

Improving *Pinus taeda* site index from rotation to rotation with silvicultural treatments

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ABSTRACT

We wanted to improve site index using fertilizer applications and planting density at a site with a site index of 16.8 m at a base age of 25 years. We installed a randomized complete block study in the Virginia Piedmont with three replications of three levels of fertilization (cumulative elemental nitrogen and phosphorous amounts of 0 and 45, 309 and 73, and 787 and 129 kg ha⁻¹, respectively) and two levels of planting density (896 and 1793 trees ha⁻¹). We measured the stand 15 times and completed our analysis after age 22 measurements. Fertilization and planting density did not affect site index and there was no planting density by fertilization interaction. Fertilizer significantly increased stem diameter and basal area but did not affect dominant height. Low planting density resulted in significantly larger diameter trees with longer crowns, but with less basal area and stand scale production than the high planting density. However, site index in all treatments improved to 24.2 m, a 7.4 m increase from one rotation to the next. We attributed the increase in site index to adding the primary limiting resource (phosphorous), better competition control, genetics and growing environment. Silvicultural inputs and environmental conditions influence site index and estimates of productivity (e.g. m³ ha⁻¹ yr⁻¹) may be more useful.

1. Introduction

In the southeastern United States, product size influences stand value because there is a premium for larger sizes moving from pulpwood, to chip 'n' saw (CNS) and saw timber (Daniels, 2005, TimberMart-South, 2019). Site index, typically defined as dominant height at a specific age (Burkhart and Tomé, 2012), provides an estimate of the productivity of a given site and is an indicator of how a stand may respond to silvicultural inputs helping foresters to make stand management decisions. For example, a site with a high site index generally would not be a good candidate for a fertilizer application because there would be low expectations for a biological response (Zhao et al., 2016). Dominant height is used because it is less correlated with stand density than tree diameter but is well correlated with stand productivity (Subedi et al., 2015). However, there is conflicting evidence regarding whether planting

density affects site index. For example, Harms et al. (1994) found no effect of planting density on dominant height when examining *Pinus taeda* L. in Hawaii and South Carolina planted at 746 to 2990 trees ha⁻¹. Antón-Fernández et al. (2011) observed a planting density effect on dominant height when examining planting densities from 745 to 6710 tree ha⁻¹ where there was a range in dominant height from 22 to 19 m at age 25, respectively.

Foresters have long practiced increasing productivity from one rotation to the next to produce larger trees in a shorter time (e.g. Fox et al., 2007b). Manipulation of stand density at planting (Zhao et al., 2012) or through thinning (Albaugh et al., 2017) can have large effects on stem diameter and productivity. Silvicultural treatments that increase productivity within a rotation include competing vegetation control (e.g. Miller et al., 1995, Albaugh et al., 2015a), fertilization (e.g. Miller and Tarrant, 1983, Albaugh et al., 1998), and planting genetically

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improved stock (McKeand et al., 2003). Fertilization may increase productivity on nutrient limited sites (Fox et al., 2007a) and those changes can be quite large (Albaugh et al., 2015b). Fertilization and competition control may simply move the stand forward in time by increasing productivity for a short time while the added resources are available (South et al., 2006, Carlson et al., 2008), which may cause the stand to begin density dependent mortality at a younger age. Manipulating planting density plays a role in whether site resources are allocated to a few or many individuals and influences the timing of density dependent mortality (Reineke, 1933, Dean and Baldwin, 1996, Zhao et al., 2012). Stand growth may not be proportional to stand density suggesting that intraspecific competition limits growth at higher densities (Barron Gafford et al., 2003). Planting large numbers of trees occupies the site and allocates site resources to the crop species quickly by shading out competition. However; when resources are distributed among a greater number of individuals more resources (in this case fertilizers) may be required to maintain a given level of productivity or site index.

There is evidence that some silvicultural treatments applied in one rotation may influence growth and productivity in a following rotation. For example, phosphorus applications on severely phosphorus deficient sites (Everett and Palm-Leis, 2009) can improve growth in a subsequent rotation. However, rotation over rotation improvements are not limited to phosphorus applications. Treatments producing large litter layers which resulted in improved nitrogen and other nutrient availability (Zerpa et al., 2010), and intensive management including large inputs of nutrients (including nitrogen, phosphorus, potassium, calcium, magnesium, and sulfur) and complete competition control (Subedi et al., 2019) have also continued to improve growth into the next rotation. However, it is unclear if changes in the productivity of a given site are maintained from one rotation to the next given the difficulty in maintaining long-term (multiple-rotation) studies (Richter et al., 2007) even in areas where rotations are relatively short (8 years for Eucalyptus in Brazil (Cook et al., 2016)).

Our interest then was in determining if site index could be increased from one rotation to the next using fertilization to make the improvement. At the same time, we were interested in how these changes would be affected by planting density and if there was a fertilizer by planting density interaction. In high planting density stands, high fertilizer application rates may induce early density dependent mortality, which would reduce growth, or conversely, low fertilizer application rates may not provide enough resources to maintain growth and both of these conditions would adversely affect site index. We hypothesized that at the end of the rotation 1) site index would increase with increasing inputs of nitrogen and phosphorus, 2) planting density would not affect site index, and 3) there would be no interaction between fertilization and planting density.

2. Methods

The study site was in the Piedmont physiographic region near Dillwyn, VA in the United States (37.583, -78.446) and year nine growth data were reported in Carlson et al. (2009). The site has a relatively

fertile geology with meta volcanic parent material and an eroded surface (Horton et al., 2017). The previous stand was machine planted in 1966 with unimproved Virginia Department of Forestry *P. taeda* seedlings at 1945 trees ha⁻¹. There was no record of competition control for this rotation. The stand was fertilized in 1977 with 230 kg ha⁻¹ of elemental nitrogen when the trees were 12 years old and then thinned in 1987 from the surviving 1077 trees ha⁻¹ to 716 trees ha⁻¹ when the trees were 22 years old. The site was harvested in 1995 at age 29 when 40, 139, and 14 Mg ha⁻¹ of saw timber, pine pulpwood and hardwood pulpwood, respectively, were removed from the site. Measured site index at age 25 was 16.8 m.

A randomized complete block study was installed at planting in 1998 with three replicates of a three (fertilization) by two (planting density) factorial design. Fertilizer treatments (Table 1) were designed using the NUTREM model (Ducey and Allen, 2001) to produce specific site indices (16.8, 21.3 and 24.4 m at 25 years of age for F1 (Low), F2 (Medium), and F3 (High), respectively) at harvest. Fertilizer was applied around the base of each tree in 1999 and 2000 and broadcast in 2001 and 2007. Planting density treatments were low (896 trees ha⁻¹, 3.0 × 3.6 m spacing) and high (1793 trees ha⁻¹, 3.0 × 1.8 m spacing). Treated plots were 0.162 ha with a 0.073 ha measurement plot centered in the treated area. After harvest and prior to planting, the site was drum chopped and burned. Bare root half sib WV108 *P. taeda* seedlings were hand planted in February 1998. Competing vegetation was comprised primarily of hardwood competition (because of the 14 Mg ha⁻¹ hardwood pulp removed with the first rotation) along with typical herbaceous weeds, grasses, vines, and forbs. Herbaceous weed control was applied in May 1998 as an aerial application of glyphosate and metsulfuron methyl. In September 1998, hardwood sprouts were treated with glyphosate and imazapyr using backpack sprayers. In April and September 1999, the herbaceous weed control and hardwood stump treatments, respectively, were repeated using the same methods as in 1998. In December 2006, the site was mowed.

We measured height, diameter (at 1.35 m, breast height), height to live crown and mortality 15 times in the dormant season (January or February) from ages one to 22. Dominant height was the average height of the largest 247 trees ha⁻¹ by volume. Live crown length was the difference between height and height to live crown. Volume (Tasissa et al., 1997) and green weight (Bullock and Burkhart, 2003) were estimated for individual trees, summed at the plot level, and scaled to an area basis.

We estimated treatment means every year we measured the trees. For the last year of measurements, at age 22, we completed a mixed model analysis (PROC MIXED, (SAS-Institute 2002–2012)) on height, dominant height, diameter, height to live crown, live crown length, basal area, volume and green weight with block as a random variable and fertilizer treatment and planting density as fixed effects. We used the Tukey-Kramer adjustment for means separation. Significant effects were determined with an alpha level of 0.05 for all tests.

Dominant height growth was linear after about age 10. We estimated site index by averaging the dominant height increment from ages 10 to 22 and then multiplied the annual dominant height increment by 3 (number of years from last measurement at age 22 to site index age of

Table 1

Fertilizer treatments applied at a Piedmont site in Virginia in the United States. Rates listed under treatment code are in kg ha⁻¹ elemental nutrient for phosphorus (P) and nitrogen (N). Sources included diammonium phosphate (DAP), triple super phosphate (TSP) and ammonium nitrate (NH₄NO₃).

Application date	Treatment code			Source	Method
	F1	F2	F3		
	Low	Medium	High		
May 1999	None	None	56P 168 N	DAP, NH ₄ NO ₃	1.2 m circle around tree
April 2000	17P	17P 85 N	17P 171 N	TSP, Urea	1.2 m circle around tree
April 2001	28P	28P 112 N	28P 224 N	TSP, DAP, NH ₄ NO ₃	Broadcast
January 2007	None	28P 112 N	28P 224 N	DAP, NH ₄ NO ₃	Broadcast

25) to estimate site index. This linear model approach provided a maximum site index at age 25. We developed diameter distributions at age 22 for the main effects by counting the number of stems for each 1 cm diameter class.

We estimated value at age 22. Trees were assigned a product class based on diameter where < 12.7 cm was waste, 12.7–20 cm was pulp wood, 20–30 cm was chip 'n' saw (CNS) and > 30 cm was saw timber. Waste, pulp wood, CNS and saw timber values were 0, 11.15, 19.28, and 27.65 (US\$/Mg ha⁻¹), respectively (with scaled data from (TimberMart-South, 2019)). We assigned each tree to the appropriate product class to obtain stem value, summed at the plot level, and scaled to an area basis to estimate the present value of trees in the plot.

We collected foliage samples at ages 9 (prior to mowing and the final fertilization), 10 (after the mowing and final fertilization) and 22 (coincident with the last measurement). Twenty fascicles were collected from the upper third of the crown of five co-dominant trees per plot. Individual tree samples were composited in each plot (total of 100 fascicles per plot) dried at 65 °C to a constant weight and analyzed with a CHN analyzer for nitrogen (CE Instruments NC2100 analyzer (1997)) and a nitric acid digest followed by inductively coupled plasma spectroscopy (Varian Liberty II ICP-AES) for phosphorous, potassium, calcium, and magnesium (Huang and Schulte, 1985). For all years of foliar nutrient data, we completed a mixed model analysis (PROC MIXED, (SAS-Institute 2002–2012)) on nitrogen, phosphorous, potassium, calcium, and magnesium foliar nutrient concentrations with block as a random variable and fertilizer treatment and planting density as fixed effects. We used the Tukey-Kramer adjustment for means separation. Significant effects were determined with an alpha level of 0.05 for all tests.

We compared environmental conditions (precipitation and temperature) for the two rotations with data from the nearest weather station (Appomattox, VA, Station ID: GHCND:USC00440243) (NOAA, 2021). We estimated carbon dioxide levels during each rotation using data from the Mauna Loa observatory (Tans and Keeling, 2022).

3. Results

The pattern of survival over time was similar for all treatments (Fig. 1). There was about 5 % mortality in the first year with relatively little additional mortality until about age 15, when mortality gradually increased each year through the end of measurements at age 22 when 92 % of trees remained alive. There were no significant treatment effects on dominant height at age 22, when average dominant height was 21.6 m (Table 2, Fig. 2). Consequently, estimated site index was the same for all treatments: 24.2 m. Planting density significantly affected height to

live crown and live crown length such that the height to live crown was 0.6 m higher and live crown length was 1.6 m shorter at high density (Table 2).

Fertilization and planting density significantly affected diameter and basal area (Table 2, Figs. 3 and 4, respectively). There was no difference between high and medium fertilization, and medium and low fertilization for diameter and basal area. Low fertilization had 1 cm less diameter and 3.2 m²/ha less basal area than high fertilization. The low density treatment produced trees with 5.7 cm greater diameter and stands with 9.1 m²/ha less basal area than the high density treatment. Density significantly affected volume and green weight such that high density had 66.4 m³/ha more volume and 56.1 Mg ha⁻¹ more green weight than low density (Table 2 and Fig. 5). There was no significant density by fertilizer interaction for any variable.

Diameter distributions for the fertilizer treatments were similar where most trees were in the 20–21 cm diameter class (Fig. 6A). These distributions resulted in most trees classified as pulpwood or CNS, with very few stems in waste or saw timber. Density diameter distributions were much different where the diameter classes with the most trees for low density was 25–27 cm, and the corresponding diameter classes for high density were 20–21 cm (Fig. 6B). There were ~ 80 % more trees in the high density 20–21 cm diameter classes as there were in the low density 25–27 cm diameter classes. High density trees were about evenly split between pulpwood and CNS classifications, and no high density trees achieved the saw timber classification. Most low density trees were classified as CNS; 80 low density trees ha⁻¹ were classified as saw timber.

We did not find a significant fertilizer by planting density interaction for any of our tree and stand measurements so we only calculated values for the main effects. The high density treatment produced the most green weight (418 Mg ha⁻¹) and the least present value (\$6920 ha⁻¹) (Fig. 7A and 7B, respectively). Conversely, the low density treatment produced the least green weight (366 Mg ha⁻¹) and nearly the greatest present value (\$7391 ha⁻¹). The high fertilization treatment had the highest present value (\$7392 ha⁻¹), just \$1 ha⁻¹ greater than the next highest treatment, low density.

At ages 9 and 10, there was a significant fertilizer effect on foliar nitrogen concentration where the treatment order was high > medium > low (Table 3). The magnitude of difference in nitrogen concentrations between the low and high fertilizer treatments was 0.1 and 0.44 before (age 9) and after (age 10) fertilization, respectively. Foliar phosphorous was significantly affected by fertilization at age 10 where the treatment order was high = medium > low. The potassium concentration was significantly less and the calcium and magnesium concentrations were significantly greater with high density at age 10. There were no significant treatment effects on foliar nutrient concentrations at age 22 and there were no significant fertilizer by planting density interactions for any element at any age measured.

The current rotation from 1998 to 2020 had about 7.6 cm yr⁻¹ more precipitation and was about 0.83 °C warmer than the previous rotation from 1966 to 1995. Over the rotation, average atmospheric carbon dioxide was 340 and 389 ppm for the rotations planted in 1966 and 1998, respectively.

4. Discussion

We rejected our first hypothesis because site index did not increase with increasing fertilizer applications. All fertilization treatments resulted in a higher site index (24.2 m) in the current rotation compared to the previous one (16.8 m). This result was surprising in that site index was improved from one rotation to the next but not for the reason that we had anticipated. Several factors may have played a part in increasing site index from one rotation to the next regardless of our fertilizer treatments.

Phosphorus may have been limiting at the site. In retrospect, a no fertilizer addition treatment would have been useful in the study design

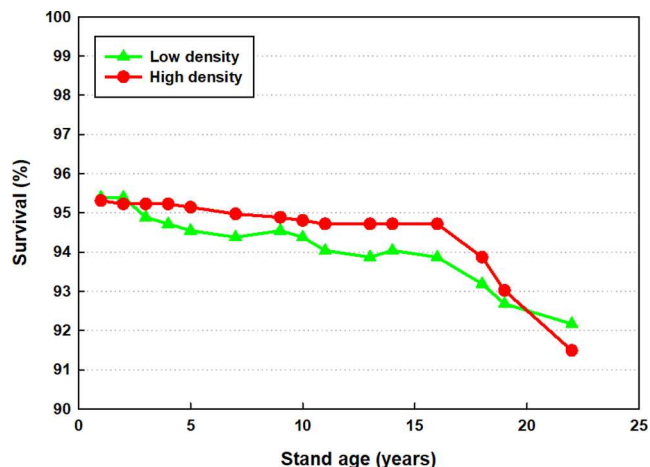


Fig. 1. Percent survival and stand age for a Piedmont site where planting density treatment was low (896 trees ha⁻¹) or high (1793 trees ha⁻¹).

Table 2

Statistics (p values) and treatment means at age 22 for tree and stand scale variables from a site in Virginia where planting density (896 and 1793 trees ha⁻¹) and fertilizer treatments (low (F1), medium (F2), and high (F3)) were applied.

Treatment	Height	Dominant height	Diameter	Height to live crown	Live crown length	Basal area	Volume	Green weight
	p values							
Density (D)	0.014	0.189	<0.001	0.042	<0.001	<0.001	<0.001	0.001
Fertilization (F)	0.472	0.434	0.014	0.697	0.104	0.023	0.263	0.259
D*F	0.436	0.439	0.838	0.325	0.635	0.963	0.587	0.589
	(m)	(m)	(cm)	(m)	(m)	(m ² ha ⁻¹)	(m ³ ha ⁻¹)	(Mg ha ⁻¹)
Low D	20.5	21.8	25.5	12.6	7.8	43.0	392	362
High D	19.4	21.3	19.9	13.2	6.2	52.0	458	418
Low F (F1)	19.9	21.6	22.2	12.8	7.1	45.9	410	376
Medium F (F2)	20.2	21.8	22.7	13.0	7.2	47.6	432	397
High F (F3)	19.7	21.3	23.2	12.9	6.8	49.1	433	398

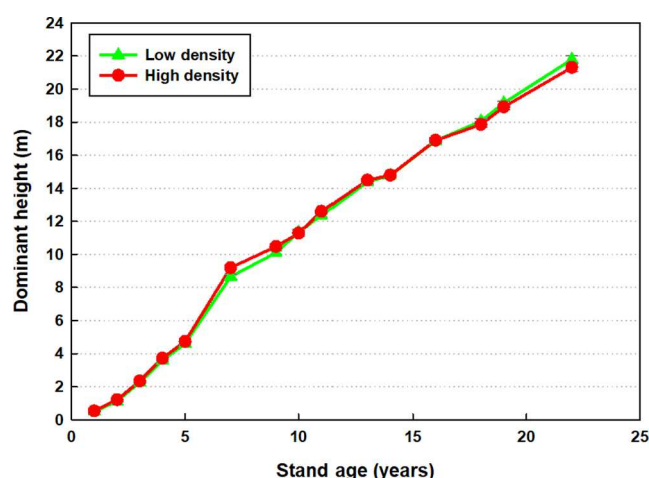


Fig. 2. Dominant height and stand age for a Piedmont site where planting density treatment was low (896 trees ha⁻¹) or high (1793 trees ha⁻¹). Dominant height was the average height of the largest 247 trees ha⁻¹ by volume.

to test this hypothesis; however, there is evidence to support this contention. Foliar phosphorous concentrations were at or below a level (0.11 %) (Fox et al., 2007a) indicating a potential for phosphorous deficiency at age 9 (Table 3) and 9 years after phosphorous was added to all plots. Phosphorous concentrations exceeded this level at ages 10 and 22 in all treatments, indicating sufficient phosphorous in all treatments

by that time. No phosphorous was added in the first rotation, but all treatments received at least 45 kg ha⁻¹ elemental phosphorous in the second rotation. This amount has been determined sufficient for at least one rotation on phosphorous deficient lower coastal plain sites (Everett and Palm-Leis, 2009) and would likely be sufficient for one rotation at our Piedmont site. Soil tests are often used to determine phosphorous deficiency (Wells et al., 1973). No soil test was completed on this site at planting and it was not possible to collect soil samples later in the rotation to test for a phosphorous limitation because phosphorous was applied to all plots. Phosphorous limitations on upland sites with soils similar to ours do occur (Fisher and Garbett, 1980, Ducey and Allen, 2001) and when ameliorated will likely result in an increase in growth over an untreated area throughout the rotation. A phosphorous-deficient, well-drained clay soil (similar to the soil at our site) that received phosphorous early in the rotation would be expected to have an improvement in site index of 1.8 to 2.4 m at the end of a 25 year rotation (Montes, 2002).

There were no records on competition control in the previous rotation; competition control in the previous rotation was likely limited to site preparation work, which commonly included drum chopping and burning at stand establishment at that time. Research on more intensive site preparation techniques including combinations of tillage, chemical vegetation control and fertilization began in the late 1970's and well after the first rotation was established (Nilsson and Allen, 2003). Given the amount of hardwood pulpwood harvested from the site in the first rotation, there would have been considerable hardwood competing vegetation at the start of the second rotation. In a study with treatments controlling hardwoods, herbaceous weeds and both types of competing

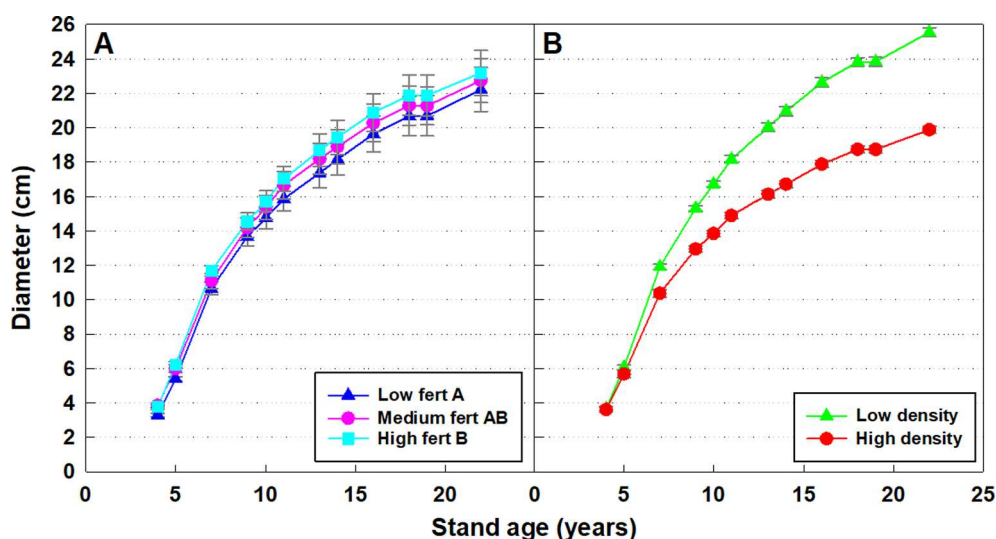


Fig. 3. Main effect mean diameter and stand age for a Piedmont site where (Panel A) fertilizer treatments were applied to produce specific site indices (17, 21, and 24 m at 25 years of age for Low, Medium, and High, respectively) at harvest and (Panel B) planting density treatment was low (896 trees ha⁻¹) or high (1793 trees ha⁻¹). At age 22, the last measurement age, there was a significant fertilizer effect where low (A) and high (B) fertilizer treatments were different from each other but not different from the medium (AB) treatment, and there was a significant planting density effect.

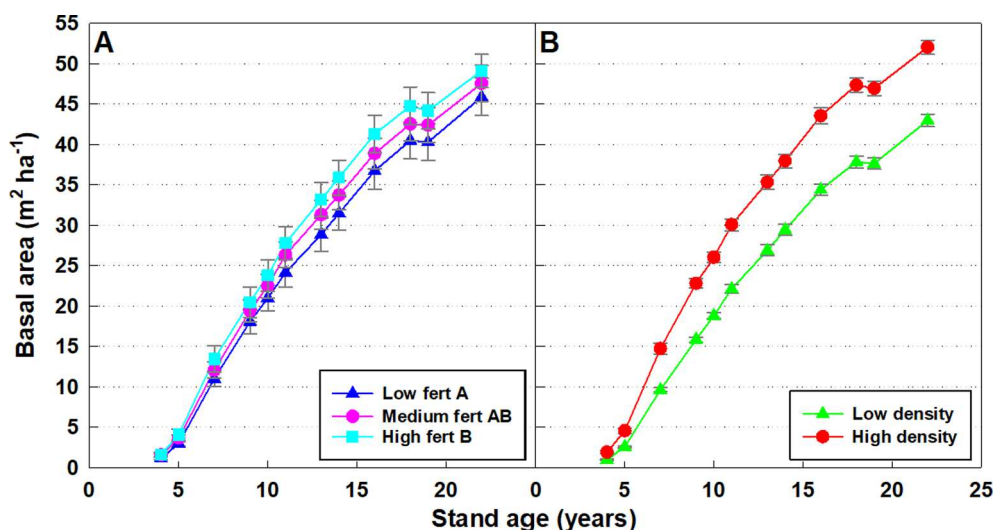


Fig. 4. Main effect mean basal area and stand age for a Piedmont site where (Panel A) fertilizer treatments were applied to produce specific site indices (17, 21, and 24 m at 25 years of age for Low, Medium, and High, respectively) at harvest and (Panel B) planting density treatment was low (896 trees ha⁻¹) or high (1793 trees ha⁻¹). At age 22, the last measurement age, there was a significant fertilizer effect where low (A) and high (B) fertilizer treatments were different from each other but not different from the medium (AB) treatment, and there was a significant planting density effect.

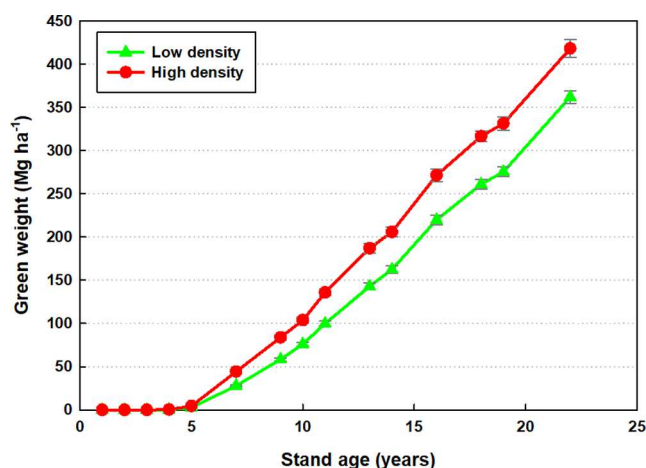


Fig. 5. Green weight and stand age for a Piedmont site where planting density treatment was low (896 trees ha⁻¹) or high (1793 trees ha⁻¹). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

vegetation for the first five years of the rotation, there were three Piedmont sites (Miller et al., 2003a). One site located in Appomattox, VA near our site and on a similar soil, had 8.4 m² ha⁻¹ of hardwood basal area at age 15 in treatments where woody vegetation was not controlled. At the same site and age where herbaceous weeds were not controlled, they found 2717 m ha⁻¹ of shrub rootstocks, with 22 %, 10 %, 3 %, 4 % cover of herbaceous weeds, forbs, grass and vines, respectively. Combined there was a significant amount of competing vegetation and this is likely representative of our site in the first rotation. In the second rotation, we applied intensive competition control treatments with drum chopping and burning during site preparation, combined with two years of herbaceous weed and woody vegetation control and, at age 9, mowing. Miller et al., (2003b) estimated that the combination of herbaceous weed and woody vegetation control could have accounted for about 1.5 m of increased site index. When we measured our site at age 22, there was almost no competition vegetation, so it is likely the increase in site index due to vegetation control was even larger than this estimate.

At the same time, the genotype planted for the second rotation may have improved site index from 1 to 2 m. The first rotation seedlings were unimproved whereas the second rotation had a known improved open pollinated family (WV108). Based on the analysis in McKeand et al.

(2021) where genetic improvement resulted in an increase in volume growth of 0.56 % annually and assuming height growth represents about one third of volume growth, we estimated genetic gain could have accounted for about 1 m of increased site index. An alternative calculation based on our knowledge of the second rotation genotype and information in the Loblolly Pine Performance Rating System (Schmidting, 2001) for WV108, the gain in site index attributable to genetic improvement could have been as much as 2 m.

The second rotation experienced more favorable growing conditions than the first rotation with higher temperatures, more rainfall and higher concentrations of carbon dioxide. Warmer temperatures are associated with more growth in loblolly pine (Nedlo et al., 2009). At our site, increased temperatures would likely have resulted in increased growth. More carbon could be fixed during the dormant season because more winter temperatures would be >5 °C when photosynthesis can occur to produce and store carbon until needed during peak summer growth periods (Sampson et al., 2001) without experiencing temperatures that would reduce carbon fixation due to vapor pressure deficits in the growing season (Teskey et al., 1987). Similarly, additional precipitation would make foliage more effective at photosynthesizing by allowing stomates to stay open more of the time (Teskey et al., 1987). Average carbon dioxide increased 49 ppm from the first to the second rotation. Carbon dioxide acts similar to fertilizer in that it can be a limiting resource and increases in growth with increased carbon dioxide in loblolly pine have been observed when other nutrients are not limiting (Oren et al., 2001). Although, foliar nutrient concentration information may not be the best diagnostic tool for identifying nitrogen limitations, our nitrogen concentrations exceeded the critical value of 1.2 % at ages 10 and 22 in all treatments (Fox et al., 2007a). We added phosphorous to all treatments so it is unlikely that nitrogen and phosphorous limitations occurred in our stands; allowing them to fully utilize the additional carbon dioxide. In a modeling examination of how increased carbon dioxide would influence loblolly pine growth, Thomas et al. (2017) found that a 200 ppm increase in carbon dioxide would increase stem mass increment about 30 %. Assuming a proportional increase and no other resource limitations, the increase in carbon dioxide observed here would likely have increased stem mass production about 7.5 % and could have contributed to the increase in site index. It would be difficult to estimate how much of an increase would be due to increased carbon dioxide without a similar modeling exercise, which was beyond the scope of our analysis. The combination of ameliorating a phosphorus deficiency, near complete competing vegetation control and improved genetics could account for a potential increase in site index of 5.9 m of the observed 7.4 m increase from one rotation to the next. It is reasonable that the observed improvement in environmental conditions

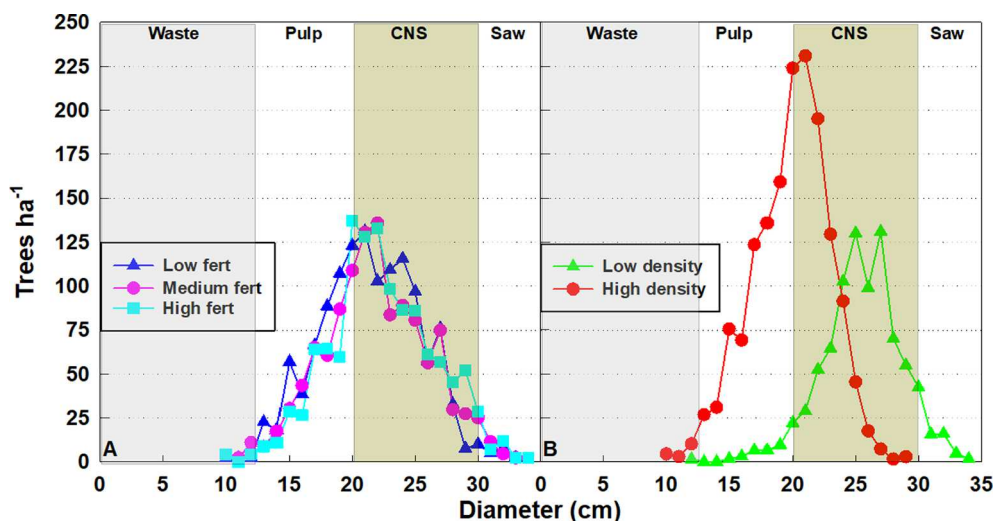


Fig. 6. Age 22 diameter distributions by product class (waste (0–12.7 cm), pulpwood (12.7–20 cm), chip ‘n’ saw (CNS) 20–30 cm, and saw timber > 30 cm) for a Piedmont site where (A) fertilizer treatments were applied to produce specific site indices (17, 21 and 24 m at 25 years of age for Low, Medium, and High, respectively) at harvest and (B) planting density treatment was low (896 trees ha⁻¹) or high (1793 trees ha⁻¹).

that were favorable to better growth could account for the remaining 1.5 m.

Our fertilizer treatments did not affect site index; however, they did have an effect on stand value. Individual tree diameter and stand basal area increased with increasing levels of fertilization which resulted in the high fertilizer treatment having the highest stand value, but that value was only slightly more than the low density treatment. While factoring in silviculture costs was also beyond the scope of our analysis, the amount of fertilizers applied in the high fertilizer treatment would have been a large investment to carry to the end of the rotation for such a small increase in stand value. Our treatment prescriptions were designed using the NUTREM model (Ducey and Allen, 2001). The model was based on 14 studies where nitrogen and phosphorous were added at different rates and the responses were recorded over time. Three sites were upland sites. One of the upland sites and two of the other 11 sites were limited primarily by phosphorous. If our conclusion that our site was phosphorous limited is correct, and NUTREM was based on only a few sites similar to ours, the model may not have been able to generate an appropriate recommendation for our study. Still, it is interesting that our low fertilizer treatment with no applied nitrogen would grow the same as our high fertilizer treatment where 788 kg ha⁻¹ of nitrogen was applied. Nitrogen budgets for the southeastern United States estimate deposition and fixation at 5–10 kg ha⁻¹ yr⁻¹ and 1–2 kg ha⁻¹ yr⁻¹, respectively (Richter et al., 2000). Based on those estimates, between 132 and 264 kg ha⁻¹ of nitrogen would have been added to all treatments during our 22-year rotation. Piedmont sites can have 2000–4000 kg ha⁻¹ of organic nitrogen and low intensity site preparation methods like the drum chop and burn used on our site are conducive to retaining nitrogen on site and making it plant available (Vitousek and Matson, 1985). Our intensive competition control would create a situation where all site resources would be available to the pines and may have increased nitrogen availability as well (Vitousek and Matson, 1985; Hanna et al., 1999). These conditions suggest that our site was able to provide enough nitrogen for rapid tree growth. The phosphorous additions in all plots ameliorated our apparent phosphorous limitation and all plots then had enough available resources to grow well. That all the plots reached the same growth level, even though large amounts of nitrogen were added to the high fertilizer treatment, suggests that some other factor became limiting following Liebig’s law of the minimum (Landsberg and Sands, 2011). However, that our site was primarily phosphorous limited and had sufficient nitrogen for good growth may not be representative of all upland sites. Ducey and Allen (2001) data included one primarily

phosphorous limited upland site and two primarily nitrogen limited ones. Similarly, Piedmont sites can have a nitrogen deficit of up to 250 kg ha⁻¹ rotation⁻¹ (Richter et al., 2000) and there would be few operational stands with the near complete level of competition control achieved at our site.

We accepted our second hypothesis because planting density did not have a significant effect on site index, in agreement with some studies (Harms et al., 1994; Binkley and Fisher, 2013) but in conflict with others (Antón-Fernández et al., 2011; Akers et al., 2013). One explanation for this difference may be in the range of planting densities used in a given study. We used 896 and 1793 trees ha⁻¹ and observed very little mortality. Harms’ et al. (1994) planting density ranged from 746 to 2990 trees ha⁻¹ at planting, all but one treatment was below 2000 trees ha⁻¹ at age 25. Akers et al. (2013) planted 740 to 4440 trees ha⁻¹, but did not observe a significant difference in height until planting density exceeded 2220 trees ha⁻¹. Similarly, Antón-Fernández et al. (2011) worked with planting densities ranging from 745 to 6710 trees ha⁻¹ and observed that the effect of planting density (initial spacing) on dominant height was larger at higher planting densities (close spacing) than at lower planting densities (wider spacing). These results suggest that planting densities less than ~ 3000 trees ha⁻¹ may have been too low to detect planting density effects on dominant height and consequently on site index.

We accepted our third hypothesis, because there were no significant interactions between planting density and fertilization. Our results are similar to those in the literature where no significant interactions were found between planting density and cultural level on site index, and where cultural level was determined by combinations of fertilization and competition control (Akers et al., 2013). Apparently, our high fertilization rates did not cause early onset of density dependent mortality and our low fertilizer rates still provided sufficient resources to maintain growth.

Contrary to the long held notion that site index is fixed, many studies, including ours, demonstrate that silviculture can improve productivity such that large changes in site index are possible from one rotation to the next. Under extensive management (no additional silvicultural treatments) with harvest removals, site index could decline depending on available site resources. Past management and future conditions influence site resource availability. For example, in the Piedmont, individual site nitrogen budgets may range from a deficit of 250 kg ha⁻¹ to a surplus of 180 kg ha⁻¹ per rotation (Richter et al., 2000). Phosphorous cycling has been changed by past agricultural and

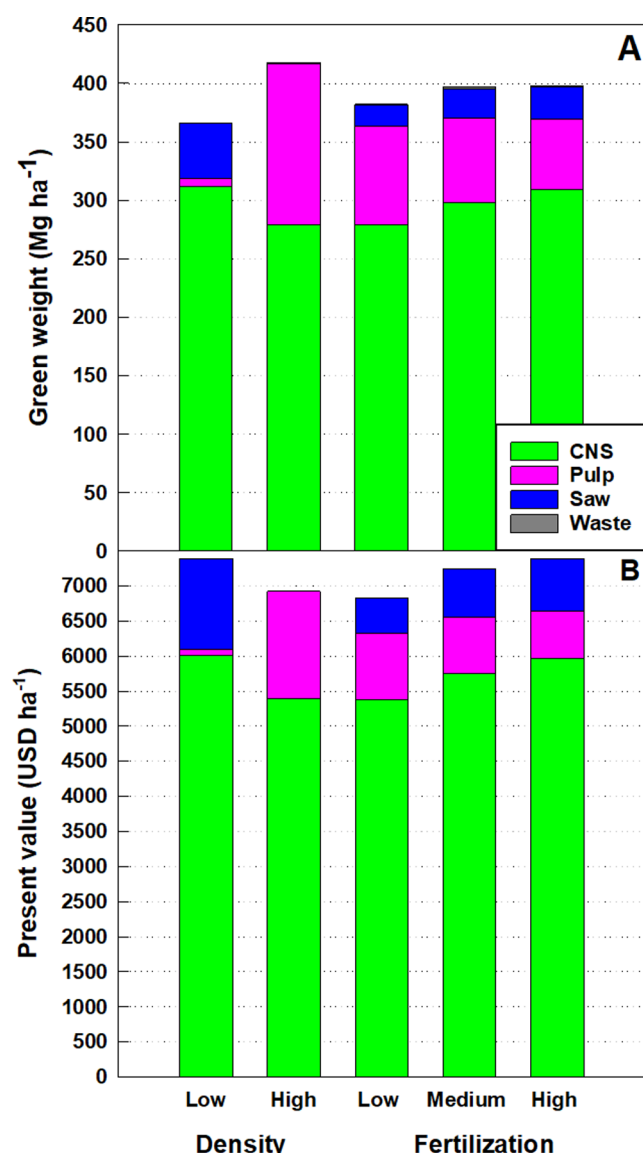


Fig. 7. Age 22 green weight (A) and present value (B) by product class (waste (0–12.7 cm), pulpwood (12.7–20 cm), chip ‘n’ saw (CNS) 20–30 cm, and saw timber > 30 cm) for a Piedmont site where fertilizer treatments were applied to produce specific site indices (17, 21 and 24 m at 25 years of age for Low, Medium, and High, respectively) at harvest and planting density treatment was low (896 trees ha⁻¹) or high (1793 trees ha⁻¹). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

forest management practices and consequently phosphorous availability continues to change over time (Richter et al., 2006). Future environmental conditions (increases in carbon dioxide, and changes in temperature and precipitation as a result of climate change) are forecast to change rapidly, possibly within a rotation (Thomas et al., 2017). All of these factors influence site resource availability, which in turn influences ‘inherent’ site index. Silvicultural management has evolved since the 1940 s resulting in increased stand productivity (i.e., site index) rotation over rotation (Fox et al., 2007b). With continued research and site management, it is reasonable to expect at least some improvement in site indices as new silvicultural tools become available. Consequently, appropriate site-specific silviculture management will be essential to sustain productivity in the future given site variation, land use legacy effects and changing climate and environmental conditions.

Measured site index (dominant height) within a rotation can be

Table 3

Foliar nutrient statistics (p values) and treatment mean concentrations for ages 9 (the year before mowing and fertilization), 10 (the year after mowing and fertilization), and 22 (the last year of measurement) for nitrogen (N), phosphorus (P), potassium (K), calcium (Ca), and magnesium (Mg) from a site in Virginia where planting density (896 and 1793 trees ha⁻¹) and fertilizer applications (low, medium, and high) were applied. Statistics in bold are less than 0.05.

Age	Effect	N	P	K	Ca	Mg
9	Density (D)	0.972	0.633	0.113	0.639	0.233
	Fertilization (F)	0.019	0.621	0.782	0.459	0.274
	D*F	0.882	0.349	0.351	0.721	0.491
	D	0.086	0.241	0.034	0.001	0.000
10	F	0.000	0.003	0.305	0.226	0.198
	D*F	0.433	0.453	0.514	0.620	0.292
	D	0.434	0.310	0.226	0.060	0.156
	F	0.659	0.884	0.876	0.286	0.661
22	D*F	0.639	0.357	0.372	0.255	0.868
	Means (%)					
	Low F	1.12	0.10	0.47	0.16	0.06
	Medium F	1.17	0.11	0.48	0.18	0.07
10	High F	1.22	0.11	0.50	0.16	0.06
	Low D	1.17	0.11	0.51	0.17	0.06
	High D	1.17	0.11	0.45	0.17	0.07
	Low F	1.24	0.12	0.55	0.17	0.07
22	Medium F	1.44	0.14	0.49	0.17	0.07
	High F	1.68	0.14	0.55	0.15	0.07
	Low D	1.42	0.13	0.57	0.14	0.06
	High D	1.49	0.14	0.49	0.18	0.08
22	Low F	1.40	0.12	0.51	0.18	0.08
	Medium F	1.41	0.12	0.52	0.17	0.08
	High F	1.42	0.12	0.51	0.17	0.08
	Low D	1.40	0.12	0.50	0.18	0.08
	High D	1.42	0.12	0.52	0.17	0.08

altered dramatically with intensive management (Borders and Bailey 2001, Albaugh et al., 2004, Jokela et al., 2010). Similarly, intensive silvicultural treatments including fertilization and/or competition control in one rotation or even past agricultural use may have carryover effects in subsequent rotations (Richter et al., 2000, Everett and Palm-Leis, 2009, Zerpa et al., 2010, Subedi et al., 2019). However, our results suggest being cautious when using site index as an indicator of potential productivity in intensively managed stands. Models to estimate site index which utilize soil characteristics including soil nutrient levels (Subedi and Fox, 2016) and biophysical characteristics including moisture and temperature (Sabatia and Burkhart, 2014) are available but potential productivity maps based on soil characteristics are not available. These models would be useful in predicting site index with changing site conditions due to fertilizer additions or climate change in that they include variables reflecting those changes. Another, potentially better, approach may be to use process based models to estimate site index and productivity for future rotations given their ability to provide not only productivity estimates but also uncertainty around those estimates (Thomas et al., 2017). Site index and biomass or volume estimates of productivity are correlated but the latter may better include effects related to tree diameter, stand basal area and density and changing environmental conditions. Ultimately, productivity may be the best metric for predicting stand performance. Perhaps we need to rethink our approach to estimating site index and use estimates of productivity (m³ ha⁻¹ yr⁻¹ or Mg ha⁻¹ yr⁻¹) for predicting future stand performance (Kimberley et al., 2005, Binkley and Fisher, 2013).

CCRediT authorship contribution statement

Timothy J. Albaugh: Conceptualization, Formal analysis, Investigation, Data curation, Writing – original draft, Writing – review & editing. **David R. Carter:** Conceptualization, Writing – review & editing, Funding acquisition. **Rachel L. Cook:** Writing – review & editing, Funding acquisition. **Otávio C. Campoe:** Writing – review & editing,

Funding acquisition. **Rafael A. Rubilar:** Writing – review & editing, Funding acquisition. **Jerre L. Creighton:** Conceptualization, Investigation, Writing – review & editing.

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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