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Herbicide, fertilization, and planting density effects on intensively managed loblolly pine early stand development

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ABSTRACT

Production forestry in the southeast US has been partially transitioned to intensively managed short rotations (~10 years), in which multiple silvicultural interventions are performed during forest development. Understanding the responses to silvicultural practices and continued refinement of site-specific recommendations is critical to sustainably maximize forest production. We evaluated the effects of silvicultural practices (herbicide, fertilization, and planting density) on growth, stand homogeneity, and above- and belowground biomass accumulation and partitioning of loblolly pine (*Pinus taeda*) throughout early stand development (age 5 years) in the southeastern US. Five treatments with eight replications each were tested: no herbicide and no fertilization (*C*); herbicide only (*H*); herbicide and half-reduced fertilization rate (*R*); herbicide and full fertilization (*F*); and increased stand density (60+ %; 1346 *vs.* 2152 trees per hectare) with herbicide and full fertilization rate (*D*). Allometric equations generated from destructive harvests were applied to annual diameter measurements to estimate plot-level biomass and allocation. Herbicide was crucial to promote stand uniformity and increase yield (~600+ % stem biomass compared with *C* at age 5). Aboveground biomass was similar in *R* and *F* treatments, which was ~25% higher than in *H* at age 5. Increasing planting density along with multiple herbicide and fertilizer applications yielded higher biomass without compromising individual tree size (diameter and height). There was little effect of silviculture practices on allocation patterns. Our results parallel what was found for fertilization with herbicide from a number of loblolly stands under similar conditions and indicate a ~28% volume gain with fertilization during early stand development. Similarly, our results were consistent with other studies implementing similar differences in planting density and suggest a ~26% volume gain through early stand development with an initial 60% increase in planting density. Our study helps to understand complex relationships between production and silvicultural practices during early stand development and demonstrates that silvicultural prescriptions can be optimized to increase sustainability of production forestry.

1. Introduction

The southeastern US is responsible for ~60% of the total US wood supply and accounts for 18% and 15% of global industrial timber and pulp products, respectively (Munsell and Fox, 2010; Wear and Greis, 2012). Loblolly pine (*Pinus taeda* L.) is the most common tree species planted in the southeast US because its overall productivity outperforms all other native tree species (Coyle et al., 2016; D'Amato et al., 2017; Zhao et al., 2019). Intensive management and silviculture advancements, such as multiple herbicide and fertilizer applications, and the proper choice of planting density (Jokela et al., 2010) have enabled loblolly to be grown profitably for a variety of uses (e.g., pulpwood, wood-pellets, chip-*n*-saw) in very short rotations (8 – 12 years) (Coyle et al., 2016; Kline and Coleman, 2010; Munsell and Fox, 2010). The continuously rising demand for wood products, especially woody feedstock towards a renewable and cleaner energy agenda (European Parliament and Council, 2009; US Congress, 2007), will require sustained productivity across rotations and continued refinement of site-specific silviculture practices (Fox, 2000).

Soil nutrient availability is the major limitation to loblolly pine productivity in the southeastern US, particularly nitrogen (N) and phosphorus (P) (Fox et al., 2007). Competition control is widely used in production forestry to ameliorate nutrient limitation and promote tree crop growth over the competing vegetation (Miller et al., 2003). Complete control of competing vegetation (herbaceous + hardwoods) has been documented to provide volume increases of up to 800% during

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loblolly pine early stand development (Britt et al., 1990; Neary et al., 1990; South et al., 2006; Zutter et al., 1987). Percentage differences may decline over time (South et al., 2006), but initial gains from competition control can persist through stand development (Jokela et al., 2010). While nutrient demand is relatively low during early stand development, multiple nutrient additions in intensively managed stands can improve soil fertility and tree growth throughout the rotation (Aubrey et al., 2012; Coyle et al., 2016; Subedi and Fox, 2016). However, null or small responses to fertilization during early stand development may result from the assart effect, in which an accelerated pulse of organic nutrient mineralization occurs following disturbances from previous stand harvest and site preparation (Amishev and Fox, 2006; Fox et al., 2007; Subedi and Fox, 2016). These inconsistent responses suggest fertilization effects are rather site-specific or not yet fully understood, and indicate that nutrient limitation is a dynamic property varying temporally and spatially (Fox et al., 2007). Moreover, the transition to intensively managed short rotations reduces nutrient recycling potential and might change nutrient dynamics and requirements (Heilman and Norby, 1998). If nutrients are applied multiple times through a rotation, temporal evaluations are essential to identify the equilibrium between demand and input and, thus, optimize nutrient application. However, most studies investigating nutrient dynamics are focused on traditional production forestry systems (e.g., ~25-year loblolly rotations) and/or skewed towards later stages of forest development (Albaugh et al., 2015, 2008, 2004; Nilsson and Allen, 2003; Subedi et al., 2012; Will et al., 2006).

Resource limitation may hasten intraspecific competition and increase heterogeneity within a stand, which can be inversely related to productivity (Aspinwall et al., 2011; Binkley et al., 2002; Soares et al., 2016). Spacing is a crucial decision for preventing anticipated competition (Aspinwall et al., 2011). There is not a single optimal planting density, and the choice interacts with other silviculture decisions (e.g., wood end-use, genotype, nutrient amendments, and thinning) (Akers et al., 2013; Zhao et al., 2011). Planting densities ranging between 1200 and 2500 trees ha^{-1} are typical for loblolly pine stands (Akers et al., 2013; Sharma et al., 2002; Subedi et al., 2012; Will et al., 2005; Zhao et al., 2011). Increasing planting density will likely result in higher biomass production during early stand development, which could be partially counterbalanced by growth inhibition and the occurrence of smaller individual trees because of increased competition for resources (Will et al., 2005). However, it has also been suggested that, within typical spacing ranges, reduced diameter growth occurs only later in the rotation (> 12 years) (Akers et al., 2013; Subedi et al., 2012; Zhao et al., 2011). Therefore, early competition might be delayed or eliminated in intensively managed short rotations; however, this is poorly documented. Moreover, information on stand uniformity as affected by planting spacing and other silvicultural practices during early stand development is rare (Yáñez et al., 2017).

Biomass allocation to aboveground components, stem or woody shoot, in relation to foliage or belowground tissues, respectively, is commonly used as a metric to infer production efficiency (Burkes et al., 2003; Ex and Smith, 2014; Fernández et al., 2011; Konôpka et al., 2010). Studies suggest that belowground biomass allocation is inversely related to nutrient availability (Haynes and Gower, 1995) and stand development (Adegbidi et al., 2004; Coyle et al., 2008). Separating effects of stand age or resource-induced allocation requires sequential multiyear samplings so that comparisons can be made among developmentally similar trees rather than among chronologically equivalent ones (Coyle and Coleman, 2005). Although there are several reports on biomass allocation and production for loblolly pine plantations (Albaugh et al., 2004, 1998; Jokela et al., 2004; Jokela and Martin, 2000; Subedi et al., 2012; Zhao et al., 2014), there is little information on sequential sampling comparisons, particularly for young stands and belowground biomass (but see Adegbidi et al., 2002; Coyle et al., 2008; Samuelson et al., 2004). Understanding how management practices can alter annual biomass accumulation and partitioning in young stands might be more cost-effective since differences caused by an accelerated initial development might persist throughout the rotation (Coyle et al., 2016, 2008; Nilsson and Allen, 2003; Subedi and Fox, 2016).

To fill knowledge gaps about loblolly pine in intensively managed short rotations in the southeast US, we tested different silvicultural practices side-by-side and evaluated their effects on growth, stand homogeneity, and above- and belowground biomass accumulation and partitioning throughout early stand development (age 5 years). Considering that nutrient demand is relatively low during early stand development, but changes rapidly through intensively managed short rotations, we hypothesized that (1) competition control would increase loblolly pine productivity by improving the uptake of existing soil resources, but expedited growth would still require nutrient amendments. Additionally, we posited that (2) annual fertilization combined with herbicide would have an additional effect on productivity, but annual rates frequently applied (e.g., ~100 kg N ha^{-1} yr^{-1}, Borders and Bailey, 2001; Carlson et al., 2009; Coyle et al., 2016; Lee and Jose, 2005; Samuelson et al., 2004; Zhao et al., 2011) could be reduced without compromising productivity. We predicted that (3) increasing planting density from most typical spacing ranges (e.g., 1300–1600 trees ha^{-1}) to higher densities (e.g., 2000–2500 trees ha^{-1}) under intensive management would result in higher biomass production with no detrimental effect to individual tree size during early stand development. In addition to these hypotheses, we investigated whether allocation would differ among silviculture practices and how allocation could influence production efficiency.

2. Material and methods

2.1. Site description

The experimental site used in this study was located within the US Department of Energy – Savannah River Site, a National Environmental Research Park located on the Upper Coastal Plain physiographic region, near Aiken, SC (33°15′ N; 81°36′ W). The region has a humid subtropical climate, with warm and humid summers and mild winters. Annual precipitation averages 1200 mm yr^{-1} distributed evenly throughout the year, and the mean annual temperature is 18 °C. The experimental stands were in a gently sloped area, ranging from 90 to 130 m *asl*, with a fine-loamy, kaolinitic, thermic Plinthic Kandiudult (Dothan series, Soil Survey Staff, 2014) as the dominant soil type. Before study establishment, the area was dominated by second rotation planted loblolly pines, which were established in 1951 following the abandonment of row crop agriculture (Aubrey et al., 2019).

2.2. Experimental design

The mature pine stands were clear-cut between January-May 2012. Harvesting included stem and low-quality small-diameter woody material, resulting in < 2 Mg ha^{-1} of coarse woody debris remaining on the soil surface. After harvesting, soil was mechanically prepared by subsoiling planting rows to 45 cm depth. Bare-root loblolly pine seedlings (ArborGen Mass Control Pollinated AGM 37) were hand-planted at the beginning of 2013, and five treatments were applied following a complete randomized block design with eight replications. Treatments were a combination of different silviculture practices (competition control, fertilization, and planting density) as follows: Control – no herbicide and no fertilization (*C*); herbicide only (*H*); herbicide and half-reduced N and P fertilization rate (*R*); full herbicide and N and P fertilization (*F*); and increased planting density (60% higher) with full herbicide and N and P fertilization (*D*). The *C*, *H*, *R*, and *F* treatments were planted at 1346 plants ha^{-1}, while the *D* treatment was planted at 2152 trees ha^{-1}. In each block, treatment plots (0.125 ha) contained 168 trees, and each plot had central measurement plots (0.04 ha) consisting of 48 trees and large end borders to accommodate selected destructive sampling. For the *D* treatment, specifically, treatment plots

consisted of 0.123 ha (264 trees), with central measurement plots of 0.03 ha (60 trees).

To reduce competing vegetation (*H*, *R*, *F*, and *D*), we performed an initial application of mixture of imazapyr (Imazapyr 4SL) and glyphosate (Rodeo®) before planting, and a second application of sulfometuron-methyl (Oust XP) and imazapyr (Arsenal®) immediately after planting. Subsequently, competing vegetation was controlled by annual Oust XP applications until year 5. Fertilization consisted of annual N and P inputs at varying rates; the first fertilizer application occurred immediately after planting at 50 kg N ha^{-1} and 56 kg P ha^{-1}; in year 2, ~100 kg N ha^{-1} was applied; fertilization in year 3 consisted of ~100 kg N ha^{-1} plus 26 kg P ha^{-1}; final fertilizer application occurred in year 4 at 196 kg N ha^{-1}. Annual fertilization rates averaged ~110 kg N ha^{-1} yr^{-1} across the 5-year observation period and were used in both *F* and *D* treatments, while the *R* treatment receives one-half the amount, and *C* and *H* treatments received no fertilizer input. A detailed description of fertilization timing, rate, and source is presented in Supplemental Table 1. All pine seedlings had Fipronil injected at their bases before the second growing season to control a Nantucket pine tip moth (*Rhyacionia frustrana*) infestation that affected ~70% of seedlings, with no differentiation between treatments. Satisfactory seedling recovery was observed during the second growing season.

2.3. Growth measurements and biomass

Diameter at ground level (dgl) and tree height (H_t) were measured annually for five years on all measurement plot trees. The last sampling (at the end of the fifth growing season) also included the measurement of the diameter at breast height (dbh). We selected one representative tree (based on average H_t) for destructive harvesting from each treatment and block combination every year. Destructive harvests began one year after planting for all treatments but *C*, which started one year later because of the very slow initial development. Before harvesting, dgl and H_t of each tree were recorded (dbh was also measured in the final sampling). Felled trees were separated into needles, branches, stem, and roots. The biomass of each component was wet weighed, and a subsample was collected to obtain the moisture content and convert to dry biomass.

Root biomass was quantified in all treatments except *C* because of the difficulty in distinguishing roots from loblolly trees and competing vegetation. Root sampling protocol changed over time as roots developed and expanded in areal extent. In the first sampling, the whole seedling root system was excavated and quantified. For the second sampling, we placed a 0.75 × 0.75 m square frame over the tree stump and excavated the soil inside this area to a 90 cm depth. All soil was sieved through a 12-mm sieve, and retained roots were wet weighed; a subsample was dried in an oven to obtain moisture content and convert to dry mass. The third sampling followed this same protocol, but an extra 0.75 × 0.75 m square frame was placed diagonally between trees to account for peripheral roots, which were quantified following the previously described method. Finally, in the last two samplings, tree roots were excavated with a hydraulic spade (1 m diam. × 0.69 m deep), and the soil volume sampled was determined for each tree. The soil was passed through a 12-mm sieve, and taproot and retained coarse-roots were quantified as previously described until 90 cm depth. Peripheral root determination followed the same method used in previous years with a 0.75 × 0.75 m square frame placed diagonally within the tree growing space.

Competing vegetation was sampled annually by placing three 0.75 × 0.75 m square frames at random azimuth and distance from plot center within each of the measurement plots. The competing vegetation rooted inside the frame was harvested, dried in an oven at 60 °C to a constant mass, and weighed.

2.4. Biomass calculations, data processing and statistical analysis

Using the destructive harvest data, we parameterized treatment-specific allometric equations to estimate above- and belowground biomass across the five growing seasons. We used dgl to estimate each biomass component as follows:

$$N_e, B, S, R_o = aX^b \quad (1)$$

in which N_e, *B*, *S*, and R_o indicate the biomass of needles, branches, stem, and roots, respectively; *a* and *b* are the estimated model parameters, and *X* is the dgl. Total aboveground loblolly pine biomass was obtained by summing needles, branches, and stem biomass. The Eq. (1) was then applied for all the living trees at each measurement plot to scale up biomass to the plot-level, which implicitly accounted for mortality. Fine-roots were presumably unaccounted for by our method since they would have passed through the 12 mm sieve. To overcome this limitation and estimate a more representative root biomass at the plot level, we used allometric equations developed from a similar age loblolly pine trial performed in an nearby area (Coyle et al., 2016) to estimate fine-root biomass as a function of coarse- and taproot biomass ($R^2 = 91\%; n = 18; p < 0.001; MAE = 0.244$); and thus, account for the total root mass fraction (RMF) – the proportion of roots to total mass – of each plot. Stem volume index (VI) was calculated as the squared dgl multiplied by H_t. Mean annual increment (MAI) for each treatment was calculated on a VI basis per year. The quadratic mean diameter (Dq) was calculated as the square root of the sum of squared dbh divided by *n* measured trees.

We used plot means to analyze stand characteristics, an approach that adequately accounts for plot variation, but eliminates variance among individual trees (Parresol, 1999). We analyzed treatment effects through a repeated measures linear mixed model (SAS PROC MIXED v.9.1.3; SAS Inc., Cary, NC, USA) with Kenward-Roger degrees of freedom correction (Kenward and Roger, 1997). Year was considered as the fixed repeated factor, silvicultural treatment as a fixed factor, and treatment-by-block combination (i.e., experimental unit) as the random subject factor. To model the correlation within experimental units over time, each response variable was analyzed following the determination of the best fit for covariance structure (e.g., first-order autoregressive, Toeplitz, compound symmetry, and variance component). The best fit was determined using Akaike's information corrected criterion (AICc) (Burnham and Anderson, 1998), in which the lowest AICc indicates the best covariance structure fit for each model. Applying Kenward-Roger degrees of freedom correction and selecting the most appropriate covariance structure within a mixed model framework yields a robust approach for repeated measures analysis, even when normality assumptions cannot be fulfilled by data transformation (Arnau et al., 2013, 2012). We performed tests of simple main effects to decompose interactions using the SLICE option in the LSMEANS statement in SAS (Littell et al., 2006; Schabenberger et al., 2000). Fisher's Least Significant Difference (LSD) contrasts were used in post hoc pairwise multiple comparisons. Variables collected only at the final sampling, i.e. dbh, Dq, and basal area (BA) were analyzed in a similar model, but without the year factor (i.e., not a repeated measure analysis).

We assessed treatment effects on stand uniformity for dbh and H_t using the coefficient of variation (CV) among trees of each plot. The CV for dbh and H_t for each treatment was compared following the same ANOVA approach previously described. Biomass allocation between tree components was evaluated by comparing the slopes of the line relating two biomass fractions to account for ontogenetic effects (after Coyle et al., 2016, 2008; Jokela and Martin, 2000). We used the natural logarithm (ln) of biomass fractions and the linearized form of Eq. (1) to assess biomass allocation in response to different silvicultural treatments among aboveground woody compartments (stem, and stem + branches – *y-axis*), as a function of foliage biomass (*x-axis*), and how biomass was allocated belowground (woody- and total-roots – *y-axis*) as function of the aboveground compartments (woody- and total-

Table 1
Loblolly pine stand characteristics (mean ± SE) in response to the five treatments (*C*, *H*, *R*, *F*, and *D*) after five growing seasons and linear mixed model ANOVA significance levels.

	H_t (m)	Dq (cm)	BA (m^2 ha^{-1})	Mortality (%)
Treatment				
C	3.05 (0.21) b	3.61 (0.28) b	1.22 (0.22) c	8.33 (1.11) a
H	5.41 (0.17) a	8.23 (0.26) a	7.03 (0.44) b	4.43 (1.27) b
R	5.57 (0.20) a	9.06 (0.48) a	8.72 (0.94) b	5.99 (1.44) b
F	5.37 (0.21) a	8.96 (0.54) a	8.20 (1.01) b	9.11 (1.62) a
D	5.36 (0.18) a	8.53 (0.27) a	11.56 (0.78) a	10.00 (3.40) a
Effect (*p-value*)				
Year (Y)	< 0.0001	n.a.	n.a.	< 0.0001
Treatment (T)	< 0.0001	< 0.0001	< 0.0001	< 0.0001
Y × T	< 0.0001	n.a.	n.a.	0.9993

Treatments: *C*: control; *H*: herbicide only; *R*: herbicide and half-reduced fertilization rate; *F*: full herbicide and fertilization; and *D*: increased stand density with full herbicide and fertilization. n.a.: not applicable. Values followed by the same letter are not significantly different (Fisher's LSD, $\alpha = 0.05$).

shoot – *x-axis*). In either case, lower *b* coefficients indicate lower woody-shoot or lower belowground allocation, respectively. Differences in *b* coefficients between treatments were examined through a covariance analysis using SAS PROC MIXED.

3. Results

3.1. Five-year stand characteristics

Indices of individual tree development, i.e., Dq and H_t, indicated that trees from the *C* treatment were significantly smaller than trees from other treatments (Table 1). Overall, for H_t and Dq, trees from *C* were ~78% and 140% smaller than from amended treatments, respectively. No influence of planting density could be observed on individual tree indices. Mortality rates were higher in *C*, *F*, and *D* compared with *H* or *R* treatments. However, no clear treatment-related pattern (e.g., herbicide, fertilization, or density) could be inferred. The highest BA was found in *D*, which was 10-times larger than the BA observed in *C*, and 1.4-times larger than the BA observed in *H*, *R*, and *F*, which did not differ from each other after five growing seasons.

3.2. Stand uniformity

We observed that dbh was more variable than H_t across all treatments (Fig. 1). The highest heterogeneity for dbh and H_t was observed in *C*. Differences in the CV of dbh and H_t were only statistically significant when treatments were compared with *C*, suggesting that herbicide was critical to obtain more uniform stands, while no fertilizer or planting density influence was observed. The dbh distribution in *C* treatment was right-skewed, which indicates a higher proportion of smaller trees in this treatment (~40% of trees were found in the lowest dbh class), while all other treatments presented a normal, or *quasi-normal*, dbh distribution (Supplemental Fig. 1).

3.3. Annual biomass production

Stem biomass ranked $D > R = F > H > C$ after five growing seasons. A similar ranking was observed for MAI, except that *F* and *H* did not differ regarding MAI (Fig. 2A and 2B). The MAI ranged from 3.8 to 44 m^3 ha^{-1} yr^{-1} at age 5, in *C* and *D* treatments, respectively. The highest stem biomass increment for all treatments occurred in the last growing season, which ranged from 0.8 to 7.7 Mg ha^{-1} for *C* and *D* treatments, respectively (Fig. 2B). Stem biomass in *R* and *F* did not differ from each other but were higher than in *H* (11.9 and 11.7 *vs* 9.7 Mg ha^{-1}, respectively). The largest difference in stem biomass from *C* occurred at age 3 when *C* was compared with *D* (1500%; Fig. 2C). For

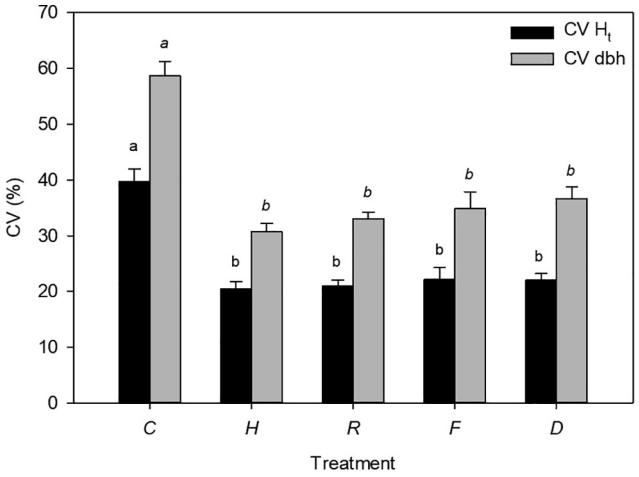

Fig. 1. Coefficient of variation (CV, %) for dbh and H_t loblolly pine stand trees as influenced by the five treatments (*C*, *H*, *R*, *F*, and *D*). *C*: control; *H*: herbicide only; *R*: herbicide and half-reduced fertilization rate; *F*: full herbicide and fertilization; and *D*: increased stand density with full herbicide and fertilization. Error bars represent standard errors. Treatments with the same letter (regular for H_t, italic for dbh) are not significantly different (Fisher's LSD, $\alpha = 0.05$).

standardly spaced treatments, the difference from *C* also peaked at age 3 years and was 827, 987, and 928% for *H*, *R*, and *F*, respectively.

Biomass components increased over time and differed among treatments, with a significant year × treatment interaction (Table 2). Exceptions occurred for total roots and competing vegetation, in which there was no significant effect for treatment or interaction between year and treatment, respectively. Roots were only evaluated in amended treatments (*H*, *R*, *F*, and *D*) and was the only variable lacking a treatment effect ($p = 0.1406$). Thus, we infer the large biomass difference between *C* and other treatments (Fig. 3; Supplemental Table 3) was likely the primary driver of treatment significance ($p < 0.0001$) for the other variables. The interaction was, however, significant for roots, and treatment differences occurred at years 4 and 5 (Supplemental Table 3). Similarly, for all other variables, treatment differences became more apparent through time (Fig. 3; Supplemental Table 3).

Across all ages, *D* was responsible for the highest biomass in above- and belowground components (Fig. 3; Supplemental Table 3). After two growing seasons, no statistical differences were observed between treatments, although *D* showed on average 12, 23, and 15-times more biomass than *C* for needles, branches, and stem, respectively. Interestingly, these ratios were higher than the ones observed in the final sampling when statistical differences were most pronounced (*D* was 12, 14, and 12-times greater than *C* for needles, branches, and stem, respectively). After the third growing season, *D* differed from *C* in all biomass components. Standardly spaced treatments were not different from *C* until age 4 years, although presenting > 10-times higher aboveground biomass than *C*. This proportional difference needs to be accounted for since the lack of a statistical difference during early stages could be a statistical artifact. For instance, because of the biomass change substantially through time and all sampling times are combined in the two-way ANOVA, it yields a large least square difference threshold, which hampers statistical significance detection during earlier years. In the fourth growing season, amended treatments exhibited more biomass than *C* in all aboveground components, with *D* exhibiting the highest biomass among all treatments and components, except when compared with *R* for needles and branches (Fig. 3; Supplemental Table 3). The *R* and *F* treatments did not differ from each other throughout the study. Fertilization influence on biomass production could only be observed after five growing seasons, in which both *R* and *F* differed from *H*, although, for instance, *R* and *F* had a sustained ~ 20% greater stem biomass than did *H* starting from the

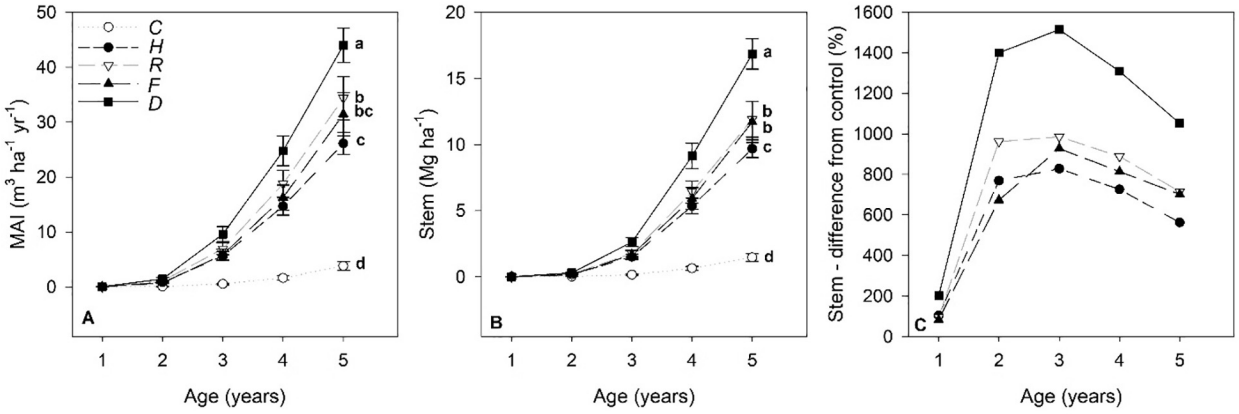

Fig. 2. Mean annual volume index increment (MAI) (**A**), stem biomass (**B**), and stem biomass proportional difference from control (**C**), over five years (mean ± SE) in loblolly pine stands in South Carolina USA under the five treatments (*C*, *H*, *R*, *F*, and *D*) tested. *C*: control; *H*: herbicide only; *R*: herbicide and half-reduced fertilization rate; *F*: full herbicide and fertilization; and *D*: increased stand density with full herbicide and fertilization. Treatments with the same letter are not significantly different after five growing seasons (Fisher's LSD, $\alpha = 0.05$).

Table 2
Significance levels (*p-values*) of linear mixed model ANOVA for biomass components after five years of treatment application.

Source	Needles	Branches	Stem	Abv. biomass	Total roots	Comp. veg.
	p-value					
Years (Y)	< 0.0001	< 0.0001	< 0.0001	< 0.0001	< 0.0001	0.0045
Treatments (T)	< 0.0001	< 0.0001	< 0.0001	< 0.0001	0.1406	< 0.0001
Y × T	< 0.0001	< 0.0001	< 0.0001	< 0.0001	0.0019	0.9736

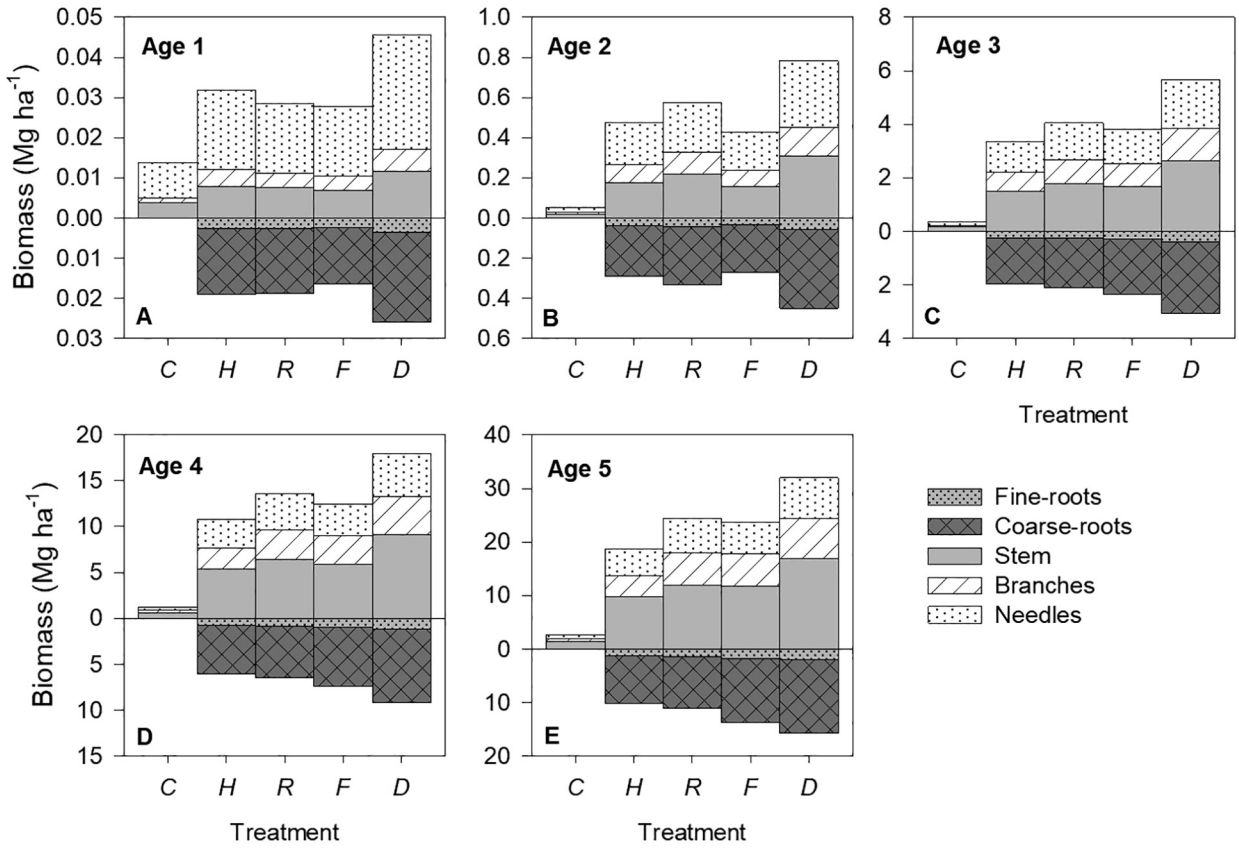

Fig. 3. Above- and belowground biomass of loblolly pine stands in response to the five treatments (*C*, *H*, *R*, *F*, and *D*) over five growing seasons in South Carolina USA. *C*: control; *H*: herbicide only; *R*: herbicide and half-reduced fertilization rate; *F*: full herbicide and fertilization; and *D*: increased stand density with full herbicide and fertilization. Statistical comparisons among treatments are presented in Supplemental Table 3.

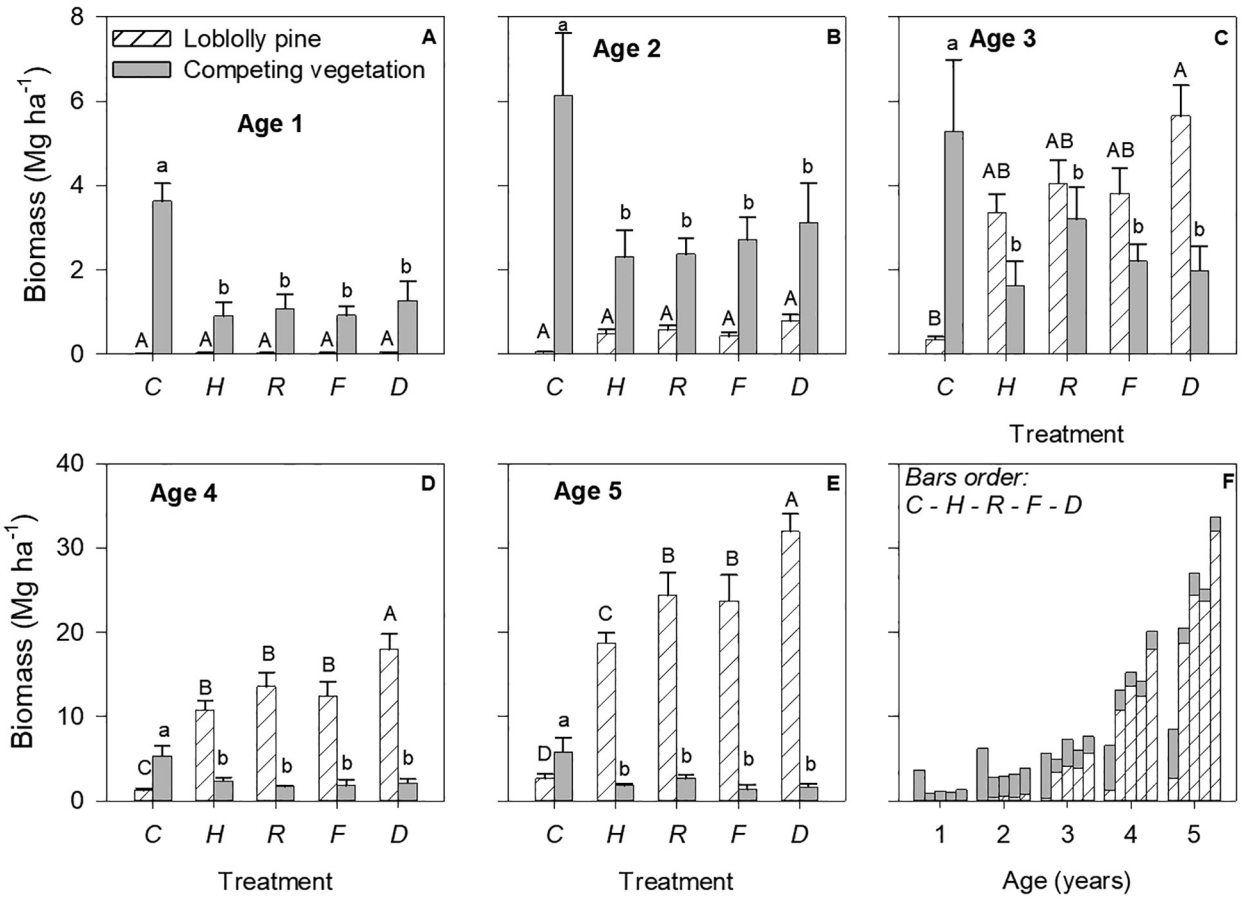

Fig. 4. Aboveground biomass for loblolly pine stands and competing vegetation within stands during five growing seasons in response to the five treatments (*C*, *H*, *R*, *F*, and *D*) over five growing seasons in South Carolina USA. *C*: control; *H*: herbicide only; *R*: herbicide and half-reduced fertilization rate; *F*: full herbicide and fertilization; and *D*: increased stand density with full herbicide and fertilization. Within each time, treatments with the same letter (upper and lower case for loblolly pine and competing vegetation biomass, respectively) are not significantly different (Fisher's LSD, $\alpha = 0.05$).

second and third growing seasons, respectively. The same caveat for the statistical significance detection during earlier years should also be considered here. Additionally, the substantial difference between *C* and other treatments inflates the least square difference in pairwise comparisons to detect differences between more comparable treatments. After five growing seasons, the biomass of needles, branches, and stem followed a similar $D > R = F > H > C$ ranking (Fig. 3, Supplemental Table 3). For belowground biomass, *D* did not differ from *F*, and both were greater than *R* and *H*, which did not differ from each other.

Loblolly pine aboveground biomass production was 700–1300% greater in amended treatments compared with *C* after two growing seasons. Consistently higher loblolly pine biomass was found in *D* throughout the five years (> 1.3-times higher), but statistical differences between *D* and other treatments occurred only after the third growing season. At age 5 (Fig. 4E), *C* treatment exhibited 2.6 Mg ha^{-1} of loblolly aboveground biomass, while *R* and *F* averaged 24 Mg ha^{-1}, which was 1.3-fold higher than *H*, and *D* yielded the highest (32 Mg ha^{-1}) loblolly aboveground biomass.

Competing vegetation accounted for > 90% of the aboveground vegetation biomass in all treatments at the end of the first growing season (Fig. 4A). At that time, competing vegetation was, however, 3.5-times greater, on average, in *C* than in the other treatments. Competing vegetation ranged from 1 to 3 Mg ha^{-1} throughout the five growing seasons where herbicide was applied, with no difference between the treatments receiving herbicide (*H*, *R*, *F*, and *D*). In these treatments, competing vegetation accounted for < 10% of total aboveground biomass at age 5. In *C*, competing vegetation biomass varied between 3.5 and 6 Mg ha^{-1}, and after five growing seasons, it was still responsible for > 65% of total vegetation aboveground biomass (Fig. 4E). Fig. 4F summarizes all vegetation biomass in stand plots and show that controlling competing vegetation during early stand development was critical to promote tree crop growth over competing vegetation and increase overall biomass production.

3.4. Biomass allocation

Differences in aboveground allocation among treatments were observed in the allometric relationships between needles and stem and between needles and woody-shoot (stem + branches) (Fig. 5A and 5B, respectively). There was a strong positive relationship between these fractions through time for all treatments ($R^2 = 0.99$, $p < 0.0001$). For both allometric relationships, the slope rank between treatments was $C > D > H > F > R$, in which higher slope indicates a greater allocation to either stem or stem + branches in relation to needles biomass. All slopes differed each other at $\alpha = 0.05$, likely because of the low error and very good fit of regressions ($R^2 = 0.99$) and the large number of replicates ($n = 8$); however, slope differences seem small to be biologically relevant to explain differences in woody-tissue production between treatments. There was a general trend in decreasing the proportions of needles to total aboveground biomass over time, irrespective of treatment, while woody biomass (stem and branches) exhibited the opposite pattern, with stem exhibiting the sharpest increase (Supplemental Fig. 2).

A slight downtrend in RMF was observed over time across all treatments, but the magnitude varied between them ($p < 0.0001$, Year × Treatment) (Fig. 6). The most pronounced decrease was

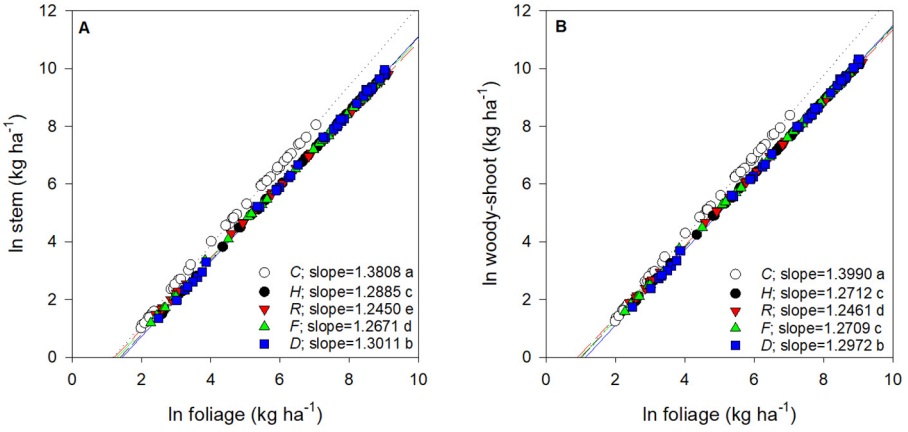

Fig. 5. Allometric relationships for aboveground components (stem *vs*. foliage (**A**), and woody-shoot (stem + branches) *vs*. foliage (**B**)) in loblolly pine stands in response to the five treatments (*C*, *H*, *R*, *F*, and *D*) over five growing seasons in South Carolina USA. *C*: control; *H*: herbicide only; *R*: herbicide and half-reduced fertilization rate; *F*: full herbicide and fertilization; and *D*: increased stand density with full herbicide and fertilization. All tissue fractions are natural log (ln) transformed plot means. The slope of the linear regression for each treatment (i.e., allometric coefficient, *b*) is presented in the figure legend. Slopes followed by the same letter are not statistically different by covariance analysis.

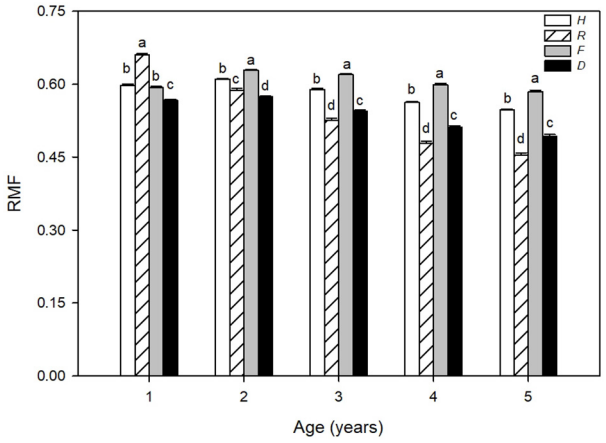

Fig. 6. Root mass fraction (RMF) for loblolly pine stands in response to the five treatments (*C*, *H*, *R*, *F*, and *D*) over five growing seasons in South Carolina USA. *C*: control; *H*: herbicide only; *R*: herbicide and half-reduced fertilization rate; *F*: full herbicide and fertilization; and *D*: increased stand density with full herbicide and fertilization. Within each year, treatments with the same letter are not significantly different (Fisher's LSD, $\alpha = 0.05$).

observed in *R*, which exhibited the greatest (0.66) and the lowest (0.45) RMF at ages 1 and 5, respectively. After the second growing season, *F* consistently showed the highest RMF, peaking at age 2 (0.63) and reducing to 0.58 at age 5. The lowest RMF during the first two samplings was found in *D*, while after the lowest RMF was observed in *R*. There was a strong relationship between woody-root (coarse-roots) and woody-shoot (stem + branches), and between total below- and aboveground biomass (Supplemental Fig. 3), and the slope rank for both relationships was $F > H > D > R$. The slopes (*b*) for woody-root *vs*. woody-shoot (Supplemental Fig. 3A) and for total root *vs* total shoot (Supplemental Fig. 3B) for all treatments were near unity, which indicates an almost isometric scale between above- and belowground biomass. In both cases, the higher the slope the greater belowground allocation, either coarse or total, in relation to woody- and total-shoot tissues, respectively.

4. Discussion

Competition control increased loblolly pine development considerably and improved the use of site resources by the crop tree. The *R* and *F* treatments produced more biomass than *H*, but did not differ each other throughout early stand development, supporting the idea that annual fertilization rates frequently adopted in intensively managed stands could be reduced to increase production forestry sustainability. Increasing planting density along with multiple herbicide and fertilizer applications did not compromise individual tree size while still producing higher biomass. Lastly, we observed significant differences in allocation patterns between treatments; however, our results suggest a strong developmental influence on allocation and that fostering overall biomass production might be more important than shifting allocation patterns during early stand development.

4.1. Competition control

Repeated competition control was critical to facilitate stand uniformity through early stand development and accelerated loblolly pine growth by improving the use of site resources by the crop tree, and suggests that stand uniformity is linked with higher forest productivity begining in early stages of stand development (Yáñez et al., 2017). Competing vegetation thrived if no herbicide was applied and was prevalent (60% of total aboveground biomass) in *C* at age 5 (Fig. 5). In contrast, loblolly pine biomass outperformed competing vegetation at age 3 in all treatments with herbicide applications (*H*, *R*, *F*, and *D*), and competing vegetation accounted for < 10% of total aboveground biomass in these treatments at age 5. Herbicide alone (*H*) yielded ~600% greater loblolly pine stem biomass than *C* at age 5 years. Woody and herbaceous competing vegetation controls, such as performed here, are suggested to be additive and most efficient, since the magnitude of a single control alone can vary across sites and with stand developmental stage (Miller et al., 1991, 2003; Tiarks and Haywood, 1986; Zutter and Miller, 1998). The method of control (e.g., mechanical *vs*. chemical; band *vs*. broadcast), in turn, has been reported to have minor influence (Campbell et al., 2013; Lauer et al., 1993). The numbers found in our study are in line to what has been reported in young loblolly pine stands across the southeast US (Britt et al., 1990; Neary et al., 1990; Zutter et al., 1987), and suggest that competition control is critical to grant increased biomass production in either resource limiting (nutrient and/or water) (Jokela et al., 2010) or nonlimiting sites (South and Miller, 2007). Competition tends to decrease through stand development because belowground competition with the developing trees, litter accumulation, and canopy closure preventing light from reaching the understory, but early gains obtained by competition control might persist throughout the rotation (Jokela et al., 2010), and can even have carryover effects to subsequent rotations (Subedi et al., 2019). However, percentage gains tend to decline over time as tree volume increases (South et al., 2006).

4.2. Herbicide + Fertilization

Tree growth and biomass accrual suggest that fertilization rates could be reduced during initial years in intensively managed stands without compromising productivity to increase the sustainability of production forests since *R* and *F* did not differ throughout the five

growing seasons. There was no influence of fertilization on stand uniformity (Fig. 2). At age 5 years, *R* and *F* yielded, on average, 22% and 28% greater stem and aboveground biomass, respectively, than *H* (Fig. 3C; Supplemental Table 3). Interestingly, while significant differences (e.g., $p < 0.05$) between standard spacing fertilized (*R*, *F*) or non-fertilized treatments (*H*) occurred only in the fifth growing season, the difference in stem biomass between *R* and *H* treatments, for example, was of similar magnitude (*R* was ~ 20% greater than *H*) since the second growing season. Therefore, we posit that the lack of difference during early stages could be an artifact of statistical procedures. For instance, because of the biomass magnitude final sampling times is significantly higher and all sampling times are combined in the two-way ANOVA, it yields a large least square difference threshold, which hampers statistical significance detection during earlier years. Additionally, the substantial difference between *C* and other treatments inflates the least square difference making it difficult to detect differences between more comparable treatments, and thus, relative treatment differences, or effect size, should also be considered. Therefore, positive effects (~20%) of fertilization might have started to occur as early as the second growing season and were maintained throughout early stand development, which highlights the importance of early fertilizer amendments, despite a possible short-lived assart effect (Fox et al., 2007).

To further explore the positive effects of fertilization during early stand development beyond our study, we calculated the effect size of fertilization in addition to herbicide on young loblolly pine (< 8-year-old) across the southeast US by plotting the volume obtained in herbicide only *vs.* herbicide + fertilization treated stands (Fig. 7). We observed that although there is a wide range of practices in these studies (e.g., differences in fertilization rate and frequency, genotypes, site properties), and regardless of reported differences between fertilization regimes (e.g., at $p < 0.05$), there was a good linear agreement of fertilizer responses through time in different experiments (Fig. 7), and ~28% in volume gain through fertilization is a reasonable expectation for intensively managed loblolly pine during early stand development.

Theoretical growth rates have forecasted that loblolly pine stands could reach up to 30 Mg ha^{-1} yr^{-1} (Farnum et al., 1983). However, maximum growth rates documented for loblolly pine plantations in the southeastern US are around 15 Mg ha^{-1} yr^{-1} (Bryars et al., 2013; Zhao et al., 2016). The growth rates observed in our study (*R*, *F*, and *D*) agree with what has been reported for intensively managed young stands in the region (4–8 Mg ha^{-1} yr^{-1}) and are expected to increase and possibly meet region documented potential as stands age (Adegbidi et al., 2005, 2002; Borders et al., 2004; Coyle et al., 2016, 2008; Martin and Jokela, 2004; Samuelson et al., 2004). The MAI is also within the range reported for slightly older (10–12-year) loblolly plantations across different sites on the Piedmont and Coastal Plain regions in the southeast US following repeated herbicide and fertilizer applications, and are on par with what has been observed for loblolly pine worldwide (Borders and Bailey, 2001).

4.3. Planting density

The *D* treatment yielded the greatest loblolly pine BA and biomass, while not showing reduced individual tree size after five growing seasons compared with amended treatments, i.e., Dq and H_t in *D* were similar to *H*, *R*, and *F* treatments (Table 1), supporting our third hypothesis. Basal area in *D* was ~40% larger than in *H*, *R*, and *F* treatments, while planting density was 60% higher, which may suggest early signs of intraspecific competition in *D*. We tested for a possible earlier growth dominance due to increased competition, which would favor bigger trees at the expense of smaller trees and create higher heterogeneity within stands (Binkley, 2004; West, 2014). There was no sign of growth dominance in early stages as influenced by increasing planting density (data not shown), although *D* showed slightly higher mortality than *H* and *R* (Table 1). However, the mortality in *D* was not different from *F* and *C* treatments. Therefore, we believe that the mortality differences were random and there was no indication that mortality occurred because of increased competition.

The difference in stem biomass, for instance, between *C* and other treatments ranged between ~600–800% for standard spacing treatments and reached 1500% between *C* and *D* during the five growing seasons (Fig. 2C). The maximum aboveground biomass accrual rate observed was 6.4 Mg ha^{-1} yr^{-1} at age 5 in the *D* treatment, which was the highest rate observed in our study. Therefore, the use of the increased density along with full fertilization rates resulted in higher biomass accumulation through early stand development and might be an efficient strategy to increase revenue in biomass production forestry. It should be noted that we did not have a full-factorial experiment to infer whether we would obtain the same biomass accrual trend by reducing the fertilizer rate, e.g., utilizing half of N and P rates. Neither can we infer later in the rotation, although similar patterns for biomass accrual and no reduced individual tree size have been reported under this stocking range in other loblolly pine trials through longer rotation

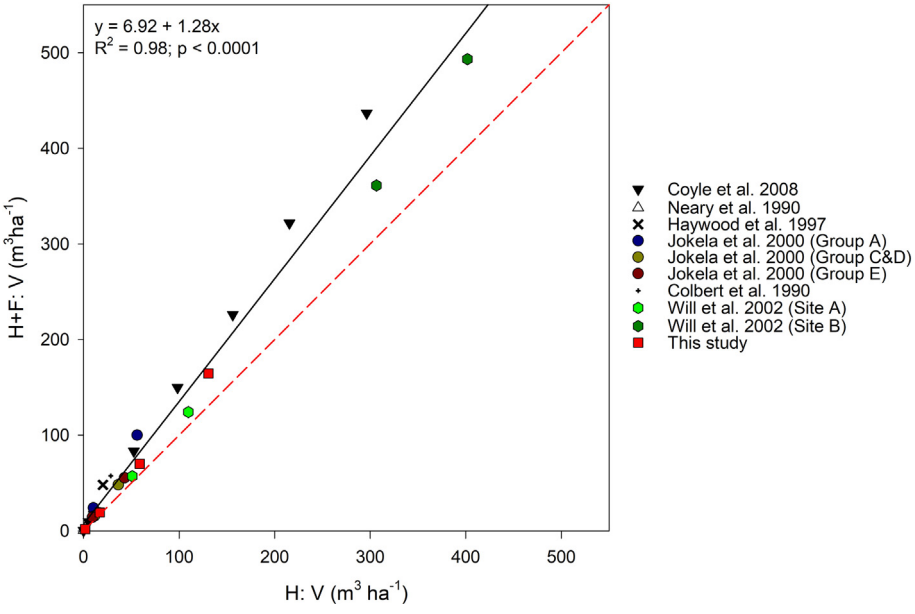

Fig. 7. Effect size of fertilization (H + F) in addition to herbicide (H) – calculated as a linear regression – on the volume of juvenile loblolly pine stands (< 6-year-old) in the southeast USA. Data from this study are plotted with those taken from published reports that reported volume or diameter (diameter at breast height (dbh) or at ground level (dgl)) and height variables. We used the stem volume (m^3 ha^{-1}) when available, or calculated volume on a height by diameter squared index. In our study, we averaged data from half-reduced (*R*) and full fertilization (*F*) treatments to compute H + F. The red-dashed line indicates 1:1. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.) (See above-mentioned references for further information.)

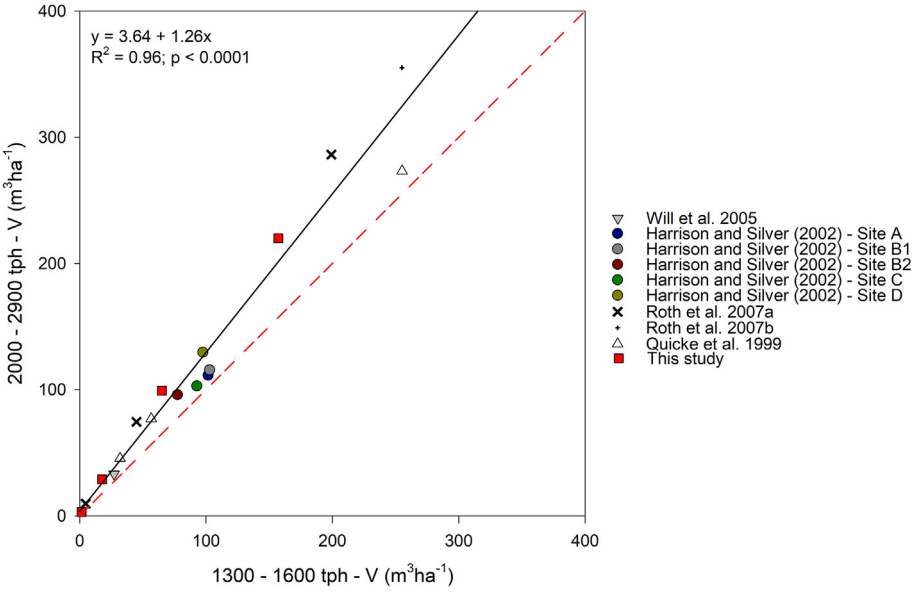

Fig. 8. Effect size of increasing planting density – calculated as a linear regression between 1300 and 1600 trees per hectare (tph) *vs*. 2000 – 2900 tph (~64% increase, on average) – on the volume of juvenile loblolly pine stands (< 8-year-old) in the southeast USA. Data from this study are plotted with those taken from published reports that reported volume or diameter (diameter at breast height (dbh) or at ground level (dgl)) and height variables. We used the stem volume (m^3 ha^{-1}) when available, or calculated volume on a height by diameter squared index. We only used data from studies that reported similar herbicide and fertilizer use in both densities. In our study, volume in the 1300 – 1600 tph axis was obtained by averaging volume index from half-reduced (*R*) and full fertilization (*F*) treatments. The red-dashed line indicates 1:1. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.) (See above-mentioned references for further information.)

time (e.g., 12-year-old stand, Zhao et al., 2011).

We calculated the effect size of volume gains across intensively managed loblolly pine in the southeastern US as a function of increasing planting density. To that end, we organized planting densities from 1300 to 1600 trees per hectare (tph) and 2100–2900 tph in *x*- and *y*-axis, respectively. These are typical planting densities used for loblolly managed in short rotations while allowing some flexibility on final wood use based on stumpage prices at harvesting time (Kantavichai et al., 2014; Munsell and Fox, 2010). We restricted our comparison to un-thinned stands during early stand developmental stages (< 6-year-old stands). Our results indicated a consistent pattern in volume production as affected by changes in planting density across young loblolly pine in the southeastern US (Fig. 8). A strong linear relationship, with an effect size of 1.26 (~26%) of higher volume production, can be observed for increased density stands *vs.* regularly spaced stands, although the average difference in planting density was ~ 60%. Therefore, one should not expect the same increased magnitude in volume as planting density increases in early rotation stages. In later rotation stages of un-thinned stands (e.g., 12 or 13-year-old), the discrepancy in the magnitude relation between planting density and volume seem to be even higher, being < 10% of volume gain with 50% increase in planting density (Akers et al., 2013; Zhao and Kane, 2010). In our study, volume index was highly correlated with aboveground biomass (data not shown); therefore, the same reasoning could be used for dry biomass production.

4.4. Allocation

The proportion of stem to total aboveground biomass increased through time (Supplemental Fig. 2), which is consistent with other loblolly pine reports that asserted more biomass to stem and less to crown as stands age (Samuelson et al., 2004; Subedi et al., 2012). Several studies used the foliage mass to explain annual stem growth (Burkes et al., 2003; Ex and Smith, 2014; Fernández et al., 2011; Konôpka et al., 2010). The allocation coefficient (*b*) between foliage *vs*. stem or woody-shoot tissues differed between all treatments (Fig. 5A; 5B). However, our results suggest that allocation between foliage and stem has low power for explaining growth differences solely. Specifically, trees from *C* showed the higher *b* values considering allocation between foliage and stem, or foliage and woody-shoot tissues (Fig. 5A; 5B), which would suggest that *C* trees were the most efficient in producing woody biomass. However, the difference in stem biomass between *C* and amended treatments was remarkably large (Fig. 2C). Therefore, this growth efficiency metric might only be meaningful when comparing similar biomass magnitudes and developmentally similar trees. All amended treatments produced much more biomass than *C* and were in a far more advanced developmental stage. Thus, although we observed significant differences in allocation coefficients, we argue that these differences are small and do not seem to be biologically relevant to explain differences in woody-tissues production. For instance, *R* presented the lowest *b* for foliage *vs*. stem or woody-shoot tissues, but *R* also resulted in the highest foliage mass and highest stem growth rate and biomass among the standard spacing treatments (Fig. 2B; Fig. 3; Supplemental Table 3). Likewise, there was a slightly higher allocation to stem at higher planting density (e.g., *F vs. D*; Fig. 5A), which is in agreement to what has been reported elsewhere for older stands (Subedi et al., 2012; Zhao et al., 2012). However, these studies indicated that allocation changes were caused by foliage and branch proportion decreases at higher density, while in our study *D* had higher needles and branch biomass than *F*, and the proportional differences were minimal (Supplemental Fig. 2). These data reinforce that fostering overall biomass production during early stand development might be more important than trying to shift foliage and woody-tissue allocation patterns (Coyle and Coleman, 2005).

The results for belowground allocation parallel what was observed for aboveground tissues. Specifically, we noticed a slight decline in RMF as stand aged, suggesting that development is an important driver of belowground allocation (Adegbidi et al., 2004; Coyle et al., 2008; Johnson, 1990). Additionally, *D* treatment had the second lowest RMF, but at the same time yielded the highest root and aboveground biomass (Figs. 3; 6; Supplemental Table 3), reinforcing that in early stand development overall biomass production might be more valuable than specific allocation patterns. The *F* treatment had higher root biomass and RMF than *R*, but these treatments did not differ regarding aboveground biomass or stem biomass at age 5 (Figs. 2B; 4; Supplemental Table 3). This result contrasts with the previous assumption of lower belowground allocation with increased resource availability (Haynes and Gower, 1995).

The fact that the slope of the relationship between root and shoot biomass was near unity (Supplemental Fig. 3B) indicates that shoot and root biomass scale isometrically through time, which has been consistently observed across a wide physiographic range of loblolly pine studies (Coyle et al., 2008). This consistent scaling factor makes it simple to estimate belowground mass based on aboveground mass using only the equation multiplier (*a'*) (Albaugh et al., 2006; Coyle et al., 2008), which is operationally less demanding. However, one

should cautiously consider using this approach since the allometric equation is inherently nonlinear, and thus small deviations from the unity can yield significant under or overestimates of belowground biomass, and the small allocation differences among studies (e.g., ours, Albaugh et al., 2006; Coyle et al., 2008) suggest that although equations can be overall simplified they should be site or stand-specific. In our study, total belowground biomass accounted for ~ half of the total aboveground mass, while coarse roots were determined as 0.9-fold of the stem mass. These differences in partitioning suggest that during early stand development there is a slightly greater allocation to aboveground ephemeral tissues (*e.g.*, needles) compared with belowground ones (*e.g.*, fine-roots), such as reported by Samuelson et al. (2004), while long-lived biomass (woody-shoot *vs.* woody-root) scale more evenly through time.

4.5. Management implications and final considerations

Sustainable use of fertilization is needed to comply with best management practices in production forestry. The replications used in this study were distributed across two watersheds and were part of a broader project investigating the effects of intensive management practices on biomass production and environmental quality (Griffiths et al., 2017). The repeated herbicide and fertilizer applications, even in high rates such as *F* and *D*, did not result in increased nitrate concentration in groundwater or streams on the site, which suggests that any nutrient excess might have been transformed or absorbed by streamside management zones (Griffiths et al., 2017). Repeated control of competing vegetation was critical to favor loblolly pine development and was the factor alone responsible for the highest increase in stand productivity by increasing resource availability to crop trees. We observed no difference between fertilized and non-fertilized plots in the first growing season, suggesting that initial fertilization practices could be slightly delayed. Afterward, fertilization had an additional effect on growth, but of smaller magnitude, which was consistent with loblolly pine studies across the southeast US despite wide variation in practices and conditions and suggests an average volume gain of ~28% during early stand development with fertilization. Given that *R* yielded similar volume index, and needles, branches, and stem biomass until the fifth growing season compared with *F* (Figs. 2A; 4; Supplemental Table 3), we may suggest that annual fertilization rates adopted during early stand development could be reduced to increase sustainability of intensively managed forests. After five growing seasons, the only difference between *R* and *F* was regarding belowground biomass, in which *F* exhibited higher root biomass and RMF compared with *R*. This allocation difference might have further implications for ecosystem carbon storage, although we are time-limited in our study to infer about long-term consequences of such difference on both ecosystem carbon storage and growth rates throughout the rotation. Considering stands that are intensively managed across short rotations (~10 years), it seems feasible to use an increased planting density to yield higher biomass without compromising individual tree size through repeated competition control and nutrient amendments. However, one should not expect the same magnitude of increase in volume as planting density increases. Although our results demonstrate that early evaluations are extremely important to fine-tuning silvicultural practices during a critical period of stand development, rotation-length and multiple rotation studies are still needed to provide a complete understanding of how intensive management practices influence productivity and sustainability of short-rotation production forests.

CRediT authorship contribution statement

Gabriel W.D. Ferreira: Conceptualization, Data curation, Formal analysis, Writing - original draft, Writing - review & editing. **Benjamin M. Rau:** Conceptualization, Methodology, Data curation, Formal analysis, Resources, Writing - review & editing. **Doug P. Aubrey:** Conceptualization, Formal analysis, Supervision, Funding acquisition, 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.

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Research data

Plot level data associated with this article can be assessed from the Dryad Digital Repository (Ferreira et al., 2020).

Appendix A. Supplementary material

Supplementary data to this article can be found online at https://doi.org/10.1016/j.foreco.2020.118206.

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