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Growth trends of loblolly pine age five or less in relation to soil type and management intensity

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ABSTRACT

We evaluated three objectives for loblolly pine (*Pinus taeda* L.) trees age five or less: 1) how height growth varies by soil type and silvicultural intensity, 2) the accuracy of predicted base-age 25 site index (SI25) using age one to five heights, and 3) if height dominance exhibited early in the rotation is maintained throughout the rotation. Data from 42 sites across the southeastern United States with an array of soil textures and management intensities (optimal, intensive, and operational) were used. Management intensity and soils significantly affected tree height. Coarse loamy soils were the most responsive to increasing management intensity. At age four, tree heights were greatest in the optimal group (4.63 m), followed by the intensive (4.31 m), and then the operational (3.06 m). Organic soils do not appear to respond to maximum management intensity. Predictability of SI25 was high especially starting at age four, with R^2 values ranging from 0.27 for the age four intensive group to 0.78 for the age four operational group. The optimal group had the greatest slope with an expected increase of 2.61, 2.75, 1.88, and 1.78 m in site index per additional meter of height at ages two, three, four, or five, respectively. Data from six different study sites indicate, the tallest (class one) and smallest (class five) trees changed percentile class the least often over time. As early as age two, over 40 % of observations in classes one and five had zero changes in class through age 13. Young tree data were effective in predicting SI25, and height dominance appeared generally set early in the rotation.

1. Introduction

Loblolly pine (*Pinus taeda* L.) is the most important commercial tree species in the southeastern United States (Schultz, 1997). Exploring new ways to maximize wood production on existing loblolly pine sites becomes increasingly important as forestland availability decreases and fiber demand increases globally (South and Buckner, 2003; Zhang and Polyakov, 2010).

Evaluating tree age and height relationships can provide insight into site productivity (Skovsgaard and Vanclay, 2008). Site index - derived from the mean height of dominant and codominant trees in fully stocked, even-aged stands – has been used as an indicator of site quality because it estimates site productivity through a single age-height pair (Avery and Burkhart, 1994; Bontemps and Bouriaud, 2014; Vissage et al., 2019). Many age-height models were developed using data from trees greater than five years of age (Amateis and Burkhart, 1985; Cao et al., 1997; Diéguez-Aranda et al., 2006; Hacker and Bilan, 1991; Trousdell, 1974). Few studies included height growth for young trees, defined as trees age five or less, in model development.

Loblolly pine height growth varies in response to management (Zhao et al., 2016). Loblolly pine sites receiving optimal site preparation, such as a combination of shearing, piling, bedding, disking, or herbicide, typically increase growth long-term, often related to decreased hardwood competition (Haywood and Burton, 1989; Martin and Shiver, 2002; Nilsson and Allen, 2003; Wilhite and McKee, 1985). Additionally, loblolly pine growth typically increases in response to herbaceous and woody vegetation control during stand development, with the greatest responses occurring with total weed control followed by herbaceous

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control only (Bacon and Zedaker, 1987; Lauer et al., 1993; Miller et al., 1991; Zutter et al., 1995). Phosphorous (P) application at establishment and mid-rotation nitrogen (N) and P fertilization yield significant growth increases (Albaugh et al., 2015; Fox et al., 2007; Gent et al., 1986). These site-specific management practices have improved stand productivity and, thus, increased site index for optimally managed loblolly pine stands (Albaugh et al., 1998, 2022; Gyawali and Burkhart, 2015; Jokela et al., 2010).

Limited information is available on the impacts of management intensity and their interaction with site-specific factors, such as soil characteristics, on the growth of loblolly pine prior to age five. Determining the effects of soil and management on age-height relationships earlier in the rotation could guide management interventions at a critical period during early stand development, identifying growth deficiencies and potentially leading to maximized site productivity.

The base-age 25 prediction potential of early age-height data has seldom been assessed. Height growth rates in year one through five of stand development may not remain consistent throughout the rotation. Stems that are dominant early in the rotation do not always remain so (Assmann 1970). In natural stands, one out of five dominant stems used to calculate site index for both jack pine (*Pinus banksiana*) and black spruce (*Picea mariana* (Mill) B.S.P) were often replaced over a 10-year period (Raulier et al., 2003). This variability can lead to over- or underestimation of site index when developing models from young tree data.

Predicting site index early could gauge site preparation effectiveness, aid prioritizing early management interventions, constitute a framework of expected early growth rates for given combinations of soil-management histories, and lead to yield projections at younger ages than historically used. For this study, we examined loblolly pine heights from ages five or less, across a range of soil types and management intensities. The objectives were:

1. To evaluate how height growth at ages two through five varied by soil type and silvicultural intensity;
2. Evaluate the accuracy of predicted site index at age 25 using age one to five heights;
3. Evaluate if height dominance exhibited by individual stems early in the rotation was maintained throughout the rotation.

2. Materials and methods

2.1. Data

We used individual tree data from plots located at 42 study locations installed by the Forest Productivity Cooperative (FPC) as a part of different regionwide trials which were established and measured from 1995 to 2018 (Carter et al., 2021) (Fig. 1). The number of plots per study site varied from two to 144. The height (m) and diameter at breast height (DBH, 1.37 m; cm) were recorded at ages ranging from one to 22, but measurement age varied by study. Plots within each study site received a mix of site preparation, vegetation control, and fertilization treatments (Table 1). Soil type and management intensity were categorized at the plot level, but individual tree data were used for analysis.

For plots with final measurements from ages 19 to 22 years, SI25 estimates were recorded at the plot level assuming linear growth from the last measurement until age 25. Albaugh et al. (2022) used a similar method to estimate site index.

Tree heights were ranked within individual plots by percentile for trees where heights were recorded at ages one through five and age 13. Data represented 6 study sites with 200 plots in total and N = 4378 individual trees. If stems had equivalent heights, the stem with greater DBH was ranked higher. Percentile rankings were combined into five classes: 0–20 %, 20.1–40 %, 40.1–60 %, 60.1–80 %, and 80.1–100 %, classes one through five, respectively. Change in class over a given time

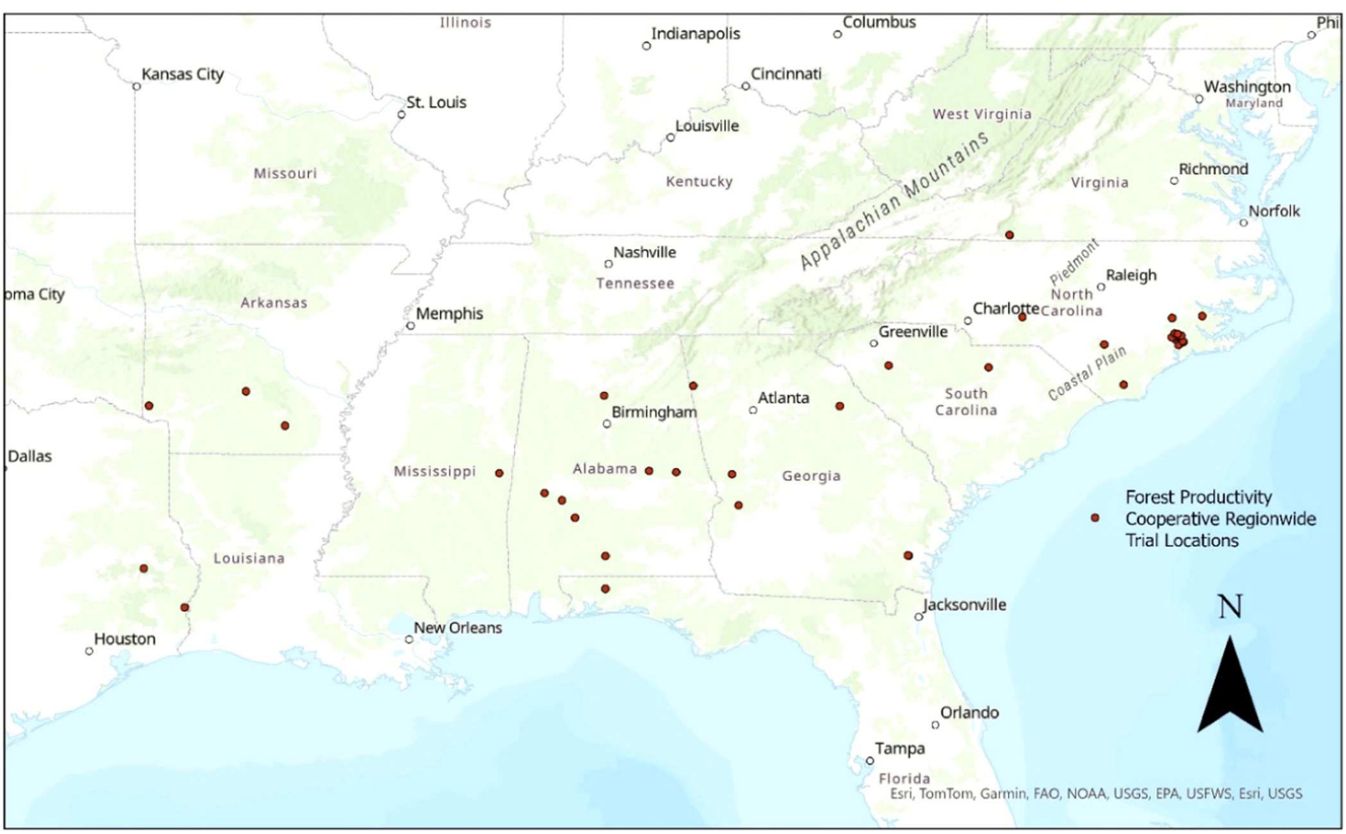

Fig. 1. Forest productivity cooperative (FPC) loblolly pine (*Pinus taeda* L.) regionwide trial locations established across the southeastern United States from 1995 to 2018 which were utilized in this study. Esri. (2024). *ArcGIS Pro 3.2*. Redlands, CA: Environmental Systems Research Institute.

Table 1
Study information per forest productivity cooperative (FPC) loblolly pine (*Pinus taeda* L.) regionwide trial location established across the southeastern United States from 1995 to 2018[a,b].

Study	Location	Year planted	Soil type (FPC major code, FPC drainage code)	Ages height measured	Site prep	Vegetation control	Fertilization Rates*
1	Laurens County, AL	1996, 2006, 2007, 2008	C	4	All plots disked	0 or 5 herbicide applications	1
2	Craven County, NC	1996	A	4	No tillage, surface tillage, subsurface tillage, or a combination of both	Complete and sustained herbicide	2
3	Cullman County, AL	1999	E	2, 4	No tillage, disk, rip, or disk and rip	0 or complete herbicide 2 years	3
4	Conecuh County, AL	1996	C	4	Spray and burn and surface tillage, subsurface tillage, or combination of both	Complete herbicide 2 years	None
5	Tallapoosa County, AL	1996	B	4	Either herbicide application or chop and burn	Complete herbicide 2 years	3
6	Elmore County, AL	1996	B	4	Herbicide and disk, rip, or combination of both	Complete herbicide 2 years	3
7	Little River County, AR	1998	F	2	No site prep, shear with v-blade, shear with v-blade and bed, or disk and rip, or 3 in 1 plow	Complete herbicide 2 years	3
8	Santa Rosa County, FL	1996	B	4	Herbicide or herbicide and disk or herbicide and rip or herbicide, rip, and disk, or herbicide, rip, disk, and shear	Complete herbicide 2 years	3
9	Wilcox County, AL	1998	C	2, 4	Bedding or no bedding and herbicide or herbicide and disk or rip, herbicide, disk and rip, or herbicide and 3 in 1 plow and	Complete herbicide 2 years	3
10	Kershaw County, SC	1996	G	4, 5	Aerial herbicide	none	4
11	Dallas County, AR	1997	B	4, 5	unknown	0 or complete and sustained herbicide	4
12	Floyd County, GA	1998	A	3–5	Herbicide and subsoil	1 herbicide application or complete and sustained herbicide	4
13	Angelina County, TX	2000	B	3–5	Herbicide, burn, rolling chopper, and subsoil	1 herbicide application or complete and sustained herbicide	4
14	Wilkes County, GA	1997	B	3–5, 19	unknown	0 or complete and sustained herbicide	4
15	Kemper County, MS	1996	B	4, 5, 13	herbicide	0 or complete and sustained herbicide	4
16	Marengo County, AL	1998	C	3–5	Bed, shear, and pile	1 herbicide application or complete and sustained herbicide	4
17	Brantley County, GA	1995	D	5, 21	Double bed, spot pile, and burn	1 herbicide application	4
18	Brantley County, GA	1996	D	4, 5, 20	Double bed, spot pile, and burn	1 herbicide application	4
19	Marion County, GA	1996	F	4, 5	Pronone and burn	0	4
20	Talbot County, GA	1998	F	5, 13	herbicide	0 or complete and sustained herbicide	4
21	Bradley County, AR	1995	E	5, 21	Herbicide and burn	1 herbicide application	4
22	Marengo County, AL	1996	A	4, 5, 20	unknown	none	4
23	Newton County, TX	1999	B	2–5	Shear, 3 in 1 plow	Bushhog and 1 herbicide application or complete and sustained herbicide	4
24	Montgomery County, NC	1999	E	4, 5	unknown	0 or complete and sustained herbicide	4
25	Dallas County, AR	2001	B	4, 5	unknown	0 or complete and sustained	4
26	Lenoir County, NC	2009	B	1–5	Chopper, herbicide, burn	2 herbicide applications	5
27	Patrick County, VA	2009	C	1–5, 13	Chopper, herbicide, burn	2 or 4 herbicide applications	5
28	Bladen County, NC	2009	B	1–5, 13	Bedding and herbicide	1 or 3 herbicide applications	5
29	Bladen County, NC	2009	B	1–5, 13	Bedding and herbicide	1 or 3 herbicide applications	5
30	Patrick County, VA	2009	C	1–5, 13	Chopper, herbicide, burn	2 or 4 herbicide applications	5
31	Onslow County, NC	2008	B	3–5	Herbicide, bedding, v-shear	1 herbicide application or compete and sustained herbicide	6

(continued on next page)

Table 1 (*continued*)

Study	Location	Year planted	Soil type (FPC major code, FPC drainage code)	Ages height measured	Site prep	Vegetation control	Fertilization Rates*
32	Onslow County, NC	2008	B	3–5	Herbicide, bedding, v-shear	1 herbicide application or compete and sustained herbicide	6
33	Onslow County, NC	2007	B	4, 5	Herbicide, bedding, v-shear	1 herbicide application or compete and sustained herbicide	6
34	Onslow County, NC	2006	B	5	Herbicide, bedding, v-shear	1 herbicide application or compete and sustained herbicide	6
35	Onslow County, NC	2008	H	3–5	Herbicide, bedding, v-shear	1 herbicide application or compete and sustained herbicide	6
36	Jones County, NC	2006	C	5	Herbicide, bedding, v-shear	1 herbicide application or compete and sustained herbicide	6
37	Onslow County, NC	2007	C	4, 5	Herbicide, bedding, v-shear	1 herbicide application or compete and sustained herbicide	6
38	Jones County, NC	2008	H	3–5	Herbicide, bedding, v-shear	1 herbicide application or compete and sustained herbicide	6
39	Jones County, NC	2008	B	3–5	Herbicide, bedding, v-shear	1 herbicide application or compete and sustained herbicide	6
40	Jones County, NC	2018	H	1–5	Herbicide, bedding, v-shear	1 herbicide application	7
41	Brunswick County, NC	2018	H	1–5	Herbicide, bedding, v-shear	2 herbicide applications	7
42	Buckingham County, VA	1998	B	2 – 5, 22	Drum chop, burn	4 herbicide applications	8

[a] FPC major soil code descriptions: A = clayey, B = fine loamy, C = coarse loamy, D = spodic, E = silty, F = deep subsoil, G = sandy, H = organic. FPC drainage code: S = somewhat poorly drained, P = poorly drained, V = very poorly drained, W = well-drained, M = moderately well-drained, E = excessively drained (i.e. sandhills), and D = somewhat excessively drained.

[b] Fertilization rates: Rate One = 0 kg hectare^{-1}(kg ha^{-1}) nitrogen (N) and 0 kg ha^{-1} phosphorous (P) or 50 kg ha^{-1} N and 56 kg ha^{-1} P, Rate Two = 38 kg ha^{-1} N and 43 kg ha^{-1} P, Rate Three = 40 kg ha^{-1} N and 45 kg ha−1 P, Rate Four = 0 kg ha^{-1} N, P, and K or 67 kg ha^{-1} N, 7 kg ha^{-1} P, and 1 kg ha^{-1} K or 135 kg ha^{-1} N, 14 kg ha^{-1} P, and 1 kg ha^{-1} K or 202 kg ha^{-1} N, 20 kg ha^{-1} P, and 2 kg ha^{-1} K or kg ha−1 N, 27 kg ha^{-1} P, and 3 kg ha^{-1} K, Rate Five = 0 kg ha^{-1} N, P and K or 112.1 kg ha^{-1} N, 11 kg ha^{-1} P, and 1 kg ha^{-1} K, Rate Six = 0 kg ha^{-1} N, P, K, boron (B), calcium (C) and micronutrients or 292.5 kg ha^{-1} N, 95 kg ha^{-1} P, 100 kg ha^{-1} K, 2 kg ha^{-1} B, 198 kg ha^{-1} C and micronutrients, Rate Seven = 28. kg ha^{-1} P and 0, 448.34, or 896.68 kg ha^{-1} calcium (Ca), Rate Eight = 0 kg ha^{-1} N and 44.83 kg ha^{-1} P or 197.27 kg ha^{-1} N and 44.83 kg ha^{-1} P or 563.79 kg ha^{-1} N and 100.88 kg ha^{-1} P.

period was calculated by subtracting the initial class number minus the final class number across two ages for individual stems. Differences in class numbers were calculated between ages one and 13, two and 13, three and 13, four and 13, and five and 13, and the absolute value of the difference was recorded.

2.1.1. Soil grouping and management intensity designations

We classified soils with the FPC soil classification system, SPOT (Table 2) (Cook et al., 2024). Plots within the sites were categorized into three management intensities: optimal, intensive, or operational. Optimal management included plots that received subsoiling, three or more fertilizations, and/or three or more vegetation control treatments in the first five years. If a plot received complete and sustained vegetation control in the absence of any other treatments, it was categorized as optimal. Intensive management included plots that received shearing, raking, or bedding, one to two fertilization treatments, and zero to two vegetation control treatments in the first five years or disking and one herbicide application. Any plots that received less than the intensive treatments were considered operational.

Table 2
Forest productivity cooperative (FPC) major soil and drainage codes for loblolly pine (*Pinus taeda* L.) (Cook et al. 2024).

Major soil code	Dominant profile texture	Textures included and special characteristics
A	Clayey	Clay, sandy clay, silty clay
B	Fine loamy	Sandy clay loam, clay loam
C	Coarse loamy	Loam, sandy loam
D	Spodic	Spodic or spodosol, usually sandy
E	Silty	Silt, silt loam
F	Deep subsoil	Sandy Clay Loam, Clay Loam, Subsoil Grossarenic (> 40 in or 100 cm)
G	Sandy	Sand, loamy sand, no clay subsoil
H	Organic	Organic (> 24 in. of organic), Histic or Histosol

2.2. Statistical analysis

To address our first objective of evaluating height growth at given combinations of age, soil type, and management intensity, a mixed effect model was used. For the first analysis, the square root transformation of height was the dependent variable and a factorial of age, management intensity, and FPC major soil code (Tables 1 & 2) were fixed effects. Random effects included a unique identifier for each tree in the study nested within plot and study site and the unique identifier representing individual trees measured over time was included as a repeated measure. The height analysis included 42 sites, 785 plots with N = 42,194 individual tree stems for trees ages two through five. For the second analysis, an analysis of variance (ANOVA) was used to test for differences in growth rate by FPC major soil code and management intensity. To calculate height growth rate (meters year^{-1}), we used a subset of the data with sites that contained year five height measurements and calculated growth rate as year five height (m) divided by five. This included 33 of the 42 sites with 638 plots and N = 23,263 individual tree stems. In this ANOVA, growth rate was included as the dependent variable, and a factorial of FPC major soil code and management intensity were included as fixed effects and plot nested within study site was included as a random effect. A Tukey's post-hoc test was used to compare management intensities within age and FPC major soil code.

To address our second objective, linear regression was used to estimate SI25 in age one through five heights. Then, plot level site index estimates were calculated using the average height of the tallest 20 % of stems. An ANOVA with plot level SI25 included as the dependent variable and a factorial of age, mean plot height of the tallest 20 % of stems, and management intensity included as fixed effects was used to determine if slopes differed by management intensity and age. As noted earlier, SI25 was calculated by using a subset of the data and linearly extrapolating height growth from ages 19 to 22. This included 6 of the 42 sites with 106 plots. A Tukey's post-hoc test was used to compare management intensities within FPC major soil code.

To address the third objective, the distribution of the absolute value of change in class number was plotted by age: one to 13, two to 13, three to 13, four to 13, and five to 13, versus initial class number. As noted earlier, a subset of the data with year 13 measurements available was used. This included 6 of the 42 study sites with 200 plots and N = 4378 individual tree stems All plots with ten or fewer trees were dropped from analysis because their percentile rankings within plots changed too dramatically over time due to the low number of trees in the plot.

All statistical analyses were completed using R Core Team (2024). R: A Language and Environment for Statistical Computing. R Foundation for Statistical Computing, Vienna, Austria. https://www.R-project.org. P-values less than 0.05 were significant.

3. Results

With height as the response variable, all fixed effects, including the interaction terms were significant, except management intensity were significant (Table 3). Coarse loamy soils were the most responsive to increasing management intensity (Fig. 2). At age four, tree heights were greatest in the optimal group (4.63 m), followed by the intensive (4.31 m), and then the operational (3.06 m) and these differences were significant. Organic soils did not appear to respond to maximum management intensity. Across ages three to five, the intensive group height was greater than the optimum group height, although only two sites had optimal intensities with N = 81, 29, 22 trees for ages three, four and five, respectively compared to 24–26 sites receiving intensive management with N = 540, 498 and 482 trees at ages 3, 4 and five respectively.

Table 3
Mixed model analysis of variance (ANOVA) results for response variable of loblolly pine (*Pinus taeda* L.) height (m). FPC major soil code – A = clayey, B = fine loamy, C = coarse loamy, D = spodic, E = silty, F = deep subsoil, G = sandy, H = organic. Management intensity – Optimal = if they fit any of the following criteria in the first five years: any subsoiling, three or more fertilizations, and/or three or more vegetation control treatments or complete vegetation control in the absence of any other treatments. Intensive = received shearing, raking, or bedding, one to two fertilization treatments, and zero to two vegetation control treatments in the first five years or a disking treatment and one herbicide treatment. Operational = anything receiving less than the intensive treatments. Bold indicates a significant p-value.

Fixed effect	DF numerator	DF denominator	F-value	P-value
Age	3	284	1463.97	< 0.05
FPC Major Soil Code	7	777	15.88	< 0.05
Management Intensity	2	1204	2.91	0.06
Age * FPC Major Soil Code	14	210	11.39	< 0.05
Age * Management Intensity	6	2361	6.46	< 0.05
FPC Major Soil Code * Management Intensity	9	856	8.41	< 0.05
Age * FPC Major Soil Code * Management Intensity	8	1444	7.48	< 0.05

Height response to management intensity across all other soil groups appeared inconclusive (Appendix A).

With growth rate as the response variable, all fixed effects including all interactions, were significant except management intensity (Table 4). Clayey, coarse loamy, and fine loamy soils showed increasing growth rates with increasing management intensity with the greatest difference occurring on fine loamy soils between the operational (0.82 m year^{-1}) and intensive groups (1.05 m year^{-1})(Fig. 3). On organic soils, similar to the height results, growth rates were slower in the optimal group (0.72 m year^{-1}) versus the intensive group (1.19 m year^{-1}), but the unbalanced nature of available data in the optimal versus intensive group could affect this result (Appendix B).

For the response variable of SI25, fixed effects of height, age, management intensity, the interaction between age and management intensity and the three-way interaction among all fixed effects were significant (Table 5). The lowest R^2 across management intensities occurred at age one (Fig. 4). Predictability of SI25 was higher especially starting at age four, with R^2 values ranging from 0.27 for the age four intensive group to 0.78 for the age four operational group. The optimal group had the greatest slope with an expected increase of 2.61, 2.75, 1.88, and 1.78 m in site index per additional meter of height at ages two, three, four, or five, respectively. At age five, although the maximum height was greater in the intensive group than the operational, the operational group had a greater slope (See Appendix C).

In general, the tallest (class one) and smallest (class five) trees changed percentile class the least often over time (Fig. 5). By age five, the tallest trees (class one) and the smallest trees (class five) had 63 % and 52 % of observations, respectively, experience zero change in class number (Table 6). As early as age two, over 40 % of observations in class one and five had zero changes in class number and more than 50 % of class one by age three. Observations with initial class numbers of two (60–80th percentile in height), three (40–60th percentile in height), or four (20–40th percentile in height) most often changed by one class number.

4. Discussion

Predicting site index with trees five years of age or less is not often done because stand dynamics and height growth have been thought of as chaotic at this point in stand development (Carmean, 1975). Dominant or codominant stems are typically selected to create site index estimates, and changes in stem dominance can affect the accuracy of site index equations (Raulier et al., 2003). However, our results from three fine loamy, two coarse loamy, and one deep subsoil sites show that whereas changes in dominant stems at the plot level can occur, a large number (47 % of observations at age two) remain in their dominant position through midrotation. Therefore, stability in dominance does occur early in the rotation, and there is value in modeling the age-height relationship during that time-frame.

Growth trends of loblolly pine at young ages differ by soil type. Similar to results of Jokela et al. (2004) and Shiver et al. (2000), coarse, loamy soils had the greatest productivity potential compared to other soil types related to increased management intensity thus greater management intensity is justified on these soils from a biological perspective, although the economic cost still needs to be considered. Additionally, organic soils, which are a less common soil type in the loblolly pine range, but are known to have high potential productivity when bedded and drained, had some of the greatest heights (Baker and Langdon, 1990; Cook et al., 2024). Interestingly though, on organic soils, trees were taller with the intensive management. The intensive group received P and Ca, while the optimal group had fertilizer additions of N, P, K, B, and Ca. The additional fertilization treatments may have changed the C:N ratio leading to immobilization of N and reduced height growth due to nutrient limitations (Gould et al., 1986). Minimal fertilization treatments may be warranted on organic soils, but results should be interpreted with caution due to the small number of intensive

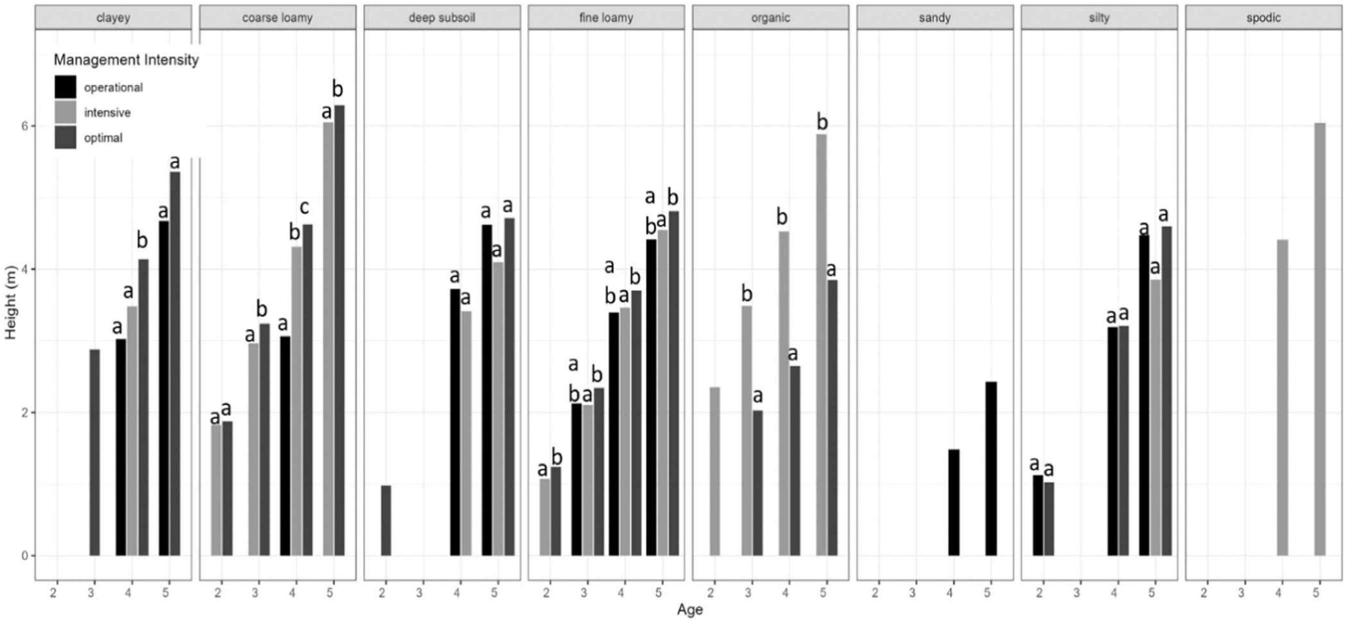

Fig. 2. Height of loblolly pine (*Pinus taeda* L.) in meters (m) by age, Forest Productivity Cooperative (FPC) major soil code and management intensity. Management intensity – Optimal = if they fit any of the following criteria in the first five years: any subsoiling, three or more fertilizations, and/or three or more vegetation control treatments or complete vegetation control in the absence of any other treatments. Intensive = received shearing, raking, or bedding, one to two fertilization treatments, and zero to two vegetation control treatments in the first five years or a disking treatment and one herbicide treatment. Operational = anything receiving less than the intensive treatments. Letters represent results for Tukey's post-hoc test for management intensity within age and soil type. Means not connected by the same letter significantly differ.

Table 4
Analysis of variance (ANOVA) results for response variable of loblolly pine (*Pinus taeda* L.) growth rate (meters year^{-1}) calculated from age five heights[a,b].

Fixed effect	DF numerator	DF denominator	F-value	P-value
FPC Major Soil Code	7	623	86.02	< 0.05
Management Intensity	2	634	2.71	0.07
Major Soil Code* Management Intensity	7	622	26.67	< 0.05

[a] FPC major soil code descriptions: A = clayey, B = fine loamy, C = coarse loamy, D = spodic, E = silty, F = deep subsoil, G = sandy, H = organic. FPC drainage code: S = somewhat poorly drained, P = poorly drained, V = very poorly drained, W = well-drained, M = moderately well-drained, E = excessively drained (i.e. sandhills), and D = somewhat excessively drained.

[b] Fertilization rates: Rate One = 0 kg hectare^{-1}(kg ha^{-1}) nitrogen (N) and 0 kg ha^{-1} phosphorous (P) or 50 kg ha^{-1} N and 56 kg ha^{-1} P, Rate Two = 38 kg ha^{-1} N and 43 kg ha^{-1} P, Rate Three = 40 kg ha^{-1} N and 45 kg ha^{-1} P, Rate Four = 0 kg ha^{-1} N, P, and K or 67 kg ha^{-1} N, 7 kg ha^{-1} P, and 1 kg ha^{-1} K or 135 kg ha^{-1} N, 14 kg ha^{-1} P, and 1 kg ha^{-1} K or 202 kg ha^{-1} N, 20 kg ha^{-1} P, and 2 kg ha^{-1} K or kg ha^{-1} N, 27 kg ha^{-1} P, and 3 kg ha^{-1} K, Rate Five = 0 kg ha^{-1} N, P and K or 112.1 kg ha^{-1} N, 11 kg ha^{-1} P, and 1 kg ha^{-1} K, Rate Six = 0 kg ha^{-1} N, P, K, boron (B), calcium (C) and micronutrients or 292.5 kg ha^{-1} N, 95 kg ha^{-1} P, 100 kg ha^{-1} K, 2 kg ha^{-1} B, 198 kg ha^{-1} C and micronutrients, Rate Seven = 28. kg ha^{-1} P and 0, 448.34, or 896.68 kg ha^{-1} calcium (Ca), Rate Eight = 0 kg ha^{-1} N and 44.83 kg ha^{-1} P or 197.27 kg ha−1 N and 44.83 kg ha−1 P or 563.79 kg ha−1 N and 100.88 kg ha^{-1} P.

management sites represented in the dataset. For sandy soils, evidence suggests high productivity potential with treatments (Albaugh et al., 2009). On our only sandy site, trees were the smallest and had the slowest growth rates, but all of these trees received minimal treatments and increasing management intensity could yield greater growth. Zhao et al. (2016) determined that sites with greater site indices were less responsive to silvicultural inputs, and this could be impacting our results. Thus, site-specific management intensities are recommended.

Our data from six site locations indicated good predictability of SI25 from height of trees greater than age one. This supports the importance of stand evaluation prior to age five. Additionally, the regressions indicated increasing slope with increased management intensity. Thus, intervention early can increase site index or shorten rotation length, but early growth lost to mismanagement cannot be recovered fully later without extending the rotation (Weng et al., 2021; Westfall et al., 2004). This analysis provides site-specific guidance for what soil and management intensity combinations can produce and thus can help managers maximize productivity.

Loblolly pine growth differed by soil type early in stand development. Management intensity affects growth, and interacts with soil type. Our results suggest that height dominance is relatively stable at young ages, but there are limitations to predicting SI25 early in the rotation.

4.1. Conclusions

Results generated by this study allow land managers to determine estimated height of their stand at age 25 when given a mean of early rotation heights for soil type, management intensity or a combination of the two. Although some fluctuations in dominance among stems at these earlier ages occurred in our study, more than half of the dominant stems stayed dominant at age three. In general, we saw the greatest positive growth response to increased management on soils with coarse loamy texture, but organic soils were not responsive to additional treatments in the form of fertilization and vegetation control. The slowest growth occurred on our one site with sandy soils with no clay subsoil, but height could potentially be increased by fertilization treatments. While conducting inventories at younger ages incurs an economic cost, this assessment shows it is possible to estimate SI25 from height measurements taken before age five, and this information can guide management decisions to maximize growth and economic benefits.

CRediT authorship contribution statement

David Carter: Writing – review & editing, Validation, Supervision, Methodology, Formal analysis, Conceptualization. **Timothy Albaugh:**

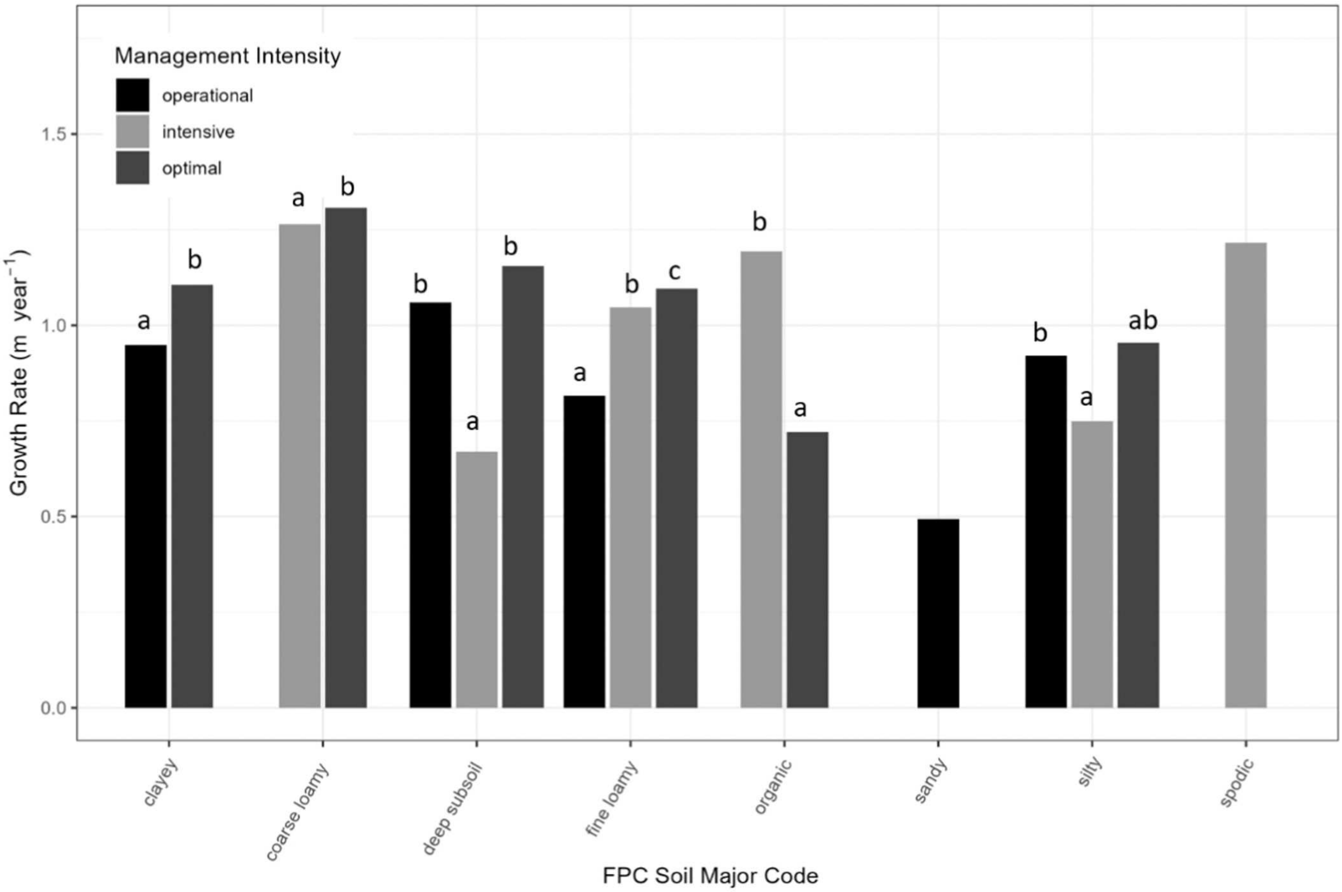

Fig. 3. Loblolly pine (*Pinus taeda* L.) mean growth rate (meters year^{-1}) through age five by Forest Productivity Cooperative (FPC) major soil code and management intensity. Management intensity – Optimal = if they fit any of the following criteria in the first five years: any subsoiling, three or more fertilizations, and/or three or more vegetation control treatments or complete vegetation control in the absence of any other treatments. Intensive = received shearing, raking, or bedding, one to two fertilization treatments, and zero to two vegetation control treatments in the first five years or a disking treatment and one herbicide treatment. Operational = anything receiving less than the intensive treatments. Letters represent results for Tukey's post-hoc test for management intensity within soil type. Means not connected by the same letter significantly differ.

Table 5
Analysis of variance (ANOVA) testing if slopes differ for the response variable of loblolly pine (*Pinus taeda* L.) base-age 25 site indices by height in meters (m) at ages one through five for given management intensities. Management intensity – Optimal = if they fit any of the following criteria in the first five years: any subsoiling, three or more fertilizations, and/or three or more vegetation control treatments or complete vegetation control in the absence of any other treatments. Intensive = received shearing, raking, or bedding, one to two fertilization treatments, and zero to two vegetation control treatments in the first five years or a disking treatment and one herbicide treatment. Operational = anything receiving less than the intensive treatments.

Fixed Effect	DF	F-value	P-value
Height	1	5.13	0.02
Age	1	2006.28	< 0.05
Management Intensity	2	7.07	< 0.05
Height * Age	1	0.74	0.39
Height * Management Intensity	2	2.01	0.13
Age * Management Intensity	2	46.96	< 0.05
Height * Age * Management Intensity	2	7.49	< 0.05

Writing – review & editing, Validation, Methodology, Investigation, Formal analysis, Conceptualization. **Christen Beasley:** Writing – original draft, Visualization, Methodology, Formal analysis, Data curation, Conceptualization. **Rachel Cook:** Supervision, Resources, Project administration, Funding acquisition. **Otávio Campoe:** Supervision, Resources, Project administration, Funding acquisition. **David Enemo:** Writing – review & editing. **Daniel Hong:** Writing – review & editing. **Rafael Rubilar:** Supervision, Resources, Project administration, 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.

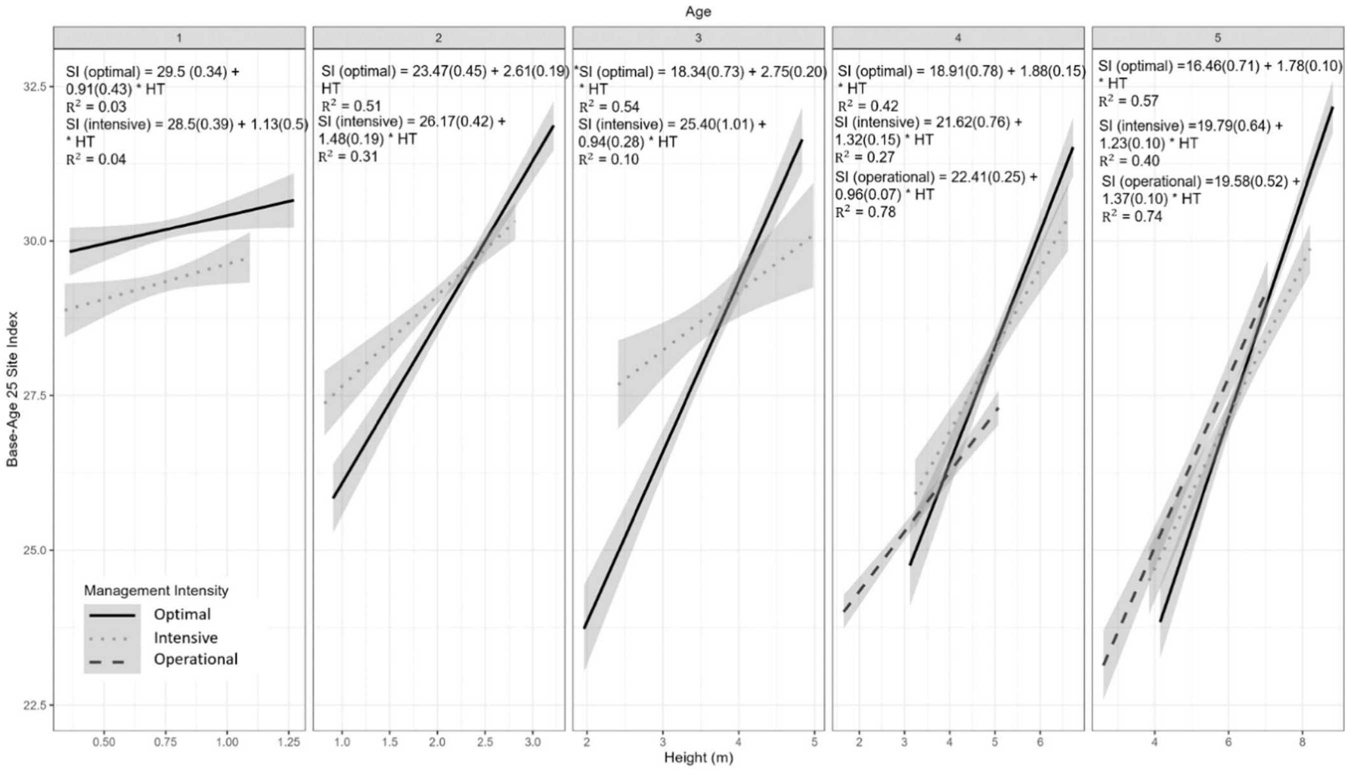

Fig. 4. Results of linear models relating loblolly pine (*Pinus taeda* L.) plot level mean height (m) at ages one through five with associated plot level base-age 25 site index projections in meters (m) for data with maximum year heights recorded at ages 19, 20, 21 or 22 from Forest Productivity Cooperative (FPC) regionwide trials across the southeastern United States for different management intensities. Plot level site index and height estimates were calculated using the tallest 20 % of stems. Management intensity – Optimal = if they fit any of the following criteria in the first five years: any subsoiling, three or more fertilizations, and/or three or more vegetation control treatments or complete vegetation control in the absence of any other treatments. Intensive = received shearing, raking, or bedding, one to two fertilization treatments, and zero to two vegetation control treatments in the first five years or a disking treatment and one herbicide treatment. Operational = anything receiving less than the intensive treatments. Standard error is in parentheses. The gray area represents the 95 % confidence interval.

Appendix A

Least squares mean of the square root of height in meters (m) at a given age, FPC major soil code and management intensity.

Age	FPC major code	Management intensity	Number of studies	Number of plots	Number of trees	Least squares mean of square root of height (m)	Standard error
3	A - Clayey	Optimal	1	18	1159	1.70	0.05
4	A - Clayey	Optimal	2	30	1627	1.74	0.08
4	A - Clayey	Intensive	1	4	132	1.87	0.08
4	A - Clayey	Operational	1	16	800	2.04	0.06
5	A - Clayey	Optimal	1	18	1057	2.16	0.07
5	A - Clayey	Operational	1	16	797	2.32	0.06
2	B - Fine loamy	Optimal	5	110	4813	1.04	0.02
2	B - Fine loamy	Intensive	2	59	3254	1.11	0.01
3	B - Fine loamy	Optimal	9	78	4427	1.45	0.02
3	B - Fine loamy	Intensive	6	19	1184	1.46	0.04
3	B - Fine loamy	Operational	1	2	124	1.53	0.01
4	B - Fine loamy	Optimal	16	183	6914	1.84	0.04
4	B - Fine loamy	Intensive	8	91	2730	1.86	0.02
4	B - Fine loamy	Operational	3	20	1122	1.92	0.02
5	B - Fine loamy	Optimal	13	147	5424	2.10	0.04
5	B - Fine loamy	Intensive	9	93	3003	2.13	0.02
5	B - Fine loamy	Operational	3	20	1110	2.19	0.02
2	C - Coarse loamy	Optimal	3	111	6034	1.35	0.03
2	C - Coarse loamy	Intensive	2	75	4883	1.37	0.03
3	C - Coarse loamy	Optimal	3	98	4782	1.72	0.03
3	C - Coarse loamy	Intensive	2	88	5436	1.80	0.03
4	C - Coarse loamy	Optimal	7	142	3238	1.75	0.06
4	C - Coarse loamy	Intensive	5	100	2783	2.08	0.03

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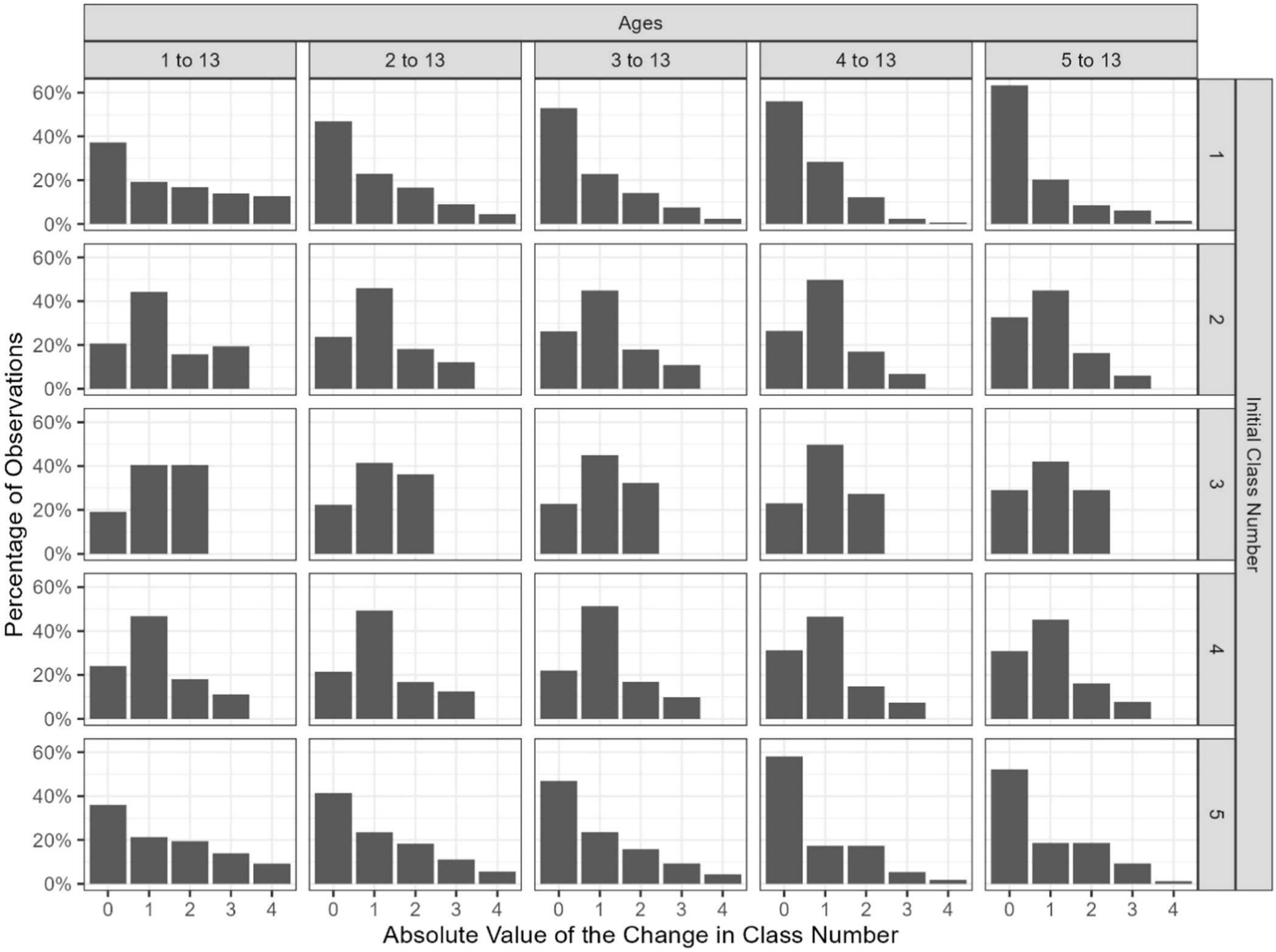

Fig. 5. Height dominance ranking for individual loblolly pine (*Pinus taeda* L.) stems as percent of observations with an absolute value of the change in class number by age difference and initial class number. Class number is based on the percentile ranking of heights by plot, 0 % being the smallest stem in the plot and 100 % being tallest. Class number 5 = 0–20 %, class number 4 = 20–40 %, class number 3 = 40–60 %, class number 2 = 60–80 %, class number 1 = 80–100 %.

(*continued*)

Age	FPC major code	Management intensity	Number of studies	Number of plots	Number of trees	Least squares mean of square root of height (m)	Standard error
4	C - Coarse loamy	Operational	1	4	132	2.15	0.03
5	C - Coarse loamy	Optimal	4	99	2270	2.46	0.03
5	C - Coarse loamy	Intensive	4	91	2715	2.51	0.03
4	D - Spodic	Intensive	1	18	945	2.10	0.07
5	D - Spodic	Intensive	2	36	1701	2.46	0.05
2	E - Silty	Optimal	1	15	762	1.01	0.05
2	E - Silty	Operational	1	3	155	1.06	0.06
4	E - Silty	Optimal	2	17	845	1.79	0.06
4	E - Silty	Operational	2	19	918	1.79	0.06
5	E - Silty	Optimal	1	2	96	1.96	0.06
5	E - Silty	Intensive	1	18	1802	2.12	0.06
5	E - Silty	Operational	1	16	780	2.14	0.07
2	F - Deep subsoil	Optimal	1	19	164	0.99	0.06
4	F - Deep subsoil	Intensive	1	16	553	1.85	0.07
4	F - Deep subsoil	Operational	1	4	115	1.93	0.07
5	F - Deep subsoil	Optimal	1	2	104	2.02	0.06
5	F - Deep subsoil	Intensive	1	16	515	2.15	0.06
5	F - Deep subsoil	Operational	2	20	929	2.17	0.09
4	G - Sandy	Operational	1	14	427	1.22	0.08
5	G - Sandy	Operational	1	14	425	1.56	0.07
2	H - Organic	Intensive	2	24	513	1.53	0.04
3	H - Organic	Optimal	2	2	81	1.42	0.08
3	H - Organic	Intensive	4	26	540	1.87	0.04
4	H - Organic	Optimal	2	2	29	1.63	0.09
4	H - Organic	Intensive	4	26	498	2.13	0.05

(*continued on next page*)

(*continued*)

Age	FPC major code	Management intensity	Number of studies	Number of plots	Number of trees	Least squares mean of square root of height (m)	Standard error
5	H - Organic	Optimal	2	2	22	1.96	0.09
5	H - Organic	Intensive	5	28	482	2.43	0.04

Appendix B

Least squares mean of the growth rate in meters per year (m $year^{-1}$), FPC major soil code and management intensity.

FPC major soil code	Management intensity	Number of study sites	Number of plots	Number of trees	Mean	Standard error
clayey	operational	1	16	797	0.948	0.03
clayey	optimal	1	18	1057	1.106	0.03
fine loamy	operational	3	20	1110	0.816	0.03
fine loamy	intensive	9	93	3006	1.047	0.01
fine loamy	optimal	13	147	5425	1.096	0.01
coarse loamy	intensive	4	91	2715	1.264	0.01
coarse loamy	optimal	4	99	2270	1.307	0.01
spodic	intensive	2	36	1701	1.216	0.02
silty	intensive	1	18	1802	0.749	0.03
silty	operational	1	16	780	0.92	0.03
silty	optimal	1	2	96	0.954	0.09
deep subsoil	intensive	1	16	515	0.67	0.03
deep subsoil	operational	2	20	929	1.06	0.03
deep subsoil	optimal	1	2	104	1.155	0.09
sandy	operational	1	14	426	0.493	0.03
organic	optimal	5	2	22	0.721	0.1
organic	intensive	2	28	508	1.193	0.03

Appendix C

Number of studies and plots by age and management intensity for site index analysis.

Age	Management intensity	Number of studies	Number of plots
1	Optimal	4	155
1	Intensive	3	131
2	Optimal	6	186
2	Intensive	3	131
3	Optimal	8	172
3	Intensive	3	102
4	Optimal	12	235
4	Intensive	8	209
4	Operational	6	54
5	Optimal	12	235
5	Intensive	10	245
5	Operational	7	70

Data availability

The authors do not have permission to share data.

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