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Long-term effects of stand density management and genotype on wood properties of loblolly pine (*Pinus taeda* L.) in the mid-South USA

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ABSTRACT

Changes in ownership and forest product use patterns have incentivized growing loblolly pine (*Pinus taeda* L.) for chip-and-saw and sawtimber in shorter rotations in the southeastern United States. These management objectives can be accomplished by relatively low stand densities and moving fast-growing genotypes from the Atlantic Coastal Plain to other regions of the loblolly pine range, but wood quality concerns accompany these silvicultural options. In three trials in the Western Gulf region of the mid-South United States, effects of stand density management options on key wood properties (specific gravity, corewood (juvenile wood) diameter, corewood proportion, latewood proportion, corewood:outerwood (juvenile wood:mature wood) transition age as determined using specific gravity) were tested. At one site, clearwood modulus of elasticity (MOE) and modulus of rupture (MOR) were measured. Genotypes of Atlantic Coastal Plain and Western Gulf origin were also tested at two sites. In a trial in which stand density was managed at diverse levels through sequential thinning, beginning at precommercial size, only a regime that was commercially thinned to half its density two times from 297 TPH at age 7 to 62 TPH by age 41 had significant reductions in MOE, MOR, and specific gravity. Corewood diameter increased with decreasing planting density at two sites at the northwestern edge of the loblolly pine range, but corewood proportion declined with decreasing planting density due to greater diameter growth and earlier transition from corewood to outerwood. Specific gravity differences among planting densities was site-specific, with no differences at the more well-drained site. Latewood proportion, which was greater at higher planting densities, was more strongly correlated with specific gravity differences among planting densities. A planting density between 1075 and 1680 TPH would likely be optimum for these site conditions for balancing tree volume growth with minimizing reductions in specific gravity associated with reduced latewood proportion and larger corewood size. The Atlantic Coastal Plain genotype retained its tendencies to transition to outerwood earlier and have greater latewood proportions relative to a local genotype when planted at these Western Gulf sites, and its specific gravity was similar to that of the local genotype. Together these trials suggest that forest managers have flexibility in managing loblolly pine stand density without altering wood properties. Furthermore, these results provide some evidence that moving genotypes may not carry a risk of reduced wood specific gravity.

1. Introduction

Forest plantations, which as of 2015 reached 278 million ha in area worldwide, have increased in their importance for meeting global timber product demands (Payn et al., 2015). The management emphasis of forest plantations is primarily on producing pulp logs and sawlogs at low cost to paper and structural timber markets (Cubbage et al., 2010; McEwan et al., 2020). The southeastern U.S. has historically produced more industrial timber than any other region of the world, and it is expected to remain one of the world's top timber supply regions along with South America, Asia, Australia, and New Zealand (Prestemon and Abt, 2002; Daigneault et al., 2008). Over the past three decades, industrial forest ownership of the Southeast U.S. has shifted primarily to timber investment management organizations and real estate

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investment trusts; these entities typically prioritize shortening rotation ages to realize earlier returns on their forest establishment costs (Stanturf et al., 2003; Lacy, 2006). Another change affecting forest plantation management priorities is changing global demands for conventional forest products, particularly pulpwood, relative to the twentieth century due to metal, plastic, and digital substitutions (McEwan et al., 2020). In the United States, pulpwood demand has declined from a peak in the late twentieth century due to marked declines in demand for newsprint and paper for printing and writing, although there is continued growth in paperboard for packaging associated with e-commerce as well as sanitary papers and tissues. Growing paper and paperboard production in other countries, particularly China, has also contributed to declining pulpwood demand in the United States (Wear et al., 2016). As pulpwood demand declined, some forestland owners and managers in the Southeast U.S. have been incentivized to manage plantations to grow chip-and-saw and sawtimber in shorter rotations without thinning for pulpwood as has been conventionally conducted (Clark et al., 2008).

Plantation rotation length and proportional yields of forest products are strongly affected by planting density and genotype selection. These silvicultural decisions are two of the most effective means by which plantation productivity can be improved (Powers, 1999; Larson et al., 2001; Allen et al., 2005; Moore et al., 2018). Both silvicultural decisions can also enhance the market value of forest products due to their influences on tree form and size (Smith et al., 1997; Larson et al., 2001). Initial stocking density strongly affects the timing of crown closure, timing of mid-rotation silvicultural treatments, yield proportions of forest products, and financial performance (Zhang et al., 1996; Sharma et al., 2002; Blazier and Dunn, 2008). Tree volume gains for loblolly pine (*Pinus taeda* L.), the most prevalent species for plantation management in the Southeast U.S., increased by more than 50% relative to that of unimproved genotypes by planting high-yielding genotypes and optimizing site nutrition through competing vegetation suppression and fertilizing when soil nutrient supply is relatively low (Allen et al., 2005; Martin et al., 2005; McKeand et al., 2006). In the western portion of the loblolly pine range (the mid-South U.S.), genotypes from the eastern portion of the species' range have been planted on sites with relatively high water-holding capacity because eastern genotypes have straighter stems, smaller crowns, and higher volume growth per tree than western genotypes (Wells and Lambeth, 1983; Talbert and Strub, 1987; Tauer and Loo-Dinkins, 1990; Douglass et al., 1993). However, some eastern genotypes are prone to drought stress even when planted on sites with sufficient water-holding capacity in the mid-South (Blazier et al., 2018).

Forest plantations managed with an emphasis on fast growth are often characterized by a higher proportion of corewood (juvenile wood) than relatively slow-growing natural forests (Clark et al., 2006). Corewood is generally less desirable for conventional forest products because it is structurally weaker and has lower alpha cellulose content than outerwood (mature wood) (Senft et al., 1985). Corewood is also associated with lower specific gravity, which is associated with low modulus of rupture (MOR) and a low modulus of elasticity (MOE). In addition, corewood has higher microfibril angles (MFA), which leads to lower MOE and higher longitudinal shrinkage and subsequent warping (Senft et al., 1985; Lassare et al., 2009). In contrast, some studies have shown that faster growth rates do not always equate to trees having less dense, weak wood (Megraw, 1985; Cregg et al., 1988).

Initial spacing selection has a strong influence on wood quality. While low initial stocking densities increases the rate at which trees reach diameter thresholds for higher-valued forest products, this trend is offset by the tendency to increase branch retention and diameter, which can degrade log quality owing to the presence of larger and more frequent knots (Macdonald and Hubert, 2002; Blazier and Dunn, 2008; Amateis et al., 2013). Low initial stocking densities can also lead to a larger proportion of corewood volume relative to higher planting densities (Martin, 1984; Clark and Saucier, 1989; Larson et al., 2001; Clark et al., 2008; Antony et al., 2012). However, as site resources become limited and competition between trees increases, latewood formation can be suppressed, particularly at higher planting densities. These trends can result in narrow rings that have a relatively low proportion of latewood (Larson et al., 2001). Clark and Saucier (1989) found that the timing of transition from corewood to outerwood was unaffected by planting density, although their methods were less accurate than x-ray densitometry methods developed later. As such, higher planting densities constrain corewood to a smaller core through reduced tree growth at earlier cambial ages rather than altering the timing of corewood to outerwood transition (Larson et al., 2001). Because ring specific gravity, timing of transition from corewood to outerwood, and proportion of corewood are relatively stable over a range of planting densities for loblolly pine, there is potential for finding a planting density and time of harvest that balances the faster growth of wider spacings with minimizing corewood size to optimize lumber quantity and quality.

Genotype affects wood quality due to genetic differences in wood properties. Moderate to strong genetic control of corewood MFA and stiffness as well as wood density has been observed in loblolly pine, slash pine (*Pinus elliottii* Engelm.), and radiata pine (*Pinus radiata* D.Don) (Kumar et al., 2002; Myszewski et al., 2004; Dungey et al., 2006; Li et al., 2007; Moore et al., 2018). Based on their findings of large differences in corewood stiffness among seven loblolly pine genotypes and interactions among genotype, planting density, and silvicultural intensity for latewood percentage, Roth et al. (2007) inferred that it should be possible to improve corewood stiffness of loblolly pine through a combination of these factors. More research is needed on the genetic diversity of loblolly pine corewood properties and their interactions with silvicultural treatments and site conditions.

Geographic location and site quality also influence wood properties. Wood specific gravity generally increases from north to south and west to east within the range of loblolly pine; these trends are strongly related to seasonal precipitation patterns and growing season length (Larson et al., 2001; Jordan et al., 2008). The duration of corewood formation is similarly affected by location; Clark and Saucier (1989) observed that the period of corewood formation of loblolly and slash pine was 6 years in the Gulf Coastal Plain of Florida and 14 years in the Piedmont of South Carolina. Jordan et al. (2008) found that loblolly pine in the South Atlantic region had higher bole specific gravity than those growing in all other regions because they had significantly higher latewood development. Sites with good edaphic and climatic conditions lead to faster growth and a larger volume of corewood, whereas the inverse is typical of sites with poor soil and climate conditions (Larson et al., 2001). Research is lacking on whether genotypes sustain corewood properties of their native region when transferred to other portions of the loblolly pine range to increase plantation productivity, as done when genotypes of the Atlantic Coast region are planted in the Western Gulf region of the mid-South US, where summer droughts are more common due to precipitation patterns.

Long-term replicated experiments, while cost- and time-intensive, are among the best means for providing data and practical demonstrations of the effects of site, genotype, and silvicultural treatments on tree wood properties (Moore et al., 2018). To better understand the long-term effects of these factors on loblolly pine wood properties in the mid-South U.S., we summarize results of two experiments conducted in that region, one conducted at two sites in the state of Oklahoma and one conducted in the state of Louisiana. Together these experiments explore the effects of planting density, genotype, and site conditions on: (1) timing of corewood to outerwood transition, (2) corewood size, (3) latewood proportion, (4) specific gravity, (5) modulus of elasticity (MOE), and (6) modulus of rupture (MOR).

2. Materials and methods

2.1. Study sites

2.1.1. Louisiana site

A study site was established in 1958 at the Louisiana State University

AgCenter Hill Farm Research Station in northwestern Louisiana (32.749025 N, −93.04111111 W); the site will hereafter be identified as the Hill Farm site (Fig. 1). Loblolly pine seed for this trial were collected by the Louisiana State Forestry Commission from natural stands in northern Louisiana. Seeds were sown in a nursery at the Hill Farm Research Station and planted by hand after one year in the nursery as bareroot seedlings at 2990 trees ha^{-1}. Prior to establishment, the site was a 40-year-old mixed pine and hardwood stand. After the prior stand was harvested in 1956, the site was prescribed burned. Soil of the site was mapped as a gravelly, fine sandy loam Darley-Sacul soil (an association of a fine, kaolinitic, thermic Hapludult and a fine, mixed, active, thermic Aquic Hapludult). This well-drained soil type is common in upland forests of northwestern Louisiana, southwestern Arkansas, and eastern Texas (USDA SCS 1989). Site index for loblolly pine on a 25-year basis for this site was 19.8 m. Average precipitation for the region is 1330 mm yr^{-1}; average annual temperature is 17 °C. Drought conditions are common due to relatively low summer precipitation (USDA SCS, 1989).

2.1.2. Oklahoma sites

Two sites were established in 1984 in southeastern Oklahoma near the town of Broken Bow (34.02895556 N, −94.73944444 W). One site was located 24 km north of Broken Bow on Carter Mountain, and the other was located 7 km northeast of Broken Bow adjacent to the Oklahoma state border (Fig. 1). The two sites will be hereafter identified as the Carter Mountain and Stateline sites, respectively. Average annual rainfall of the region of the Oklahoma study sites is 1250 mm, and average annual temperature is 17 °C (USDA, 1974). Rainfall is generally adequate through May, but late growing season droughts are common. Prior to planting, the sites were prepared for planting by drum chopping, hexazinone herbicide, prescribed burning, and subsoiling to 450-mm depth. Both sites were planted by hand in 1984 with bareroot seedlings. Two genotypes of seedlings were planted at the sites: a genotype of local origin (Oklahoma/Arkansas seed source) and a genotype of Atlantic Coastal Plain (North Carolina) origin. In the year after planting, both sites were operationally sprayed with hexazinone herbicide (Velpar L®) for herbaceous vegetation suppression.

Soil at the Carter Mountain site was classified as a Goldston-Carnasaw-Sacul association, which is an upland, gravelly, moderately steep silt loam. The soil at Carter Mountain is primarily comprised of the Goldston series, which is a well-drained to excessively drained loamy-skeletal, siliceous, semiactive, thermic shallow Typic Dystrudept. Permeability of the soil is moderately rapid, and its available water holding capacity is low. Will et al. (2010) determined a site index of 19.3 m (base age 25) for the Carter Mountain site.

Soil of the Stateline site was also comprised of a Goldston-Carnasaw-Sacul association, but it had greater water holding capacity than the Carter Mountain site. Although the two sites were mapped as the same soil series, the Stateline site soil was less gravelly, more developed, and comprised primarily of the Sacul series (a fine, mixed, active, thermic Aquic Hapludult). Permeability is slower and available water holding capacity is higher in the Sacul series than in the Goldston series (USDA, 1974). Based on dominant and codominant heights measured at age 15 by Abbey (2002) and site index curves (base age 25) for loblolly pine plantations in the Western Gulf Coastal Plain of Popham et al. (1979), site index of the Stateline site was 21.3 m.

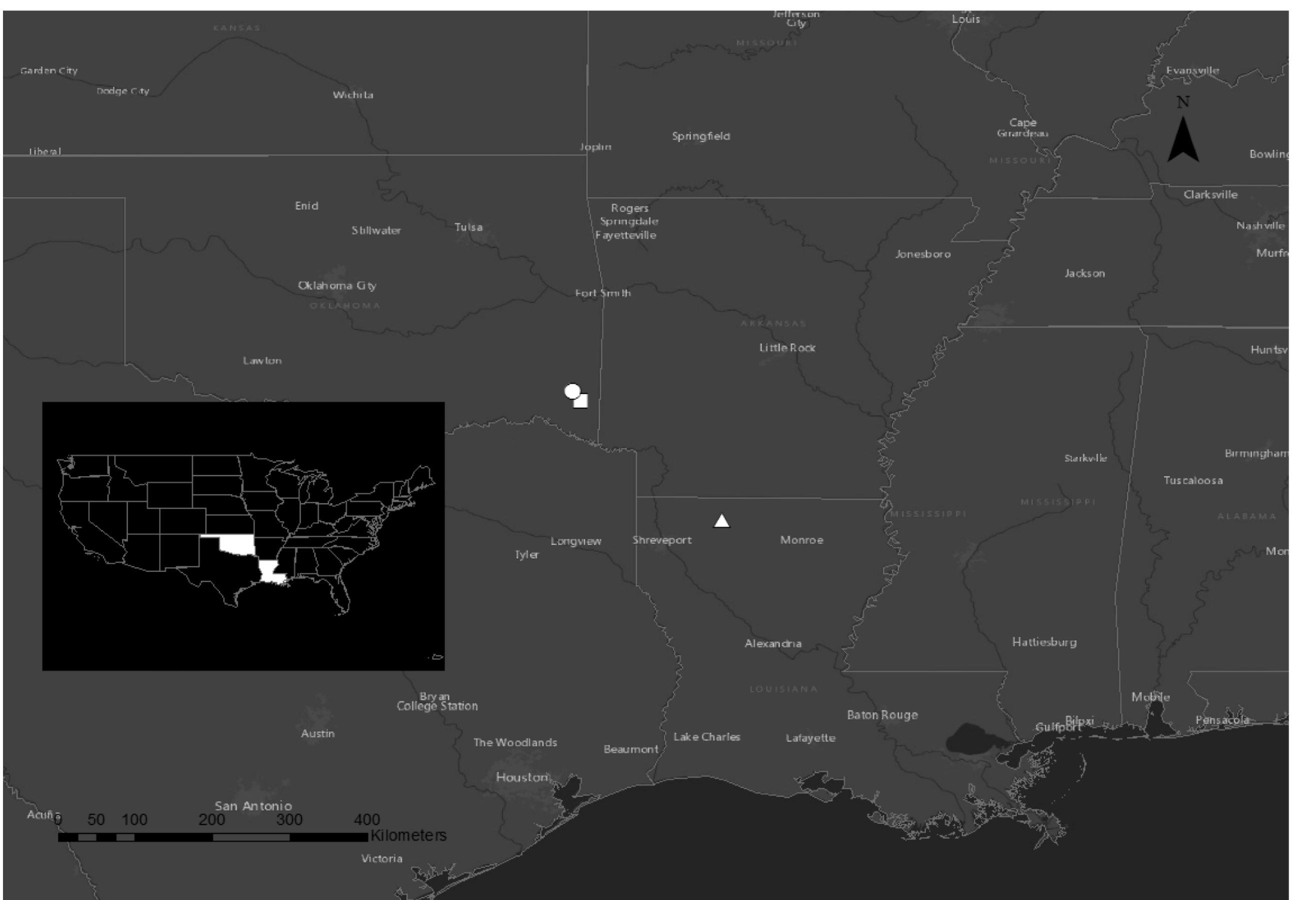

Fig. 1. Location of loblolly pine study sites in the mid-South United States. Triangle, square, and circle shapes respectively denote sites in the state Louisiana (Hill Farm site), adjacent to the Oklahoma state line (Stateline site), and on Carter Mountain in the state of Oklahoma (Carter Mountain site). Insert highlights states in which sites were located on United States map.

2.2. Treatments and experimental design

2.2.1. Louisiana site

The Hill Farm trial was conducted with correlated curve trend (CCT) protocol (O'Connor, 1935; Craib, 1947) to explore stand densities that minimized intraspecific competition for site resources. With this protocol, a range of five stand density regimes were created through sequential thinning (Table 1). With the CCT approach to stand density study, trees within a treatment are thinned when its annual basal diameter (in years before trees exceed 1.4 m in height) or diameter at breast height (in years after all trees exceed 1.4 m in height) growth declines by 2.5 mm relative to that of the closest-density treatment (Clason, 1994). Upon reaching this thinning threshold, a treatment is thinned to the density equal to the density immediately below it within the density treatments tested. For example, if a 600 trees ha^{-1} (TPH) density treatment reaches this threshold and the density treatments tested in the study are 600, 300, and 100 TPH, the 600 TPH density would be thinned to 300 TPH. In the same example, if the 300 TPH treatment reached the threshold it would be thinned to 100 TPH. Stand density regime differentiation was imposed beginning at stand age 4 by pre-commercially felling trees. By age 7, five density treatments, each replicated four times, were created by CCT thinning: 2470, 1482, 741, 494, and 247 trees ha^{-1} (TPH). From age 7 through 21, no changes were made in these densities to observe stand development until merchantable size. Upon reaching merchantable size as pulpwood, chip-and-saw, and sawtimber, CCT thinning regimes were conducted from age 21 through 41 by commercially felling and harvesting trees within experimental units. Between the final thinning to 62 TPH for all treatments and the time of sampling for this study, continued mortality from lightning strikes and insects resulted in an average of 56 TPH by the time of the study. Treatments were arranged in a randomized complete block design, with slope as the blocking factor, and applied to 0.2-ha plots (Clason, 1994).

2.2.2. Oklahoma sites

Two treatments (genotype and planting density) were conducted at the Oklahoma sites. The aforementioned Oklahoma/Arkansas and North Carolina genotypes comprised the genotype treatment. At the Carter Mountain site, planting densities were 2990, 1680, 1075, and 746 TPH. The same densities were planted at the Stateline site, with the exception of 2990 TPH. At the Stateline site the highest density was 4304 instead of 2990 TPH. At both sites, treatments were applied as a randomized complete block design with soil texture as the blocking factor. Treatments were replicated three times each; the experimental units were 0.04-ha plots.

2.3. Sampling

2.3.1. Louisiana site

A destructive harvest of trees was conducted in July and September 2007. The trees were 49 years old at the time of sampling. Sampling was stratified by stem DBH distributions in each plot, based on stem DBH measurements collected in June 2007. For each plot, DBH distributions were divided into three size classes (upper, middle, lower), and one tree from each DBH class was felled using a feller-buncher during the site's operational harvesting. Only trees with straight, single boles with no crown defects were selected for sampling. Upon felling, cross-sectional disks of 4-cm thickness were cut at the stump, DBH, and at 4.9-m intervals (which coincides with log lengths used for forest products manufacturing in the U.S.). A bolt of 0.6 m length was also cut at 2.4 m along the stem because this sampling point was the midpoint of the first log (Clark et al., 2008).

Table 1
Stand densities (trees ha^{-1}) of five thinning regimes conducted in a loblolly pine plantation in northwestern Louisiana (Hill Farm site).

	Density management regime				
Thinning age (*year*)	1	2	3	4	5
0	2990	2990	2990	2990	2990
4	2471	1482	1482	1482	1482
5	2471	1482	741	741	741
6	2471	1482	741	494	494
7	2471	1482	741	494	247
21	741	741	494	247	124
26	494	494	247	124	124
31	247	247	124	124	124
36	124	124	124	124	124
41	62	62	62	62	62

2.3.2. Oklahoma sites

As with the Louisiana site, sampling was stratified by stem DBH distributions within each plot. Ten trees were sampled in each plot. Increment cores 12 mm in diameter were collected in spring 2000 at DBH using a hydraulic increment borer due to its efficiency and sample integrity (Johansen, 1987). The trees were 14 years old at the time of sampling. If excess knots or other biasing material was in or on the core, the tree was bored again until a clear sample was retrieved. Cores were then frozen at 0 °C until analysis.

2.4. Wood properties analyses

Samples for all sites were analyzed at the U.S. Department of Agriculture Forest Service Southeastern Forest Experiment Station in Athens, Georgia. Preparation methods were consistent with those of Jordan et al. (2008). From each disk and core of the Louisiana and Oklahoma sites, respectively, a pith-to-bark sample was dried at 50 °C for approximately one day. The sample was glued between two wood core holders and cut on a twin-blade table saw with a power feed to yield a densitometry sample measuring 1.6 mm (longitudinal) by 12 mm wide (tangential), and the radial dimension determined by the length from pith to the bark. The specific gravity of the samples was measured at 0.06 mm radial resolution using a X-ray densitometer (model QTRS-01X, Quintek Measurement Systems, Inc., Knoxville, TN) to determine ring specific gravity and percent latewood (ring latewood proportion). Latewood was differentiated from earlywood using a threshold specific gravity value of 0.48 (Clark et al., 2006). Within a disk, specific gravity and percent latewood for each ring were weighted by its basal area.

For all study sites the year of corewood to outerwood transition and corewood diameter were estimated. Ring specific gravity from samples taken at DBH were used to estimate the year of transition. The threshold approach was used to determine the transition; the first year in which ring specific gravity was ≥0.5 was defined as the year of corewood-to-outerwood transition (Clark et al., 2006). Clark et al. (2006) determined that for loblolly pine the threshold approach was similar to the other prevailing method for corewood-to-outerwood transition determination, segmented methods, for loblolly pine in the Southeast U.S. Corewood diameter was determined as the diameter of the tree in the year of corewood-to-outerwood transition. Bole proportion of corewood was calculated as corewood diameter divided by the tree diameter at the time of felling/sampling.

Clear wood modulus of elasticity (MOE) and modulus of rupture (MOR) were measured for the Louisiana site using defect-free static bending samples (dimensions 25.4 mm radially × 25.4 mm tangentially × 406.4 mm longitudinally) cut from the 0.6-m bolts. The samples were prepared by cutting each bolt into a bark-to-bark slab measuring 38-mm thick (radially) centered on the pith. Slabs were kiln-dried to approximately 12 percent moisture content. After drying, slabs were cut in half through the pith and samples were cut from each half of the slab, starting at the bark. Static bending samples that included pith were omitted from the study. The static bending samples were equilibrated to approximately 12 percent moisture content and then tested to failure with a Tinius Olsen universal test machine using the procedures of ASTM

D143 (2003). MOE and MOR were calculated using the procedures detailed in ASTM D143 (ASTM, 2003). Whole-bolt MOE and MOR values were then estimated by weighting the basal areas of each static bending sample obtained from each side of the bolt with the measured MOE and MOR values of the small clear samples.

2.5. Tree and stand dimensions

Tree dimensions were measured at all sites. At the Hill Farm site, tree height and DBH was measured periodically for all trees in plots from which trees for this study were sampled for wood analyses. Clason (1994) reported tree and stand dimensions in all years measured prior to 1994; measurements collected in 2000, 2005, and 2007 are reported here. At Carter Mountain, tree heights and DBH were measured for all trees in the plots from which trees sampled for wood coring were drawn. At the Stateline site, height and DBH were measured for all trees sampled for wood coring. Quadratic mean diameter and relative density was determined from the plot-level data of the Hill Farm and Carter Mountain sites.

2.6. Statistical analyses

Analysis of variance (ANOVA) was performed for all parameters measured; parameters measured from multiple wood samples per tree were averaged for each sample tree for ANOVA. For the Hill Farm site, the model used for ANOVA consisted of density treatment as a fixed effect and block as a random effect. For the Stateline and Carter Mountain sites, the ANOVA model was comprised of density, genotype, and their interaction as fixed effects and block as a random effect. The model used for ANOVA of QMD and relative density for the Hill Farm site also included measurement year and its interaction with density treatment as fixed effects; a repeated measures ANOVA with an autoregessive correlation structure was performed for these two parameters. The GLIMMIX procedure of the SAS System (SAS Institute, Inc., Cary, NC) was used to conduct ANOVA at $\alpha = 0.05$. When ANOVA revealed significant fixed effects, an F-protected least significant difference (LSD) means separation was carried out by the LINES option of the LSMEANS procedure. When a significant interaction of fixed effects was found, the SLICEBY option of the SLICE procedure was used to conduct an F-protected LSD means separation within each level of independent variables within the ANOVA model.

For each site, correlations among parameters were also explored at $\alpha = 0.05$. The CORR procedure of the SAS System was used to generate Pearson correlation coefficients and their associated probabilities. In correlation analysis for the Oklahoma sites, North Carolina was assigned a value of 1 and Oklahoma/Arkansas was assigned a value of 2 to facilitate correlation analysis of genotype with measured parameters.

3. Results

3.1. Louisiana site

Significant differences among density treatments for specific gravity, ring latewood proportion and clearwood MOE and MOR were found at the Hill Farm site (Table 2). For specific gravity and latewood proportion, the 1482 TPH initial density treatment exceeded that of 247 TPH. The 247 TPH density treatment had lower MOE and MOR than all treatments except 494 TPH (Fig. 2). No differences in transition age, corewood diameter, and corewood proportion were found among treatments (Table 2, Fig. 3A).

Diameter at breast height differed among treatments, but tree height did not (Table 2). There was no significant year × treatment interaction for either tree dimension parameter. The 247 TPH initial density treatment had DBH greater than that of all other treatments, and the 494 TPH treatment had DBH that exceeded that of the 741, 1482, and 2470 treatments for the 2000–2007 period.

Table 2
Wood properties and tree dimensions in response to stand densities created by an age 4 precommercial thinning in a loblolly pine plantation in northwestern Louisiana (Hill Farm site). Following precommercial thinning all densities were sequentially thinned via correlated curve trend protocols to a density of 62 trees ha^{-1} by age 41. Standard errors are in parentheses. For each row, means followed by a different letter differ at $P < 0.05$.

	Early-rotation density (trees ha^{-1})				
	2470	**1482**	**741**	**494**	**247**
Specific gravity	0.47 (0.01) *ab*	0.49 (0.01) *a*	0.46 (0.01) *ab*	0.46 (0.02) *ab*	0.44 (0.02) *b*
Ring latewood proportion (%)	44 (2.1) *ab*	48 (1.6) *a*	44 (1.4) *ab*	42 (2.6) *ab*	40 (2.3) *b*
Transition age (years)	8.9 (0.8) *a*	8.0 (0.8) *a*	9.2 (0.8) *a*	9.5 (1.0) *a*	8.0 (1.0) *a*
Corewood diameter (mm)	97 (13) *a*	113 (12) *a*	117 (13) *a*	124 (15) *a*	108 (15) *a*
Tree height (m)	28.4 (0.7) *a*	28.7 (0.7) *a*	26.9 (0.5) *a*	28.4 (0.8) *a*	28.1 (0.7) *a*
DBH (cm)	45.0 (1.1) *c*	44.2 (1.1) *c*	47.8 (1.1) *c*	55.6 (1.2) *b*	60.7 (1.3) *a*

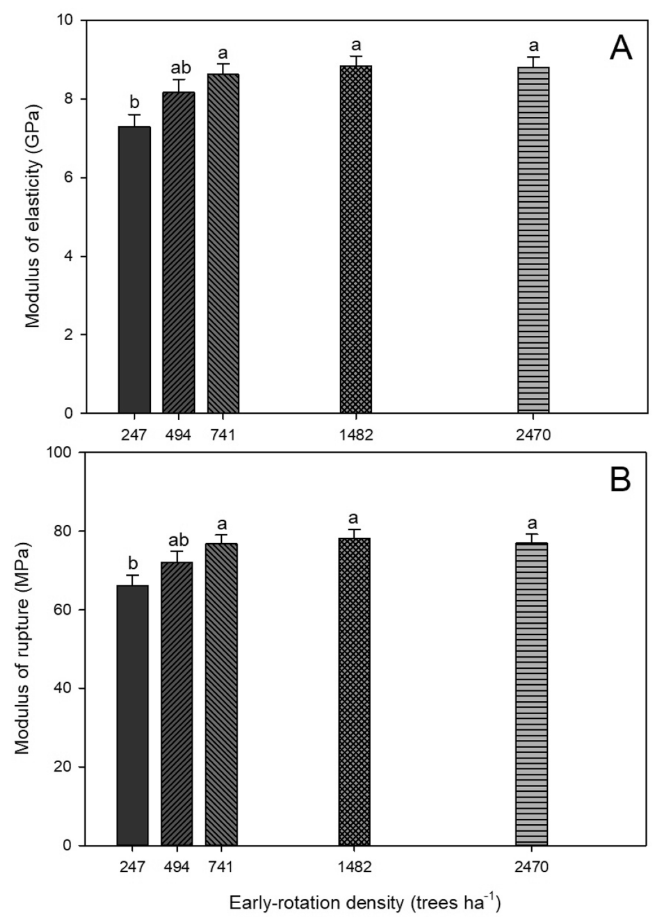

Fig. 2. Modulus of elasticity (A) and modulus of rupture (B) in response to stand densities created by an age 4 precommercial thinning in a loblolly pine plantation in northwestern Louisiana. Following precommercial thinning all densities were sequentially thinned via correlated curve trend protocols to a density of 62 trees ha^{-1} by age 41. For each parameter, columns headed by a different letter differ at $P < 0.05$.

Quadratic mean diameter and relative density differed among density treatments. The 247 TPH initial density treatment had greater QMD than all other treatments, and the 494 TPH treatment had QMD greater than that of the 741, 1482, and 2470 density treatments (Fig. 4A).

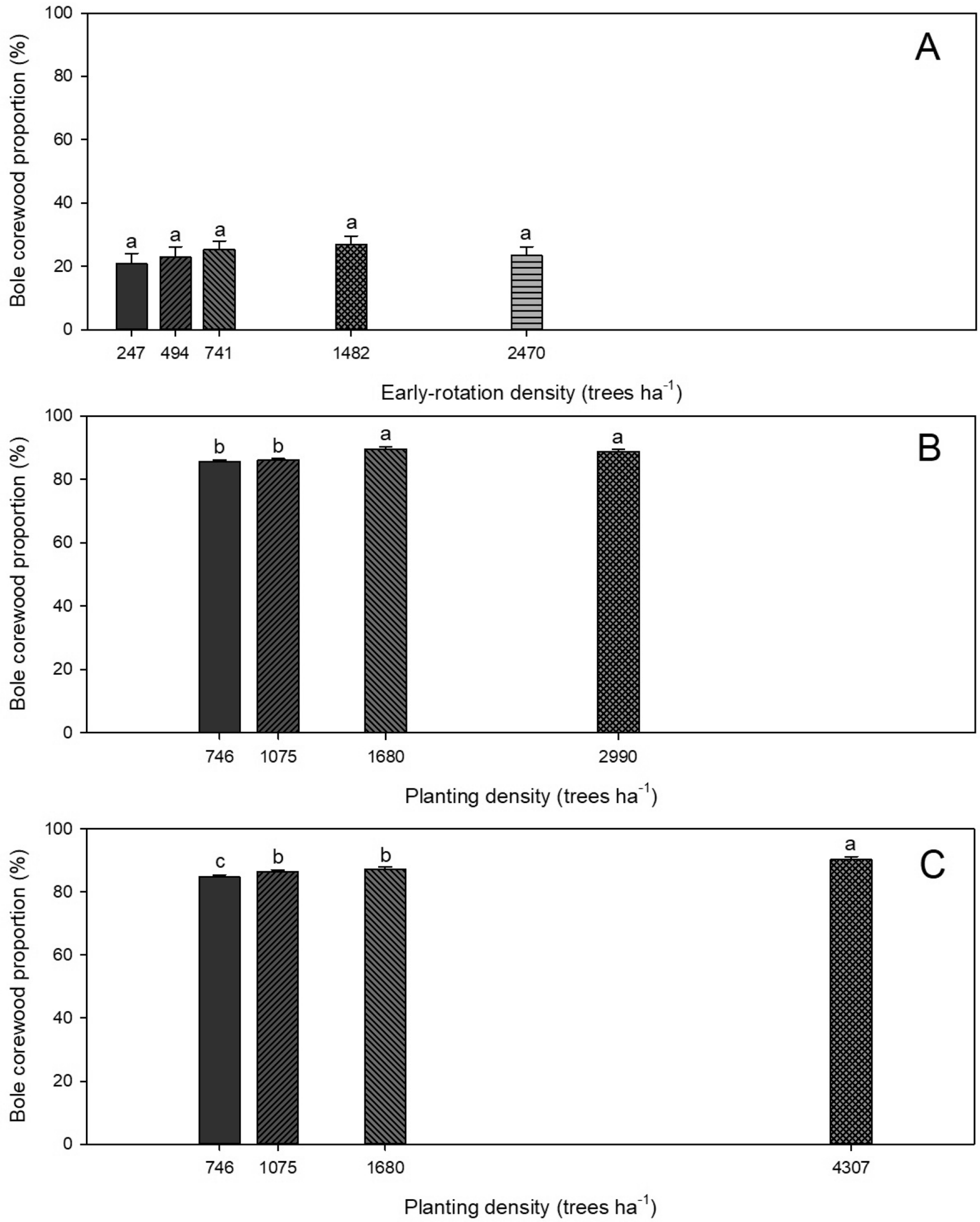

Fig. 3. Bole corewood proportion in response to: (A) stand densities created by an age 4 precommercial thinning in a loblolly pine plantation in northwestern Louisiana and planting density treatments at sites in southeastern Oklahoma (B) near Carter Mountain and (C) near the Oklahoma state border (Stateline site). For each parameter, columns headed by a different letter differ at $P < 0.05$.

Relative densities of the 741, 1482, and 2470 density treatments were higher than those of the 247 and 494 TPH treatments (Fig. 5A).

Several parameters were significantly correlated (Table 3). Density treatment was negatively correlated with MOE, MOR, and latewood proportion. Density treatment was positively correlated with DBH. Latewood proportion was positively correlated with MOE and MOR. Corewood:outerwood transition age was positively correlated with corewood diameter, corewood proportion, and DBH, Strongly positive correlations between corewood proportion, corewood diameter, and DBH as well as between MOE and MOR were observed. A strong positive correlation was also observed between DBH and MOE; DBH was also negatively correlated with QMD. Specific gravity and relative density were not significantly correlated with any other parameters for the Louisiana site. Quadratic mean diameter was negatively correlated with corewood diameter and corewood proportion.

3.2. *Carter Mountain site*

The age of corewood:outerwood wood transition, corewood diameter, and bole corewood proportion differed among density treatments

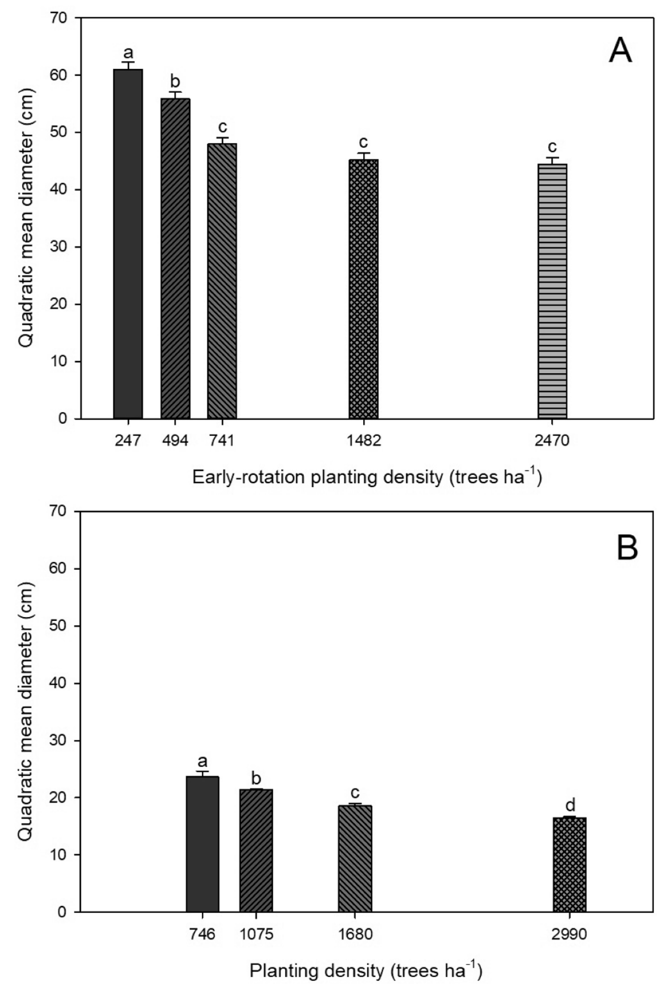

Fig. 4. Quadratic mean diameter in response to: (A) stand densities created by an age 4 precommercial thinning in a loblolly pine plantation in northwestern Louisiana and (B) planting density treatments at a site in southeastern Oklahoma near Carter Mountain. For each parameter, columns headed by a different letter differ at $P < 0.05$.

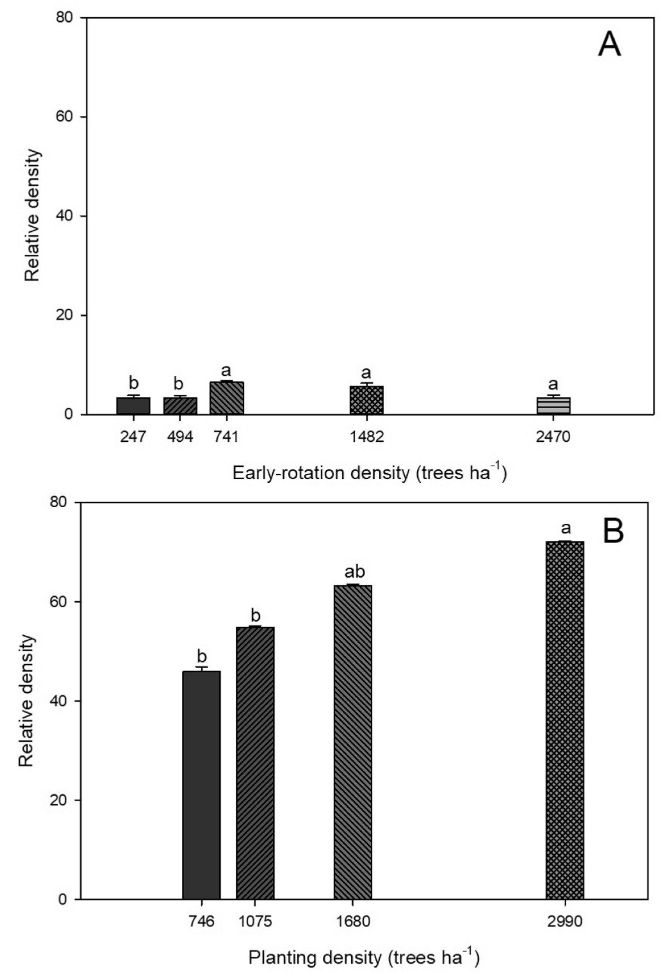

Fig. 5. Quadratic mean diameter in response to: (A) stand densities created by an age 4 precommercial thinning in a loblolly pine plantation in northwestern Louisiana (Hill Farm site) and (B) planting density treatments at a site in southeastern Oklahoma near Carter Mountain. For each parameter, columns headed by a different letter differ at $P < 0.05$.

at the Carter Mountain site (Table 4, Fig. 3B). Transition age of the 2990 and 1680 TPH treatments was greater than that of 1075 TPH. The ranking of corewood diameter among treatments was 746, 1075 > 1680 > 2990 TPH. Corewood proportion of the 2990 and 1680 TPH treatments exceeded that of the 1075 and 746 TPH treatments. Specific gravity and ring latewood proportion were similar among density treatments at Carter Mountain.

As with the Louisiana site, treatments differed in DBH but not tree height (Table 4). The 746 TPH planting density treatment had greater DBH than that of the 2990 TPH treatment. No other differences in DBH were found.

Genotype significantly affected only ring latewood proportion among all parameters at the Carter Mountain site (data not shown). The North Carolina genotype had higher latewood proportion (28%) than the Oklahoma/Arkansas genotype (26%). The North Carolina genotype exceeded the Oklahoma/Arkansas genotype in tree height, with heights of 14.1 m and 12.5 m, respectively. There were no differences in genotypes in DBH, QMD, and relative density.

Quadratic mean diameter and relative density differed among treatments. Among planting densities, QMD differed as 746 > 1075 > 1680 > 2990 TPH (Fig. 4B). The 2990 TPH planting density has greater relative density than the 746 and 1075 TPH densities at the time of wood core sampling (Fig. 5B).

Significant correlations among parameters were observed for the Carter Mountain site (Table 5). Genotype was negatively correlated with latewood proportion and tree height. Spacing treatment was positively correlated with corewood:outerwood wood transition age, corewood proportion, and relative density; spacing was negatively correlated with corewood diameter, latewood proportion, and DBH. Corewood:outerwood wood transition age was negatively correlated with corewood diameter and latewood proportion; it was strongly positively correlated with corewood proportion. There were negative correlations between corewood proportion, corewood diameter, and specific gravity. Relative density was positively correlated with corewood proportion and negatively correlated with corewood diameter. Specific gravity had a strong positive correlation with latewood proportion. Quadratic mean diameter was negatively correlated with height and DBH; DBH and height were positively correlated.

3.3. Stateline site

All parameters were affected by stand density treatments at the Stateline site (Table 6, Fig. 3C). Specific gravity of the 4307 and 1680 TPH treatments was greater than that of the 1075 and 746 TPH treatments; ring latewood proportion of the 4307 and 1680 TPH treatments also exceeded that of the 746 TPH treatment. The 4307 TPH treatment had a higher transition age than 1075 and 746 TPH treatments. All treatments differed in corewood diameter, with diameter increasing

Table 3
Pearson correlation coefficients for density management regime treatments (Dense), latewood proportion (Lwd), transition age of corewood:outerwood (Trans), corewood diameter (Cdia), corewood proportion (Cpr), modulus of elasticity (MOE), modulus of rupture (MOR), specific gravity (SG), tree height (HT), diameter at breast height (DBH), quadratic mean diameter (QMD), and relative density (RD) at a loblolly pine plantation in northwestern Louisiana (Hill Farm site). Coefficients with a single asterisk superscript are significant at 0.05 < P < 0.001; those with double asterisks are significant at P < 0.001.

	Dense	Lwd	Trans	Cdia	Cpr	MOE	MOR	SG	HT	DBH	QMD	RD
Dense	–											
Lwd	−0.33*	–										
Trans	0.97**	−0.20	–									
Cdia	0.12	−0.14	0.74**	–								
Cpr	−0.13	−0.87	0.70**	0.90**	–							
MOE	−0.52**	0.41*	−0.22	−0.20	−0.01	–						
MOR	−0.49**	0.59**	−0.20	−0.18	0.02	0.89**	–					
SG	−0.11	0.07	0.07	0.10	0.18	0.19	0.23	–				
Ht	−0.41	0.04	0.04	−0.27	−0.34	−0.01	0.07	−0.07	–			
DBH	0.97**	−0.20	−0.20	0.97**	0.99**	−0.80**	−0.59	0.42	−0.31	–		
QMD	−0.53	−0.25	−0.25	−0.66*	−0.67*	0.51	−0.02	−0.22	0.13	−0.67*	–	
RD	0.18	−0.07	−0.07	0.25	0.08	−0.15	−0.15	0.11	−0.48	0.12	−0.05	–

Table 4
Wood properties and tree dimensions in response to early stand density at a loblolly pine plantation in southeastern Oklahoma (Carter Mountain site). For each row, means followed by a different letter differ at P < 0.05.

	Planting density (trees ha^{-1})			
	2990	**1680**	**1075**	**746**
Specific gravity	0.41 (0.004) *a*	0.41 (0.004) *a*	0.41 (0.004) *a*	0.42 (0.003) *a*
Ring latewood proportion (%)	27 (0.8) *a*	28 (0.8) *a*	29 (0.8) *a*	29 (0.9) *a*
Transition age (years)	11.8 (0.2) *a*	11.9 (0.1) *a*	11.4 (0.1) *b*	11.5 (0.1) *ab*
Corewood diameter (mm)	118 (6) *c*	141 (6) *b*	151 (6) *a*	158 (6) *a*
Tree height (m)	11.7 (0.7) *a*	13.3 (0.7) *a*	13.8 (0.8) *a*	13.1 (1.3) *a*
DBH (cm)	41.7 (3.8) *b*	48.1 (5.3) *ab*	48.3 (4.3) *ab*	58.7 (7.1) *a*

with each decrease in initial stand density. Corewood proportion of the 4307 TPH density was greater than that of all other treatments, and corewood proportion of the 746 TPH treatment was lowest among all treatments.

Similar to the other two sites, treatments differed in DBH but not height (Table 6). From the lowest to highest planting density, each level had greater DBH than the preceding level. Treatments differed as 746 > 1075 > 1680 > 4307 TPH in DBH.

Genotype significantly affected transition age and corewood diameter at the Stateline site (data not shown). Transition age of the Oklahoma/Arkansas genotype (11.9 years) slightly exceeded that of the North Carolina genotype (11.6 years). The North Carolina genotype had greater (149 mm) corewood diameter than the Oklahoma/Arkansas genotype (135 mm). The North Carolina genotype had greater height (15.3 m) and DBH (52.6 cm) than those of the Oklahoma genotype (height of 13.5 m, DBH of 48.5 cm).

Many correlations were observed between the spacing and genotype treatments and wood parameters at the Stateline site, with spacing treatments correlated with all parameters (Table 7). Genotype was positively correlated with corewood:outerwood wood transition age and negatively correlated with corewood diameter, and tree height. Spacing had a negative correlation with corewood diameter and positive correlations with corewood:outerwood transition age, corewood proportion, latewood proportion, and specific gravity.

There were several correlations among wood and tree parameters at this site (Table 7). Specific gravity had a high positive correlation with latewood proportion and negative correlations with corewood:

Table 6
Wood properties and tree dimensions in response to early stand density at a loblolly pine plantation in southeastern Oklahoma (Stateline site). For each row, means followed by a different letter differ at P < 0.05.

	Planting density (trees ha^{-1})			
	4307	**1680**	**1075**	**746**
Specific gravity	0.42 (0.004) *a*	0.42 (0.004) *a*	0.41 (0.003) *b*	0.40 (0.004) *b*
Ring latewood proportion (%)	31.7 (0.6) *a*	31.5 (0.6) *a*	30.4 (0.5) *ab*	29.6 (0.8) *b*
Transition age (years)	12.3 (0.2) *a*	11.8 (0.2) *ab*	11.5 (0.1) *b*	11.4 (0.1) *b*
Corewood diameter (mm)	108.2 (3.7) *d*	135.8 (3.6) *c*	152.8 (3.7) *b*	170.3 (3.6) *a*
Tree height (m)	14.1 (0.4) *a*	14.4 (0.5) *a*	14.9 (0.5) *a*	14.1 (0.4) *a*
DBH (cm)	36.8 (0.8) *d*	48.5 (1.4) *c*	54.6 (0.9) *b*	62.2 (1.4) *a*

Table 5
Pearson correlation coefficients for density management regime (Dense) and genotype (Geno) treatments, latewood proportion (Lwd), transition age of corewood: outerwood (Trans), corewood diameter (Cdia), corewood proportion (Cpr), specific gravity (SG), tree height (HT), diameter at breast height (DBH), quadratic mean diameter (QMD), and relative density (RD) at a loblolly pine plantation in southeastern Oklahoma (Carter Mountain site). Coefficients with a single asterisk superscript are significant at 0.05 < P < 0.001; those with double asterisks are significant at P < 0.001.

	Dense	Geno	Lwd	Trans	Cdia	Cpr	SG	HT	DBH	QMD	RD
Dense	–										
Geno	0.03	–									
Lwd	−0.13*	−0.90**	–								
Trans	0.15*	0.06	−0.13*	–							
Cdia	−0.57**	0.06	0.03	−0.33**	–						
Cpr	0.30**	0.10	−0.10	0.71**	−0.31**	–					
SG	−0.11	−0.08	0.89**	−0.09	−0.57**	−0.08	–				
Ht	−0.31	−0.52*	0.38	−0.29	0.22	0.01	0.15	–			
DBH	−0.57*	−0.22	0.02	−0.14	0.46*	−0.11	−0.04	0.61*	–		
QMD	0.07	0.21	−0.22	0.15	0.03	−0.17	−0.04	−0.85**	−0.48*	–	
RD	0.84**	−0.18	−0.25	0.37	−0.70**	0.65*	−0.20	0.04	−0.38	−0.16	–

Table 7
Pearson correlation coefficients for density management regime (Dense) and genotype (Geno) treatments, latewood proportion (Lwd), transition age of corewood: outerwood (Trans), corewood diameter (Cdia), corewood proportion (Cpr), specific gravity (SG), tree height (HT), and diameter at breast height (DBH) at a loblolly pine plantation in southeastern Oklahoma (Stateline site). Coefficients with a single asterisk superscript are significant at $0.05 < P > 0.001$; those with double asterisks are significant at $P < 0.001$.

	Dense	Geno	Lwd	Trans	Cdia	Cpr	SG	HT	DBH
Dense	–								
Geno	0.01	–							
Lwd	0.16*	0.02	–						
Trans	0.28**	0.13*	−0.21*	–					
Cdia	−0.66**	−0.20**	−0.08	−0.55**	–				
Cpr	0.34**	0.09	−0.14*	0.80**	−0.55**	–			
SG	0.21**	0.07	0.86**	−0.13*	−0.14*	−0.05	–		
Ht	−0.11	−0.81**	0.02	−0.43*	0.32	−0.33	−0.19	–	
DBH	−0.96	−0.20	−0.61*	−0.83**	0.97**	−0.61*	−0.70**	0.29	–

outerwood wood transition age, corewood diameter, and DBH. Corewood:outerwood transition age was negatively correlated with corewood diameter, latewood proportion, height, and DBH and positively correlated with corewood proportion. Corewood proportion was negatively correlated with corewood diameter, latewood proportion, and corewood proportion. Diameter at breast height was negatively correlated with latewood proportion and corewood diameter and positively correlated with corewood proportion.

4. Discussion

Different trends among parameters among the study sites illustrated the influences of silvicultural history on wood property responses to stand density. Only at the Hill Farm site were there no differences among density treatments in parameters associated with corewood (corewood: outerwood transition age, corewood diameter, corewood proportion). Due to the nature of the CCT experiment at Hill Farm, all treatments spent the first four years post-planting at the same stand density until sequential reductions in stand density were initiated by precommercial thinning, and all trees were subjected to a similar amount of density-induced growth stress prior to density reduction. In addition, after sequential reductions in stand density among treatments began, treatments differed in density for two to five years before transitions from corewood to outerwood occurred between ages 8–9.5 years. As such, there was less time for corewood differences to occur among stand density treatments compared to the Oklahoma trials. Another factor that may have contributed to the lack of differences in corewood characteristics in this experiment was its site preparation. The Hill Farm site was prescribed burned prior to planting, whereas the Oklahoma sites had herbicide in addition to burning. Prescribed fire can result in greater richness of understory vegetation relative to that of herbicide in loblolly pine plantations (Iglay et al., 2010). Consequently, the Hill Farm site likely had greater potential for non-crop vegetation to reduce loblolly pine growth. The seedlings planted at the Hill Farm site were of unimproved local origin whereas both genotypes in the Oklahoma trials had at least one generation of tree breeding. Faster growth rates and greater growth uniformity are emphasized in tree breeding, which may have made the genotypes of the Oklahoma trials more prone to corewood parameter differences in response to stand density treatments. Conversely, greater variability in growth from unimproved seedlings of the Hill Farm site may have contributed to the site's lack of corewood parameter differences.

The lack of differences in corewood parameters at the Hill Farm site has silvicultural implications. There was no divergence in corewood transition to outerwood and diameter in the years between precommercial thinning (ages 4 through 6) and the transition to outerwood of this site (ages 8–10), which suggests that the earliest years after planting had the greatest impacts on these corewood attributes. Clason (1994) found that diameter growth of the density regimes of the Hill Farm study were similar at age 4 but diverged such that diameter increment decreased with increasing stand density between ages 4 and 9, which provides further evidence that the initial years after planting had the greatest influence on corewood diameter in this study. Although it is atypical for planting loblolly pine plantations with a density that is then reduced soon after planting as conducted for the CCT protocol of the Hill Farm trial, sites sometimes become overstocked in the year of planting by loblolly pine seedlings of natural origin (volunteer seedlings). Such sites are pre-commercially thinned to foster faster development of merchantable trees. Our results indicate that reducing loblolly pine densities by as much as a six-fold amount by pre-commercial thinning had no impacts on residual tree corewood diameter, proportion, and age of its transition to outerwood. These results contrast with prior research in jack pine (*Pinus banksiana* Lamb.) that found pre-commercial thinning generally led to increased corewood volumes, although their thinning intensities were greater (10- to 30-fold reductions in stand density) than those of this study (Zhang et al., 2006). The transition of loblolly pine to outerwood within four to six years after pre-commercial thinnings of the Hill Farm trial may have also influenced this difference in results. Consideration of the timing of pre-commercial thinning relative to the species' corewood to outerwood transition may help with avoiding increasing corewood diameter and proportion.

The Hill Farm trial indicated that with timely thinning, loblolly pine plantations could be sustained at a wide range of densities without affecting specific gravity and clearwood MOE and MOR at 2.4 m in height. Only the treatment with the lowest stand density (regime 5, which had a density of 247 TPH as of age 7) had lower clearwood MOE and MOR than most of the density regimes tested. Regime 5 also had lower specific gravity than regime 2, which was 1482 TPH as of age 7. Due to the lack of differences in corewood diameter and proportion, the lower MOE, MOR, and specific gravity of the lowest stand density treatment was likely due to differences in latewood proportion (which declined with decreasing density) throughout the rotation. This trend contrasts with the inference of Roth et al. (2007) that loblolly pine trees harvested from more tightly spaced stands would have higher MOE due to smaller corewood diameter, but the Roth et al. (2007) study observed loblolly pine in a density study at age 6 without precommercial thinning. The Hill Farm results of similar clearwood MOE for all treatments except the regime kept at the lowest density also contrasts with a thinning study in Calabrian pine (*Pinus nigra* Arnold subsp. *calabrica*) that found MOE generally declined with greater thinning intensity, but in their experiment thinning was conducted at a single time to different densities (0, 25, 50, and 75% reductions in stand density) instead of the sequential reductions within thinning regimes as conducted in the Hill Farm trial (Russo et al., 2019). Zhang et al. (2006) similarly found lower MOE and MOR in their most intensive precommercial thinning of jack pine relative to all other lower thinning levels, but they found a higher corewood proportion with heavier precommercial thinning as well. The Hill Farm results bolster the recommendation of Larson et al. (2001) that timely thinning, from the standpoint of avoiding substantial reductions in tree volume growth, balances volume production with acceptable wood quality. However, in earlier analyses in the Hill Farm study, Clason (1994) inferred that the age 7 stand densities of 494 and 247 TPH (regimes 4 and 5) were optimum for sawtimber volume production; this assessment of wood quality parameters suggests that the 247 TPH regime would lead to wood with lower specific gravity than that of the 1482 TPH regime and lower MOE and MOR than that the regimes with densities 741 TPH and above at age 7.

Corewood characteristics were affected by planting density at both Oklahoma sites. Interestingly, higher planting densities led to later transition from corewood to outerwood at both sites. This finding contrasts with that of a highly similar planting density study of loblolly pine and slash pine in eastern portions of the species' range by Clark and Saucier (1989). The Clark and Saucier (1989) study tested a range of planting densities (746, 1075, 1681 and 2990 TPH) for loblolly pine, identical to all of those of the Carter Mountain site and the lower three densities of the Stateline site in this study, but planting densities did not significantly affect transition age. The eastern portion of the loblolly pine range generally has greater growth rates attributable in part to higher summer rainfall than in the western portion of its range (Lambeth et al., 1984). As such, greater competition for water in the western portion of its natural range may be intensified by higher stand densities, leading to a lower proportion of latewood relative to earlywood and a delay in the transition to outerwood as seen at both Oklahoma sites in the uppermost planting densities tested. Further research that monitors soil water supply in tandem with measuring the corewood to outerwood transition is needed to elucidate a relationship between these parameters.

The increase in corewood diameter with decreasing planting density observed at the Stateline and Carter Mountain sites is consistent with prior planting density studies (Clark and Saucier 1989; Larson et al., 2001; Roth et al., 2007). The increasing corewood proportion with increasing planting density at both sites is also consistent with inferences in a study modeling effects of planting density on wood properties of loblolly pine in the eastern portion of the species' range (Antony et al., 2012). Trees sampled in the Antony et al. (2012) study were planted in the same year as those of the Carter Mountain and Stateline sites, and the range of densities within their study was similar to those of the Oklahoma sites. Trees producing high annual diameter increments after converting to outerwood contain proportionally less basal area in corewood than slower-growing trees (Clark and Saucier, 1989). Diameter growth differences after conversion to outerwood may have contributed to corewood proportion trends at the Carter Mountain and Stateline sites. At both sites, Abbey (2002) found significantly greater annual basal area growth with decreasing planting density from ages 8–15 years. Another contributing factor to the lower corewood proportions for lower stand densities at the Carter Mountain and Stateline sites was their earlier transition to outerwood relative to the higher planting densities, although this likely had less effect than diameter growth because transition differentials ranged from 0.4 to 0.9 years between lower and higher densities.

The different responses of specific gravity at the Carter Mountain and Stateline sites were likely due to differences in site conditions. Only the Stateline site had lower specific gravity at lower planting densities, and its specific gravity trends were much more strongly correlated with latewood percentage than corewood diameter and transition of corewood to outerwood. Consequently, although the 4307 TPH planting density had the lowest corewood diameter it had specific gravity comparable to 1680 TPH. Likewise, a planting density of 1075 TPH had similar specific gravity to 746 TPH despite having significantly lower corewood diameter. Latewood proportion was also closely correlated with specific gravity at the Carter Mountain site, so similarities among all densities in specific gravity at that site were likely related to their similar latewood proportions. Prior studies have similarly found close correlation with latewood proportion (Megraw, 1985; Tasissa and Burkhart, 1998; Jordan et al., 2008). Similarity in latewood proportions among all densities at the Carter Mountain site may be attributable to its more well-drained soil than the Stateline site, which would tend to curtail earlywood formation relative to latewood due to greater drought stress.

Differences in latewood proportion and corewood:outerwood wood transition age between genotypes of Coastal Plain and Western Gulf origin reported in their native regions were also observed when the Coastal Plain genotype was grown at the western edge of the species' range. In a studies of wood parameters conducted across the loblolly pine range, trees of the Western Gulf (Hilly Coastal) region had later corewood to outerwood transition ages than genotypes of South Atlantic and Upper Coastal origin (Clark et al., 2006; Jordan et al., 2008). In this study, the Oklahoma/Arkansas genotype had a later transition age than the North Carolina genotype of South Atlantic Coast origin at the Stateline site. However, this difference in transition age between genotypes was site dependent as evidenced by their similarity at the more well-drained Carter Mountain site. Loblolly pine growing in the South Atlantic physiographic region typically has greater latewood proportions due to better late-season precipitation and longer growing season of the region relative to all other loblolly pine physiographic regions (Jordan et al., 2008). The higher latewood proportion of the North Carolina genotype at the Carter Mountain site provides some evidence that its tendency to produce more latewood in its native region could occur when planted in the Western Gulf. Despite South Atlantic loblolly pine genotypes having greater specific gravity than genotypes from northern and inland regions in a previous study conducted in the eastern portion of the loblolly pine range (Jayawickrama et al., 1997) and the correlations often observed between latewood proportion, corewood:outerwood wood transition age and specific gravity (Megraw, 1985; Tasissa and Burkhart, 1998; Jordan et al., 2008), no differences in specific gravity were observed between the genotypes at either Oklahoma site. The North Carolina genotype's earlier transition to outerwood at the Stateline site and higher latewood proportion at the Carter Mountain site may have been too modest to confer differences in specific gravity. The greater corewood diameter of the North Carolina genotype, attributable to its greater diameter growth as observed by Abbey (2002), at the Stateline site likely also contributed to the lack of specific gravity differences between genotypes at that site.

5. Conclusions

These trials suggest that forest managers have flexibility in managing loblolly pine stand density without altering several wood properties on sites similar to these tested within the Western Gulf region. In the Hill Farm trial stand density was managed at diverse levels through sequential thinning, beginning at precommercial size, and only a regime that was commercially thinned to half its density two times from 297 TPH at age 7 to 62 TPH by age 41 had significant reductions in MOE, MOR, and specific gravity. Corewood diameter increased with decreasing planting density at two sites in Oklahoma at the northwestern edge of the loblolly pine range, but the corewood proportion declined with decreasing planting density due to greater diameter growth of the lower planting densities as well as their earlier transition from corewood to outerwood. Specific gravity differences among planting densities at the Oklahoma sites was site-specific, with no differences at the more well-drained site. Latewood proportion, which was greater at the higher planting densities, more strongly influenced specific gravity differences among planting densities. A planting density between 1075 and 1680 TPH would likely be optimum for these site conditions for balancing tree volume growth with minimizing reductions in specific gravity from reduced latewood proportion and larger corewood diameters. The Atlantic Coastal Plain genotype retained its tendencies to transition to outerwood earlier and have greater latewood proportions relative to a local genotype when planted at the Western Gulf sites, and its specific gravity was similar to that of the local genotype. These results suggest that moving a Atlantic Coastal Plain genotype to the Western Gulf region to improve plantation yields may not carry a risk of reduced wood specific gravity, although further study with a greater array of genotypes from these regions is necessary to better substantiate this potential.

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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