil Group	Drainage Class *	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	P – 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 cm or absent to 200 cm
G	SE – E	No Spodic, No Argillic

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

Table 2
The plot number, stand age ranges and means, surface (0–15 cm) soil Mehlich 1 P (M1-P, mg kg^{-1}), and site index (SI, m) by the CRIFF soil groups.

CRIFF Soil Group	Plot Number	Age		M1-P		SI	
		Range	Mean	Range	Mean	Range	Mean
A	12	8 – 27	21.0	1.7 – 5.8	3.4	23.0 – 25.7	24.6
B	25	9 – 28	19.1	1.6 – 48.5	6.5	23.0 – 28.4	25.6
B1	13	9 – 28	20.6	1.6 – 8.6	3.6	23.3 – 28.4	25.6
B2	2	9 – 28	18.5	2.2 – 3.1	2.6	23.0 – 26.9	25.0
B3	10	9 – 25	17.2	2.4 – 48.5	11.0	24.0 – 27.9	25.8
C	20	13 –28	22.0	1.2 – 3.2	2.0	20.2 – 24.5	22.1
D	4	13	13.0	0.8 – 1.3	1.1	16.5 – 18.3	17.6
E	19	7 – 21	11.5	2.5 – 86.5	31.5	23.0 – 27.2	25.2
F	26	7–23	15.0	2.4 – 48.7	15.6	17.9 – 27.7	23.7
F1	15	7–21	12.5	2.4 – 48.7	20.0	24.0 – 27.7	25.5
F2	5	7 – 20	14.8	3.5 – 24.5	11.2	22.8 – 25.4	24.0
F3	6	20 – 23	21.5	4.0 – 15.6	8.4	17.9 – 19.8	18.8
G	12	20 – 29	25.1	8.4 – 54.5	30.1	13.3 – 18.8	16.3

Individual tree outside-bark stem volume and green weight were estimated using loblolly pine tree equations updated by Zhao et al. (2024). Stand-level volume and green weight were calculated by summing each plot at the time of measurement and then converting to a per hectare basis using the appropriate expansion factor based on the plot size.

2.2. Site productivity

Site index (SI) was quantified based on the average height of dominant and codominant trees (HD) at the reference age of 25 years. In this analysis, dominant and codominant trees were defined as those with a dbh greater than the average dbh of the stand in unthinned stands (Zhao et al., 2019) or as the tallest 80 % of trees in thinned stands. The SI for each of 118 NRCS study plots and eight UGA Warnell School site preparation and HWC study plots was determined using the PMRC proprietary SI model (Borders et al., 2014). Summary information, including plot number, stand age ranges and means, M1-P, and SI categorized by soil groups, is presented in Table 2 for the NRCS study plots.

In the PMRC CPCD study, the most recent measurement was used to calculate the SI for each of 180 chosen unthinned loblolly pine plots. The base SI was determined as the SI of operational plots with a planting density of 1,483 trees ha^{-1}. The impact of planting density and cultural intensity on SI variation was investigated through a scatter plot depicting the base SI and the corresponding expressed SI.

2.3. Soil-based site index model – regression trees approach

The regression trees approach was employed to establish the relationship between SI and soil parameters using data from the NRCS study plots. The explanatory variables comprised a set of pertinent soil predictors: modified CRIFF soil groups, M1-P, presence/depth to an argillic horizon (Bt_Depth), presence/depth to spodic horizon (Bh_Depth), and presence/depth to seasonal high-water table (Water_-Depth). The model was fitted in R (R Core Team, 2023) version 4.2.3, using rpart package version 4.1.19 (Therneau and Atkinson, 2022).

2.4. Soil-based site index model – linear regression model

The dummy variables were set to identify the modified CRIFF soil groups:

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

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

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

Utilizing data collected from the NRCS study plots, the dependent variable, observed SI values, was regressed against CRIFF soil groups (represented as dummy variables), M1-P, Bt_Depth, Bh_Depth, Water_-Depth and various interaction terms. Only variables with statistically significant coefficient estimates ($p < 0.05$) were retained in the final model. Variation inflation factors (*VIF*s) were calculated to detect multicollinearity in the final model. The coefficient of determination (R^2) and root mean square error (*RMSE*) were computed to evaluate the model's performance.

2.5. Mean annual increments (MAI)

After comparing the two modeling approaches for soil-based SI, the better SI model was employed to estimate the SI value for each NRCS study plot. Subsequently, the estimated SI values were averaged for each soil group and subgroup. The average estimated SI values from the NRCS study were then compared with the base SI values from the CPCD study. Utilizing the average estimated SI values and tree densities of 1,236, 1,483, and 1,730 trees ha^{-1} at age 5 years, the stand volume and green weight MAIs at ages 10, 15, and 20 years were simulated for each soil group using the PMRC loblolly pine growth and yield model system (Borders et al., 2004, 2014).

For the operational plots with a planting density of 1,483 trees ha^{-1} in the CPCD study, the MAIs in stand volume and green weight at measurement ages were also calculated. Subsequently, these observed MAIs from the CPCD study were compared with the simulated MAIs from the NRCS study on the soil group basis.

3. Results

3.1. Regression tree model for loblolly pine SI

The optimal regression tree model identified two major predictor variables for loblolly pine SI in the Coastal Plain: modified CRIFF soil groups and soil M1-P (Fig. 3 and Table 3). The R^2 of the tree model is 0.866 and the root mean squared error (*RMSE*) is 1.23 m.

The optimal regression tree (Fig. 3) resembles a classic regression tree, where each cell (representing terminal nodes or leaves of the tree) contains a constant estimate of SI, specifically reflecting the sample mean of the SI in that cell. The first three leaves were determined by soil groups: G, (D + F3), and C, with average SI values of 16.4, 18.3, and 22.1 m, respectively (Table 3). The last two leaves represent the interaction between soil groups and M1-P. However, all observed M1-P values in loblolly pine plots on soil groups A and B2 are less than 6.18 mg kg^{-1} (Table 2 and Fig. 4), and only one observed M1-P value on soil group B1 is greater than 6.2 mg kg^{-1} (8.6 mg kg^{-1}). Consequently,

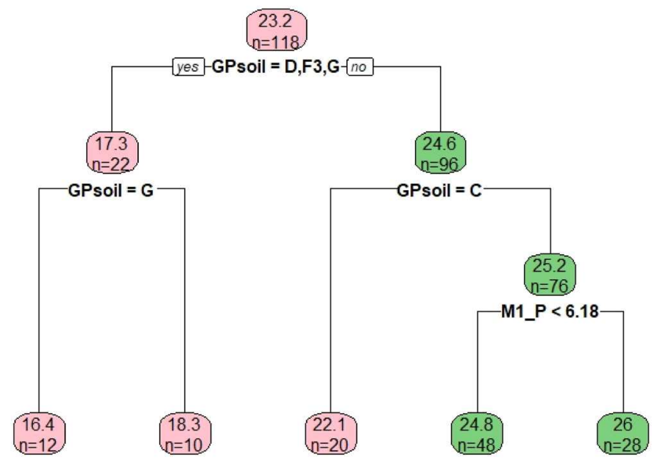

Fig. 3. Regression tree for predicting loblolly pine SI in the Coastal Plain. Note that the order in which variables are examined depends on the answers to previous questions. The numbers in rounded rectangles indicate the predicted SI and how many cases belong to each node or leaf.

Table 3
The prediction rules for the optimal regression tree model (Fig. 3).

Terminal node (leaf)	Conditions (soil groups and M1-P)	SI (m)
(1)	G	16.4
(2)	(D, F3)	18.3
(3)	C	22.1
(4)	(A, B1, B2, B3, E, F1, F2) & M1-P < 6.2	24.8
(5)	(A, B1, B2, B3, E, F1, F2) & M1-P >= 6.2	26.0

all data points from soil groups A, B2 and B1 (except one point) were grouped into one cluster (the fourth leaf), rather than the fifth leaf. In other words, the interaction between soil groups and M1-P was predominantly detected on soil groups B3, E, F1, and F2, characterized by a wide range of M1-P values. In loblolly pine stands situated on soil groups B3, E, F1, and F2, the mean SI is 24.8 m if soil M1-P is below 6.18 mg kg^{-1}, and 26.0 m if soil M1-P equals or exceeds 6.18 mg kg^{-1}.

3.2. Linear regression model for loblolly pine SI

The estimated parameters, the associated p-values and VIFs for the final linear regression model are presented in Table 4. The VIFs ranged from 1.09 to 3.95, all below 4, indicating that multicollinearity is not a concern and is within acceptable limits. A low p-value (i.e., ≤ 0.05) indicates that the corresponding parameter is significantly different from zero. The positive coefficient for soil group B3 indicates that loblolly pine on B3 group soils exhibited a significantly higher SI value compared to that on A group soils. Conversely, the negative coefficients for C, D, F3, and G group soils suggest that loblolly pine on these group soils demonstrated significantly lower SI values than on A group soils. The positive coefficients for the interaction terms demonstrated that loblolly pine SI exhibited an increase with the increasing M1-P on B1, B2, E, F1, F2, and G group soils. However, this positive response varied among these soil groups with consistent responses observed between soil groups B1 and B2, as well as between soil groups F1 and F2.

The final linear regression model, with an R^2 value of 0.899 and an *RMSE* value of 1.12 m, outperformed the optimal regression tree model, which had an R^2 value of 0.866 and an *RMSE* value of 1.23 m. This suggests that the final linear regression model offered a superior fit compared to the optimal regression tree model. Additionally, the scatterplots comparing the predicted and observed SI for both model approaches further confirmed a more reasonable fit for the final linear regression model in contrast to the optimal regression tree model (Fig. 5). Consequently, the final linear regression model was selected for

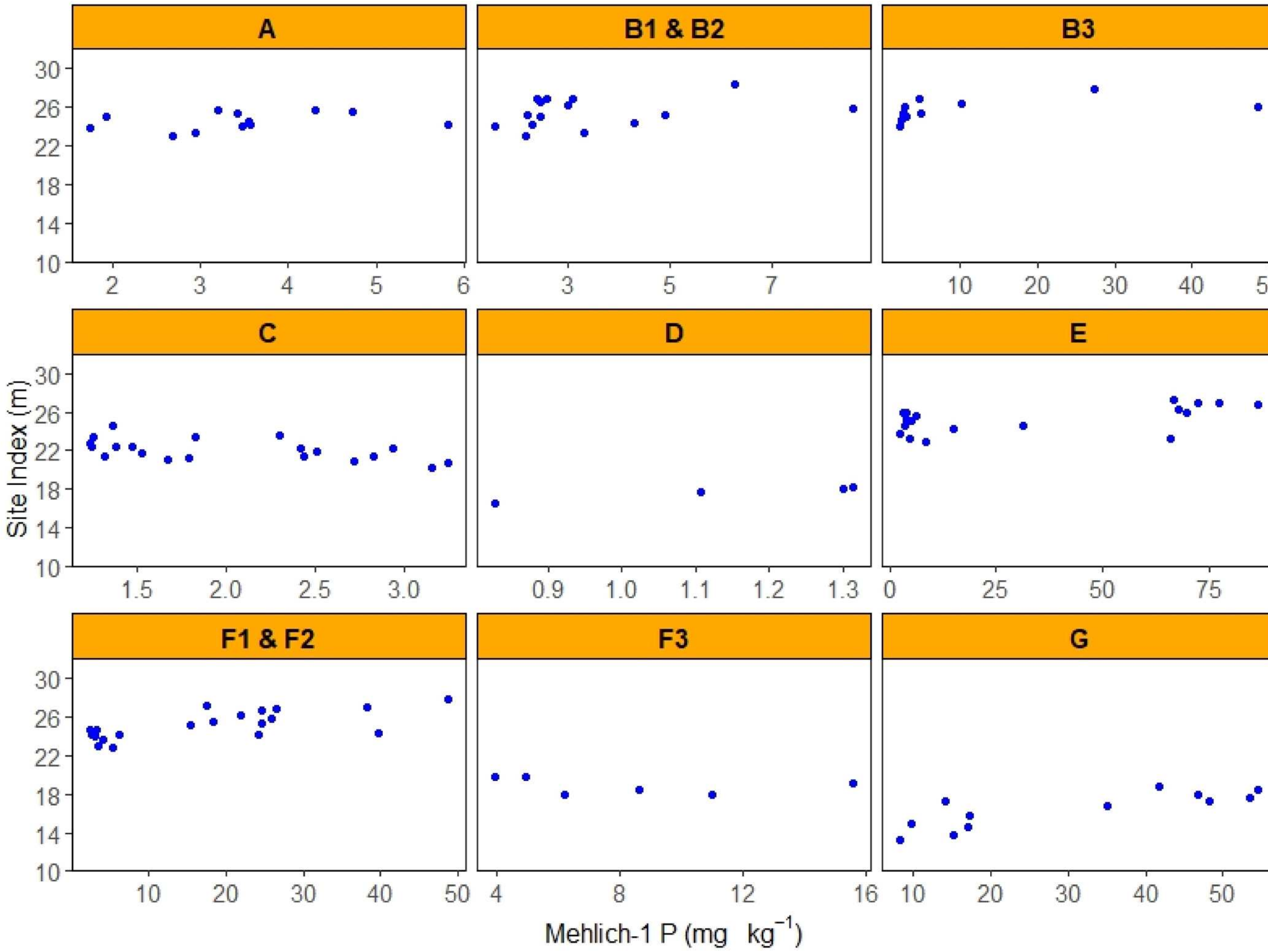

Fig. 4. Relationship between the observed site index and soil Mehlich 1 P for loblolly pine plots by modified CRIFF groups in the NRCS study.

Table 4
The estimated parameters, standard errors, p-values, and VIFs for the reduced model that regresses loblolly pine SI on soil Mehlich 1 P (M1_P) along with dummy variables for CRIFF soil groups in the NRCS SI and MAI study.

Variable	Parameter Estimate	Standard Errors	p-value	VIF
Intercept	24.3978	0.1964	< 0.0001	
$(I_{B1}+I_{B2})\times M1\_P$	0.3126	0.0864	0.0004	1.23
I_{B3}	1.4187	0.4041	0.0007	1.20
I_C	-2.3112	0.3177	< 0.0001	1.34
I_D	-6.7497	0.5920	< 0.0001	1.09
$I_E\times M1\_P$	0.0246	0.0065	0.0002	1.19
$(I_{F1}+I_{F2})\times M1\_P$	0.0517	0.0131	0.0001	1.24
I_{F3}	-5.5810	0.4965	< 0.0001	1.13
I_G	-10.5432	0.6760	< 0.0001	3.95
$I_G\times M1\_P$	0.0828	0.0186	< 0.0001	3.72

Notice: $R^2 = 0.899$ and $RMSE = 1.12$ m.

subsequent analysis, allowing for the prediction of loblolly pine SI in the Coastal Plain using the following equation:

$$SI = 24.3978 + 1.4187I_{B3} - 2.3112I_C - 6.7497I_D - 5.5810I_{F3} - 10.5432I_G + [0.3126(I_{B1}+I_{B2}) + 0.0246I_E + 0.0517(I_{F1}+I_{F2}) + 0.0828I_G]M1\_P \quad (1)$$

The average estimated SI values by soil groups for the NRCS study are presented in Fig. 6, comparing with the average observed base SI values in the CPCD study. For CRIFF A, the average loblolly pine SI was 24.4 m in the NRCS study plots and 26.6 m in the CPCD study. There was no significant difference in the average estimated SI among soil groups B1, B2, B3, E, F1 and F2 in the NRCS study, ranging from 25.0 to 25.8 m. In the CPCD study, the average base SI was 27.1 and 26.0 m on soil groups B1 and (B2/B3), respectively. The mean SI values for soil groups C and D were 22.1 m and 17.6 m in the NRCS study, and 27.5 m and 22.4 m in the CPCD study, respectively. In the NRCS study, the range of the average estimated SI was from 25.0 m to 25.4 m among soil groups F, F1 and F2, while the mean SI values were 18.8 and 16.3 m for soil groups F3 and G, respectively.

3.3. Mean annual increments (MAI)

Utilizing the average estimated SI derived from the final linear regression model mentioned above, simulations were conducted to estimate stand volume and stem green weight MAIs for each soil group using the PMRC growth and yield model system. Figs. 7 and 8 depict the MAIs at ages 10, 15, and 20 years for loblolly pine stands with tree densities of 1,236, 1,483, and 1,730 trees ha^{-1} at age 5 years, representing stand volume and stand green weight respectively. Given tree density and stand age, MAIs in either stand volume or green weight followed the same order among soil groups: B3 > (B1, F1) > (B2, E) > F2 > A > C > F3 > D > G.

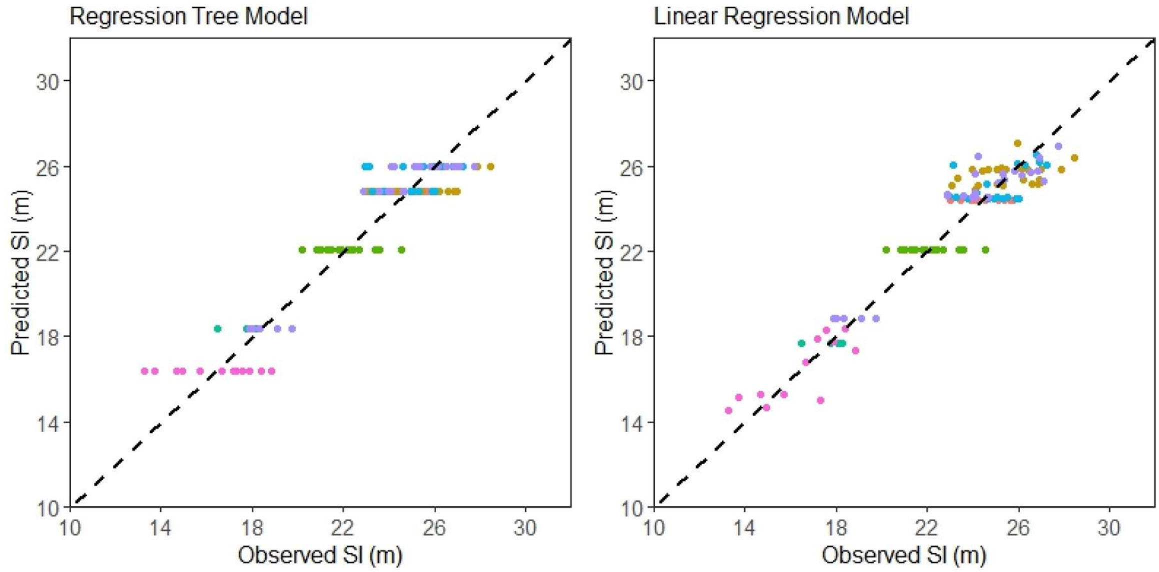

Fig. 5. Predicted vs. observed values of loblolly pine site index (SI, m) at base age 25 years using the optimal regression tree model (left) and the final linear regression model (right). The dashed line is the one-to-one line.

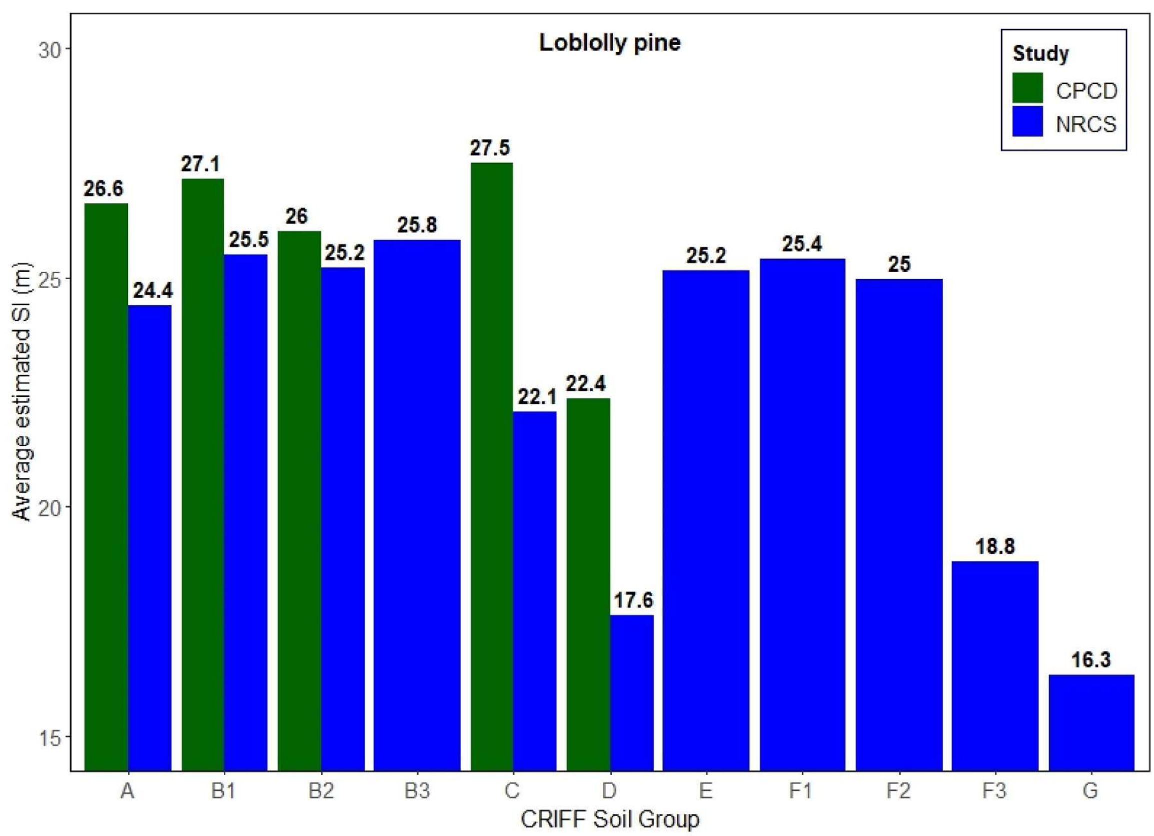

Fig. 6. The average site index (SI, m) for loblolly pine in the CRIFF soil groups estimated with the linear regression model (1) in the NRCS study (blue bars) and the average base SI from the "operational" plots with a planting density of 1,483 trees ha^{-1} in the CPCD study.

4. Discussion and conclusions

In this study, both the regression tree model and linear regression model approaches identified modified CRIFF soil groups and surface soil extractable P (M1-P) as significant factors influencing the site index of loblolly pine plantations in the Coastal Plain region. The CRIFF soil classification already encompasses information on drainage level as well as the presence and depth of the argillic and spodic horizons. Consequently, after explaining the effects of soil groups, variables such as depth to the argillic horizon, depth to the spodic horizon, and presence /depth to seasonal high-water table became nonsignificant and were excluded from both models.

Both modeling approaches also suggested that CRIFF soil groups B and F could be subdivided into two groups based on the depth to argillic

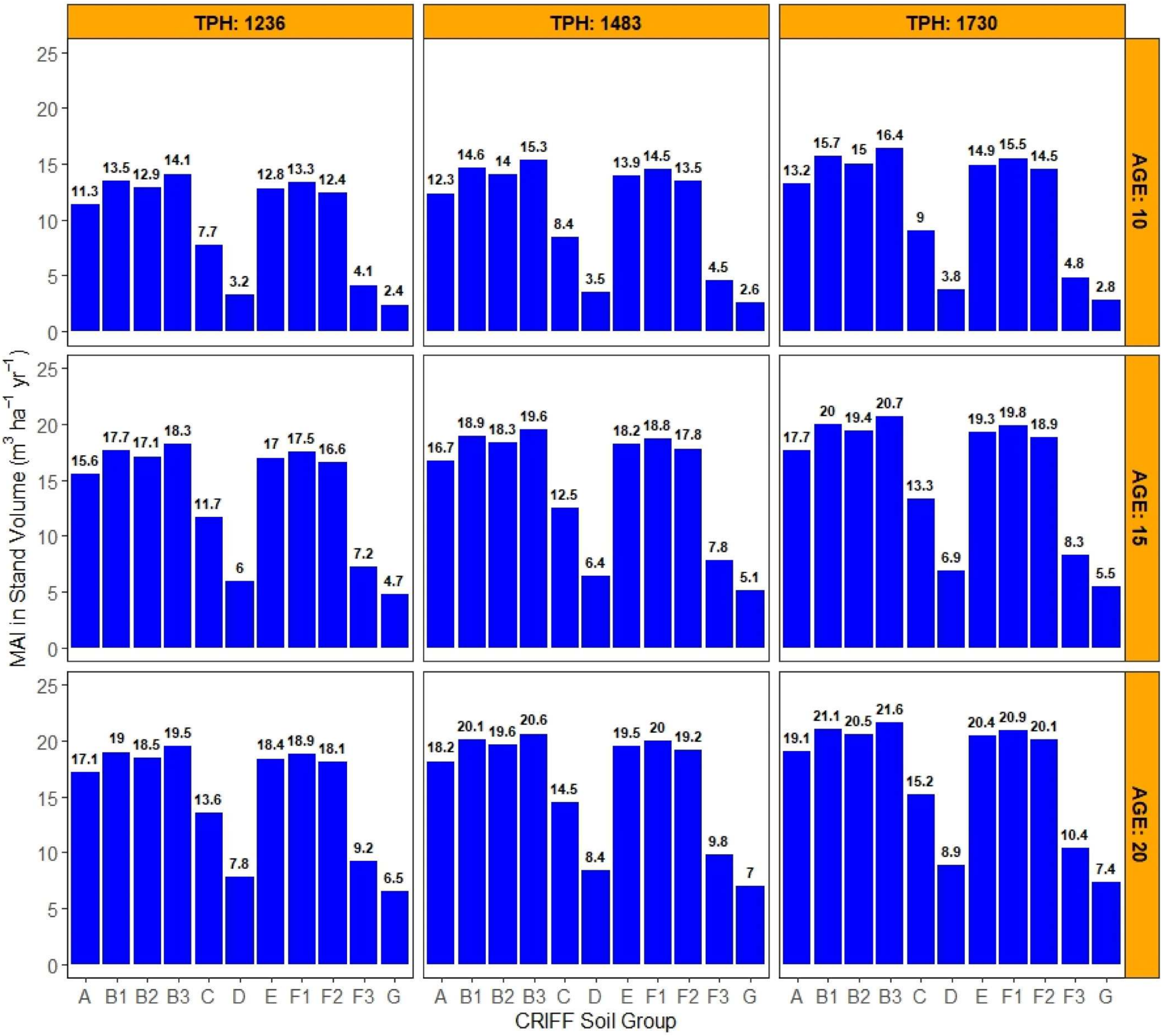

Fig. 7. The mean annual increments (MAI) in stand volume (m^3 ha^{-1}) that were simulated using the PMRC growth and yield model system for loblolly pine plantations based on the average estimated SI from the final linear regression model and tree densities of 1,236, 1,483 and 1,730 TPH at age 5 years.

horizon (50 – 150 cm versus greater than 150 cm), combining soil groups B1 and B2 together and soil groups F1 and F2 together.

While the optimal regression tree model enables rapid prediction without the need for complicated calculation, the final linear regression model explained a greater variation in site index observed in the NRCS study and outperformed the optimal regression tree model. Our research further underscores the utility of the CIRFF soil classification in informing forest management decisions in the Coastal Plain.

The final linear regression model not only detected significant differences in site index among soil groups but also indicated a lack of correlation between soil M1-P and loblolly pine site index in soil groups A, B3, C, D and F3. Conversely, it unveiled a strong positive correlation between soil M1-P and loblolly pine site index in B1, B2, E, F1, F2, and G group soils.

Surface soil M1-P concentrations in NRCS loblolly pine plots on CRIFF A soils ranged from 1.7 to 5.8 mg ka^{-1}, averaging 3.4 mg kg^{-1} (see Table 2 and Fig. 4). Critical levels for loblolly pine are 3 mg kg^{-1} (Wells et al., 1973) or 5 mg kg^{-1} (Ballard and Prichett, 1975). Despite most plots on CRIFF A soils being below 5 mg kg^{-1}, no correlation with site index was found. CRIFF B1 and B2 soils showed a range of 1.6–8.6 mg kg^{-1}, with a positive correlation to site index, each unit increase in M1-P raising site index by 0.31 m. CRIFF B3 soils had varied M1-P levels (2.4–48.5 mg kg^{-1}), but no correlation with site index was observed in the final model. Site indices were higher on CRIFF A and B soils, averaging 24.4–25.8 m. CRIFF C and D soils, with lower fertility and M1-P concentrations (C: 1.2–3.2 mg kg^{-1}, D: 0.8–1.3 mg kg^{-1}) had lower site indices, 22.1 m for C and 17.6 m for D, despite low hardwood competition (Table S1).

In the UGA Warnell School site preparation and HWC study on CRIFF D soils, all plots received site preparation, including strip clearing, bedding, and pre-plant herbicide treatments, and fertilization (25 kg N ha^{-1} + 28 kg P ha^{-1} in the first year; 162 kg N ha^{-1} + 17 kg P ha^{-1} + 47 kg K ha^{-1} in the fourth year). Half the plots received the first-year banded HWC. Loblolly pine stands with additional post-plant HWC had a mean site index of 23.1 m, compared to 22.3 m without, a difference of 0. 8 m. These values were higher than the average site index of 17.6 m in the NRCS study.

The final linear regression model showed a positive correlation

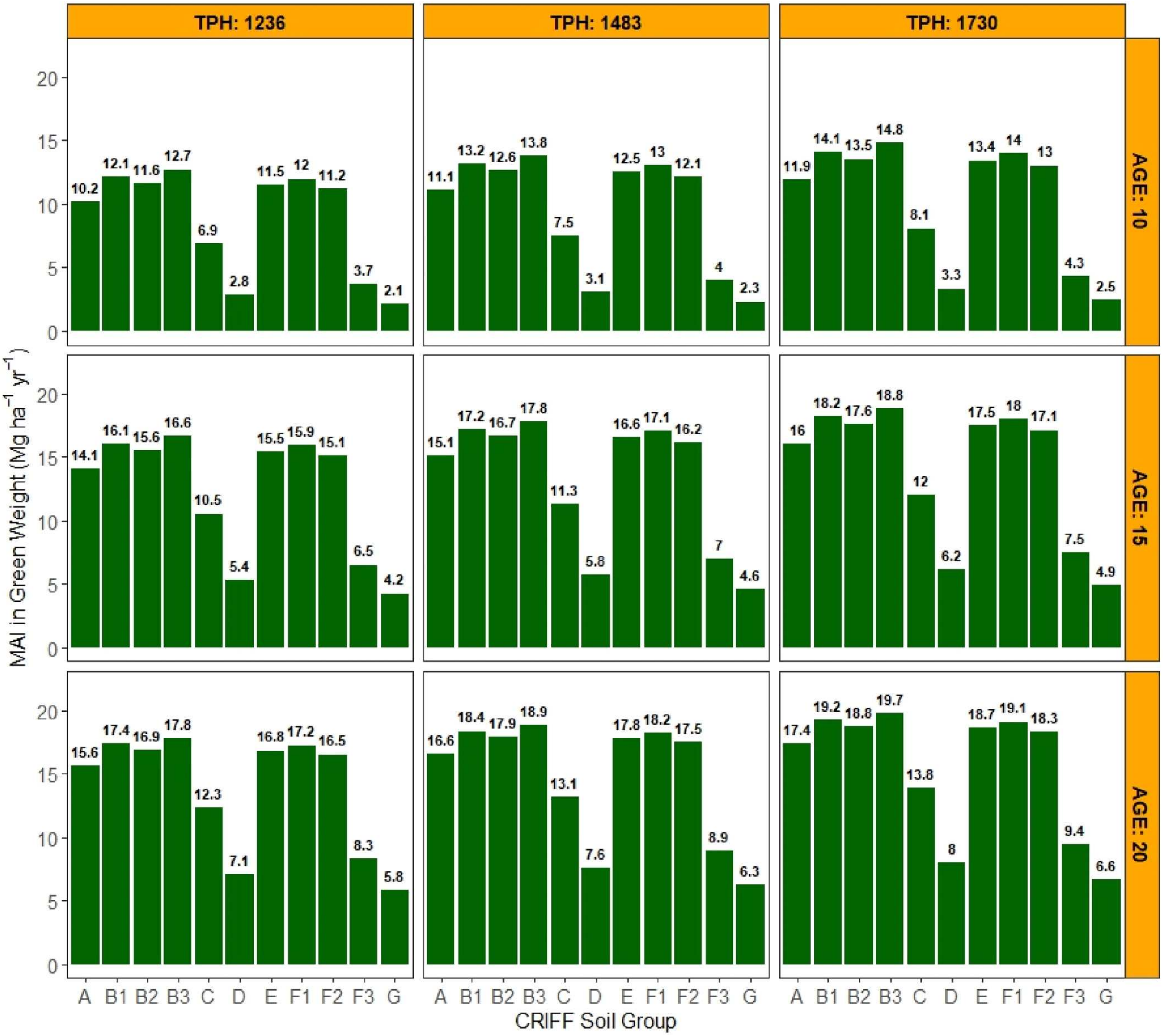

Fig. 8. The mean annual increments (MAI) in stand outside-bark stem green weight (Mg ha^{-1}) that were simulated using the PMRC growth and yield model system for loblolly pine plantations based on the average estimated SI from the final linear regression model and tree densities of 1,236, 1,483 and 1,730 TPH at age 5 years.

between M1-P and site index for loblolly pine on CRIFF E soils, with an average site index of 25.2 m. Six plots, previously a seedling nursery and progeny test site, had high M1-P levels (67.0–86.5 mg kg^{-1}) and minimal woody competition (Table S1), resulting in an average site index of 26.7 m. The remaining 13 plots, with M1-P levels from 3.2 to 66.0 mg kg^{-1}, had an average site index of 24.6 m.

CRIFF F1 and F2 soils, combined in the analysis, showed a positive correction between M1-P and site index, averaging 25.4 m and 25.0 m, respectively. F1 soils had M1-P levels from 2.4 to 48.7 mg kg^{-1}, and F2 soils ranged from 3.5 to 24.5 mg kg^{-1}. Both had low woody competition. Overall, loblolly pines exhibit excellent growth on the CRIFF E, F1 and F2 soils. On CRIFF F3 soils, M1-P averaged 8.4 mg kg^{-1}, with a site index of 18.8 m due to high under- and mid-story woody competition (Table S1). On CRIFF G soils, M1-P levels ranged from 8.4 to 54.5 mg kg^{-1}, with a mean of 30.1 mg kg^{-1}. High hardwood competition and poor soil conditions (deep, coarse-textured, drought-prone, and low in nutrient reserves) resulted in a low site index of 16.3 m, making these soils unsuitable for loblolly pine. Instead, sand pine (*P. clausa*) and longleaf pine (*P. palustris*) are recommended (Jokela and Long, 2018).

In the NRCS study, the plots were established primarily on properties owned by private non-industrial forest landowners, where management practices were relatively less intensive compared to industrial forest lands or experimental studies like the CPCD, and the UGA Warnell School site preparation and HWC study. Although certain CRIFF A group soils with high base status (e.g., the Meggett series, a Typic Albaqualf in the Alfisol order) in the subsoil might not exhibit as much nutrient deficiency, these A group soils are generally considered the most phosphorus-deficient in the Southern region, while CRIFF B group soils are known to be responsive but generally less responsive to phosphorus fertilizer additions than CRIFF A soils (Ballard and Prichett, 1975; Kushla and Fisher, 1980; Gent et al., 1986; Jokela and Long, 2018).

In the CPCD study, the “operational” culture adopted was inherently intensive, incorporating practices such as bedding, chemical site preparation, post-plant herbaceous weed control, and repeated fertilization with NPK and NP, while the “intensive” culture was more intensive, encompassing the “operational” treatments but with complete competition control and additional repeated fertilization. The “operational” management regime notably increased the site index to 26.6 m for

CRIFF A group soils, 27.1 m for CRIFF B1 group soils, and 26 m for CRIFF B2 group soils (refer to Fig. 6). Compared to the NRCS study plots, the "operational" culture in the CPCD study resulted in site index increases of 2.2 m, 1.6 m, and 0.8 m on A, B1, and B2 group soils, respectively. Meanwhile, the "more intensive" regime led to site index increase of 3.4, 3.4, and 1.1 m on the same soil groups.

CRIFF C and D soils often exhibit deficiencies in both nitrogen and phosphorus (Jokela and Long, 2018). In comparison to site index values from the NRCS study, the "operational" culture implemented in the CPCD study yielded site index values of 27.5 m and 22.4 m on C and D group soils, respectively, representing increases of 5.4 m and 4.8 m in site index values (Fig. 6). The "more intensive" culture in the CPCD study resulted in site index increase of approximately 6.1 m and 11.2 m on C and D group soils. These findings confirm that loblolly pine is particularly responsive to fertilizer and weed control treatments on CRIFF C and D group soils (Jokela and Long, 2018).

The productivity of a site is influenced by both natural factors inherent to the location and management-related factors (Skovsgaard and Vanclay, 2008). According to the CPCD study, the expressed site index exhibited significant variation, driven by the base site index (inherent to the location), initial planting density, and management intensity (refer to Figure S1). Extremely high initial planting densities have been shown to potentially reduce site index (also referenced in Zhao et al., 2008; MacFarlane et al., 2000). Although more intensive silvicultural treatments, including fertilization, generally lead to an increase in site index, there have been instances where a positive response in site index was not apparent, or a decrease in expressed site index was observed, particularly on inherently productive sites with higher base site index (Figure S1; Zhao et al., 2016).

In the NRCS study, most plots were planted at operational planting densities ranging from 1,112 to 2,224 trees ha^{-1} and were subjected to extensive or less intensive silvicultural treatments. Consequently, the final linear regression model incorporating only modified CRIFF soil groups and surface soil M1-P was able to account for 89.9 % of the variation in site index. This study demonstrates the efficacy of modified CRIFF soil groups in capturing the variability in site productivity within extensively-managed loblolly pine plantations across the Coastal Plain region.

Whether assessed based on either site index or mean annual increments, soils classified under CRIFF B, E, F1 and F2 groups consistently rank among the most inherently productive. CRIFF group A soils exhibited higher productivity compared to soils categorized under C, D, F3 and G group. Notably, G group soils are identified as the least productive (Figs. 6, 7 and 8). In the study by Borders and Harrison (1989), the CRIFF B and F soil groups were not further subdivided, and no plots were included for CRIFF E soils. Their findings indicated that loblolly pine significantly performed better on soils classified under CRIFF A and F groups, while exhibiting the worst performance on G group soils compared to soils categorized under B, C, and D groups. When comparing management intensities, intensive or more intensive management significantly increased site index particularly on C, D, A and B1group soils (Fig. 6). On B1 and D group soils, mean annual increment responses to intensive silviculture showed substantial increases at earlier ages (before age 15 years) followed by a decrease, while significant MAI responses on A and C group soils are sustained over time (Figure S2).

The expected maximum expressed site index of loblolly pine in the southern US is approximately 32 m at a base age of 25 years (Zhao et al., 2016). However, even on more productive soils, the observed site index in the NRCS study falls considerably below this maximum value (refer to Table 2 and Fig. 6). There exists significant potential to enhance site productivity through intensive silvicultural treatments such as site preparation, herbaceous and woody competition control, fertilization, and the utilization of suitable genotypes. It is worth noting that the response to increased silviculture is inversely correlated with the base site index, and both the maximum and average responses can be estimated based on the base index (Zhao et al., 2016).

In summary, the predictive models offer NIPFLs valuable tools to evaluate the site productivity of loblolly pine plantations in the Coastal Plain, especially beneficial for areas where forest stands have not yet been established. The revised site index and mean annual increments associated with each modified CRIFF soil group assist NIPFLs and practicing foresters in strategically planning the planting or replanting of their lands.

CRediT authorship contribution statement

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

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.

Acknowledgments

This work was supported by the Cooperative Agreement with USDA Natural Resources Conservation Service (NRCS) SI and MAI Project (Agreement # NR204310xxxC035). The authors appreciate the efforts of the Plantation Management Research Cooperative (PMRC) in establishing, maintaining, and monitoring the CPCD long-term experimental study. We acknowledge the efforts of the three NRCS Resource Soil Scientists: Charles Lagoueyte, Casey Sowell, and Sherry Williford that worked with author Dee Pederson to verify approximately 80 % of the NRCS 118 loblolly plots. We also thank the many forest landowners who allowed us to install plots on their properties.

Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.foreco.2024.122054.

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