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LONGITUDINAL VARIATION OF RING WIDTH, WOOD DENSITY AND BASAL AREA INCREMENT IN 26-YEAR-OLD LOBLOLLY PINE (*PINUS TAEDA*) TREES

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ABSTRACT

Longitudinal variations in select wood quality parameters were examined in 26-year-old loblolly pine trees planted in Anhui Province, China. Wood density and ring width were measured from cross-sections of different heights of merchantable stems. The average ring width decreased from the base to 1.3 m, then increased to the maximum at 7.6 m, and thereafter reduced with stem height. The longitudinal patterns varied with cambial age in ring width. The coefficient of variation in ring widths along the stem height was greater than 21% at the cambial age 5–8 years and 9–12 years, and small variations were observed in other cambial age groups. The average wood density declined from 1.3 m to 7.6 m and then slightly increased with increasing stem height. The wood density showed great variation at different growth stages below 7.6 m, but varied less above 7.6 m. Basal area increment (BAI) gradually increased with increasing ring number (from the pith to the bark) at different stem heights, and markedly reduced after the 22nd ring. These results indicate that the longitudinal variations of wood density, ring width and BAI in loblolly pine are greatly affected by cambial age. The detailed information of the wood properties along stem heights could be useful to wood utilization of loblolly pine.

Keywords: loblolly pine, ring width, wood density, basal area increment (BAI), longitudinal variation.

INTRODUCTION

Loblolly pine (*Pinus taeda* L.), native to the southeastern United States, is an important timber species (McKeand *et al.* 2003). It has been widely planted in the tropical and sub-tropical regions around the world, such as in South Africa, New Zealand, Australia and Brazil. Loblolly pine was first introduced in China in the 1930s. Because of its favorable properties, especially its rapid growth and wide adaptability, loblolly pine has become a major tree species for construction and pulp timber in the south of China with a yearly plantation area of 200,000 ha (Xu *et al.* 2008).

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Wood density and ring width are the most commonly used indicators of wood characteristics. Wood density is considered the key index for wood quality, pulp yield and quality (Bendtsen 1978), whereas ring width is related to the volume of wood produced as well as end product uniformity (Park *et al.* 2009). Additionally, many studies have shown that annual basal area increment (BAI) (Le Blanc 1990), another measure of radial growth, is well suited to represent individual and stand-level changes (Bigler and Bugmann 2003; Piovesan *et al.* 2008; Voelker *et al.* 2008).

The detailed radial variations in wood density were studied for many conifers and hardwood trees species (*e.g.* Panshin and de Zeuuw 1980; Jozsa and Middleton 1994; Kennedy 1995). However, most of these studies were performed

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at breast height. There are relatively few data available on radial variation in wood density at different stem heights (Park *et al.* 2009). Previous studies showed that the longitudinal variation of wood density tended to decrease with stem height (Singh 1984, 1986) mainly because the proportion of juvenile wood increased with stem height (Zobel and Sprague 1998). Some studies showed that ring width had an increasing trend with stem height in loblolly pine (Megraw 1986; Tasissa and Burkhart 1997; Gartner *et al.* 2002). These results suggest that wood properties vary with stem position.

However, the patterns vary considerably and sometimes contradictorily, even for the same species. For example, some studies showed that ring density had an increasing trend with stem height in Norway spruce (*Picea abies*) (Molteberg and Høibø 2006; Jyske *et al.* 2008), but Mäkinen *et al.* (2007) found no significant height effect on ring density. Megraw (1985) showed that the longitudinal patterns of wood density in loblolly pine were dependent on radial position or cambial age. Additionally, many studies on BAI growth of individual trees were only performed at breast height. Little is known about the variation of BAI at different growth stages and at different stem heights. To effectively utilize wood, it is necessary to understand the detailed information of the wood on the within-stem position.

The objectives of this study were to (1) examine the patterns of ring width, wood density, and basal area increment along stem height, and (2) relate longitudinal patterns in ring width and wood density to tree cambial age.

MATERIALS AND METHODS

Site Description

The experiment was conducted at the Matou forest farm (118°32′E, 30°45′N) in Jing County, Anhui Province, China. Typical of a subtropical monsoon climate in the study site, the mean annual temperature is 15.7°C, mean annual precipitation is 1553 mm, and the frost-free period is 239 days. The soil type is a yellow-red soil evolving from Quaternary red clay with a sticky texture and medium fertility. The original vegetation of this area was naturally scattered *Pinus massoniana*.

The experimental loblolly pine forest was planted in the spring of 1969 at an original stand density of 1200 trees per ha. The stand was thinned in 1982 (stand density reduced by approximately 25%). The stand density at the time of this study was 850 trees per ha. The slope of the experimental area is approximately 20% with a northeastern aspect. Three average trees (tree height is 17.4 m, 16.1 m and 15.6 m, respectively; diameter at breast height is 33.78 cm, 33.78 cm, 29.03 cm, respectively; vertical span of living crown is 8.5 m, 7.6 m and 7.2 m, respectively) were randomly selected for sampling in March, 1995. Loblolly pine was cultivated for industrial timber (*e.g.* plywood and construction lumber) in the experimental area.

Measurement of Growth Ring Width

After felling the trees, we marked the node from tree base to the top at 0 m, 1.3 m, 3.6 m, 5.6 m, 7.6 m, 9.6 m, 11.6 m, 13.6 m, and 14.6 m along the tree stem. Nine tree stem disks of 5 cm thickness were taken from these heights. A straight line was marked through the pith in the south-north and east-west directions. We measured the width of each ring (earlywood width and latewood width) in the east, south, north and west directions by using measuring meter of tree-ring width (LINTAB) with 0.01 mm accuracy, and tested results of crossdating and measurement by adopting COFECHA procedures (Holmes 1983).

Measurement of the Wood Density of a Disk

With the wood pith at the center, fan-shaped wood blocks at 30° angles with directions clearly marked were intercepted from the pith to the cambial in four directions and dipped in water for 40 days to stabilize the size by absorbing moisture. Then, ring samples, each representing two years, were cut from bark to pith with a wood chisel. Surfaces were kept wet for the measurements, so that the wood density was measured using the water immersion method (Hein *et al.* 2009). Samples were subsequently oven-dried at the

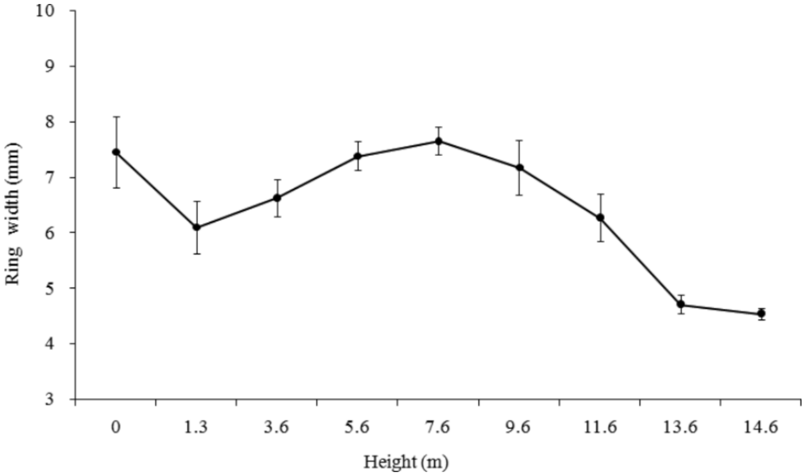

Figure 1. Longitudinal variation of the average annual ring width in 26-year-old loblolly pines (n varies from 312 at the bottom to 36 at the top, mean ± SE).

temperature of 103°C until the mass was constant. The dry matter content was determined to 0.001 g accuracy. The wood density (G) was defined as:

$$G = M/V \quad (1)$$

where M is the sample dry weight (g) and V is the sample volume with water saturation (cm^3).

Calculation of the Basal Area Increment (BAI)

Because BAI at year t is equivalent to annual ring area (Biondi and Qeadan 2008), so it can be calculated with following equation:

$$BAI = \pi(R_t^2 - R_{t-1}^2) \quad (2)$$

where R_t is the stem radius at the end of the annual increment, and R_{t-1} is the stem radius at the beginning of the annual increment.

Data Analysis

Radial profiles of wood density, ring width and basal area increment were produced for each disk. Wood density and ring width at each stem height were the mean of all trees in the four directions. To determine the change of growth ring and wood density at different growth stages (cambial age) along the stem height, the growth rings were classified into several groups by cambial age. Each group contains four growth rings.

RESULTS

Longitudinal Variation in Ring Width

The average ring width decreased from the base to 1.3 m, but increased and reached the maximum at 7.6 m, and then reduced with stem height (Figure 1). The ring width varied from 4.54 mm to 7.66 mm among nine stem heights, and the average value was 6.44 mm. Longitudinal variation of the annual ring width greatly differed among different ring ages (Figure 2). Annual ring width generally decreased from the base to 1.3 m at different cambial age groups. Ring width increased above 1.3 m and then declined near the top at the age groups of 1–4 years, 5–8 years and 9–12 years. Tree-ring width consistently decreased with stem height at 13–16 years, while it increased from 1.3 m to 3.6 m at the 17–20 years. The mean ring width was 4.71 mm at 1–4 years, which was lower than other cambial age groups (6.52–8.13 mm, except 1.93 mm at the 25–26 years). The coefficient of variation in ring width along the stem height was 21.84% and 23.19% for cambial age 5–8 years and 9–12 years, respectively, and it varied from 10.37% and 16.19% in other cambial age groups. Especially, the younger cambium age (1–4 years) showed less variation with stem height.

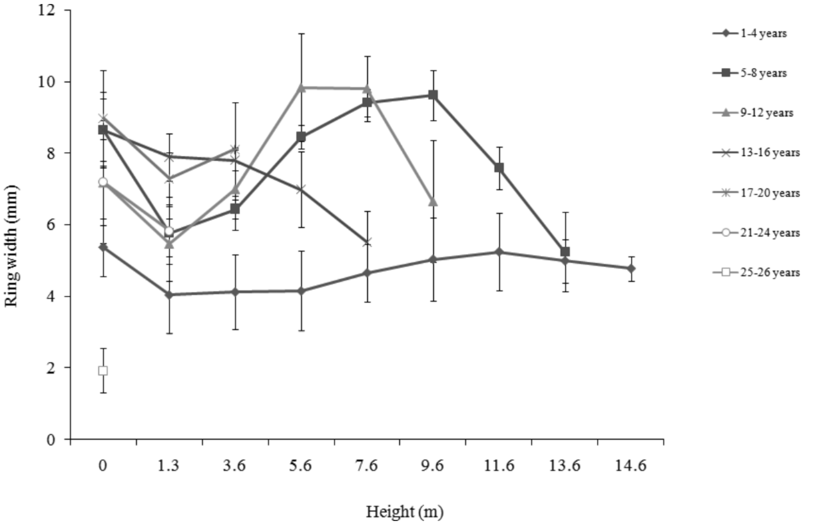

Figure 2. Longitudinal variation of the annual ring width by cambial age groups (n = 12, mean ± SE).

Longitudinal Variation in Wood Density

Longitudinal variations in wood density at different heights are shown in Figure 3. From the tree base to the top, the average wood density was high below 1.3 m. It declined from 1.3 m to 7.6 m, reaching a minimum of 0.33 g cm^{-3}, and then slightly increased with stem height (except for a sudden increase at 11.6 m). Overall, the average wood density presented a decreasing trend with stem height. The pattern of longitudinal variations in wood density was similar at different cambial age groups (Figure 4). The wood density showed great variation at different growth stages below 7.6 m, and less variation was found above 7.6 m.

Longitudinal Variation in Basal Area Increment

Temporal variations of basal area increment (BAI) at different heights of loblolly are shown in Figure 5. The variation pattern of BAI was similar

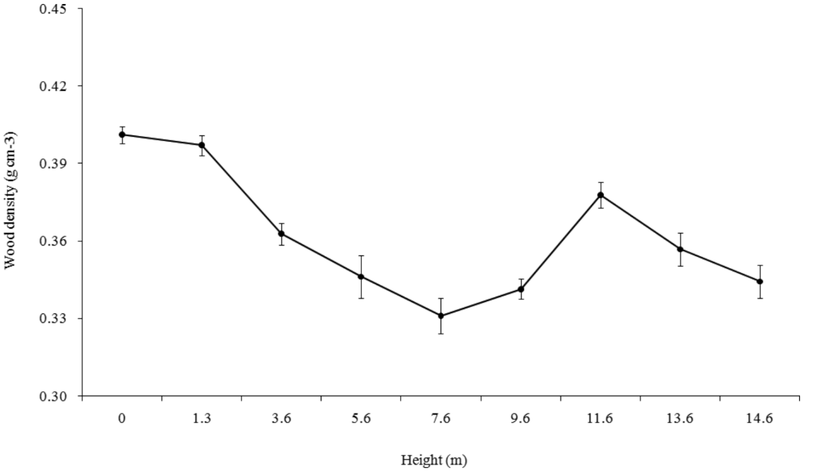

Figure 3. Longitudinal variation of the wood density in 26-year-old loblolly pines (n varies from 156 at the bottom to 12 at the top, mean ± SE).

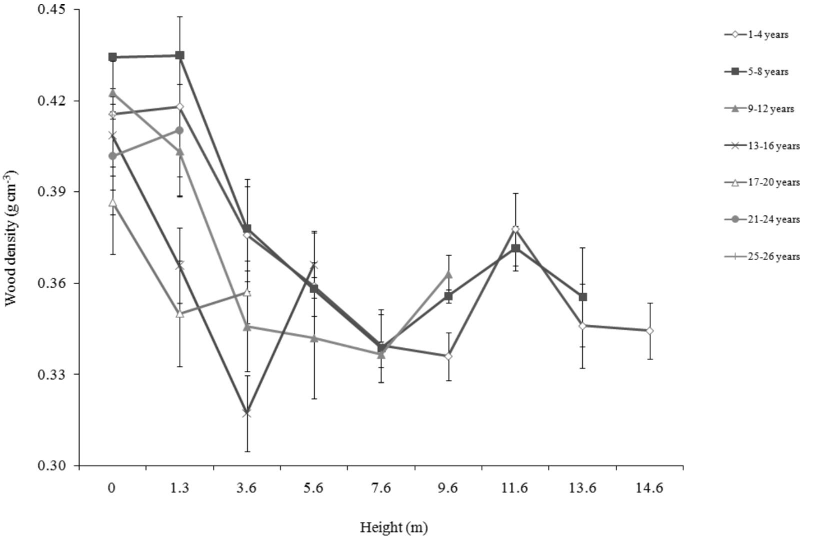

Figure 4. Longitudinal variation of the wood density by cambial age groups (n = 12, mean ± SE).

from the base (0 m) to 11.6 m stem height. BAI was low near the pith, gradually increased to reach a maximum at about the 22nd ring (except for a sudden decline from the 17th to 19th ring), and then markedly reduced after the 22nd ring. However, the magnitude of variations in BAI was different within each stem height. BAI increased with ring number at the 13.6 m and 14.6 m stem height. The value of BAI at the 26th ring was 19.06 cm^2 yr^{-1} at 1.3 m, which was 38.50% of the maximum (49.52 cm^2 yr^{-1}, at the 22nd ring).

DISCUSSION

Variation of Ring Width in Loblolly Pine

Ring width reflects the speed of tree growth, while the growth rate has a direct impact on timber productivity and wood quality. Previous studies found little longitudinal variation in ring width or wood density (Duff and Nolan 1953; Olesen 1982; Mäkinen *et al.* 2007). However, in this study, a clear height effect was observed for ring width during the study period. Ring widths

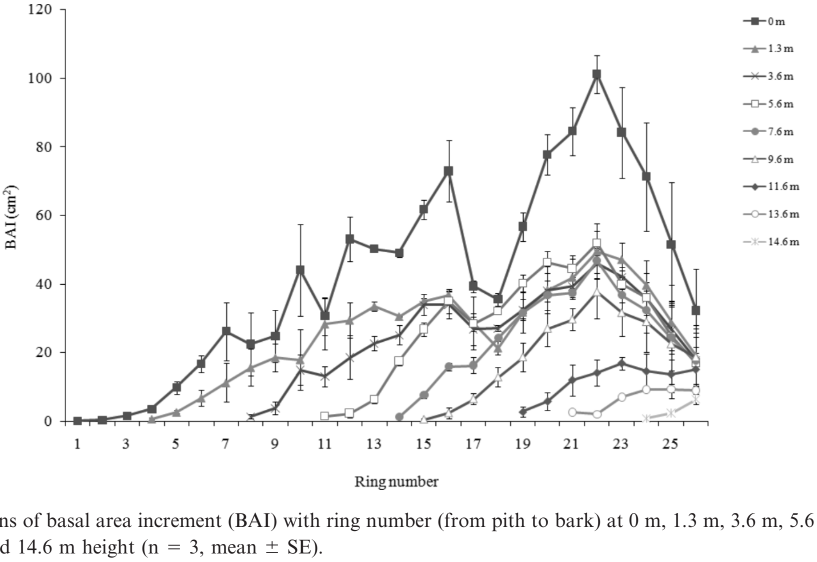

Figure 5. Variations of basal area increment (BAI) with ring number (from pith to bark) at 0 m, 1.3 m, 3.6 m, 5.6 m, 7.6 m, 9.6 m, 11.6 m, 13.6 m and 14.6 m height (n = 3, mean ± SE).

generally increased from 1.3 m upward and declined near the top (Figure 2). Great variations were found for tree-ring width along the stem heights at cambial age 5–8 years and 9–12 years, whereas small variations were observed at other cambial age groups. The tree rings in the middle-bottom of the living crown (approximate half of tree height) were markedly wider than the lower stem at cambial age 5–8 years and 9–12 years. After age 12, ring width constantly decreased almost linearly from the base to the top. However, some studies showed that there was a clear trend of decreasing growth ring width from the tree top downward, with growth rings being wider within the crown than below the crown (Megraw 1986; Gartner *et al.* 2002). Tasissa and Burkhart (1997) showed that ring width of 25-year-old loblolly pine decreased with increasing height and reached a minimum close to the 1.3 m height from where it gradually increased until the vicinity of living crown. Trees first allocate photosynthate in the actively growing region of the crown. As trees grow and the lower branches become less efficient and begin to die, the point of maximum growth shifts upward (Tasissa and Burkhart 1997). Once the need for growth and photosynthesis has been met in the actively growing region of the crown, materials are transported down the stem for storage and other needs (Kozlowski 1971). Although trees having more resources because of less competition can transport materials down the stem for diameter growth, those that are subject to more intense competition use up their resources within the vicinity of the live crown. These results indicate that, at a given cambial age, tree-ring widths have great variation at different stem heights.

Variation of Wood Density in Loblolly Pine

Wood density reflects the amount of substances in the wood cell wall and constitutes an important property in tree breeding. The longitudinal variation in wood density of loblolly pine was reported in several studies. Early studies reported a decrease in wood density from stump-to-tip of the loblolly pine tree (Megraw 1985; Zobel and van Buijtenen 1989). A typical pattern of wood density with stem height for loblolly pine, as reported by Pearson and Gilmore (1971), is that wood density decreased from 3 ft. (*ca.* 0.9 m) to 23 ft. (*ca.* 7.0 m) and reached a minimum, and then slightly increased with stem height. In this study, the pattern of longitudinal variation in wood density had similar trends with Pearson and Gilmore's result. Although wood densities showed great variation at different cambial age groups below the 7.6 m stem height, especially at the base and 1.3 m, they varied little at different cambial age groups above 7.6 m. This suggests that the longitudinal patterns of wood density in loblolly pine were dependent on stem height and cambial age. Park *et al.* (2009) also found that cambial age greatly affected the patterns of wood density with stem height in jack pine (*Pinus banksiana*). In their study, wood density increased from stem base to top at cambial age 2 years. After age 10, wood density constantly decreased almost linearly from stem base to the top. However, Antony *et al.* (2010) reported that longitudinal variation of wood density with stem height can be divided into three segments based on investigation of the natural range of loblolly pine (20–25 years old). The average wood density decreased rapidly from the base of the tree to a relative height of *ca.* 0.1; it then decreased at a decreasing rate between relative heights of *ca.* 0.1 to 0.3; for relative heights $>$ *ca.* 0.3, wood density decreased at constant rate.

Marked longitudinal and regional variation in wood density has been reported for loblolly pine by Jordan *et al.* (2008) and Antony *et al.* (2010). The average wood density of the whole tree was 0.36 g cm^{-3} (ranged from 0.31 g cm^{-3} to 0.41 g cm^{-3}) for 26-year-old loblolly pine in the current study. The wood density varied from 0.34 g cm^{-3} to 0.58 g cm^{-3} for loblolly pine (20–25 years old) in the USA. The mean wood density observed for the southern Atlantic Coastal Plain and Gulf Coastal Plain was 0.46 g cm^{-3}, and it was 0.42 g cm^{-3} for the other regions (Antony *et al.* 2010). The wood density in our results was lower than that of the research of Antony *et al.* The reason for their higher wood density might partly result from the increased latewood percentage (35–40%) of these trees (Antony *et al.* 2010). The average latewood percentage was 24.9% in our study.

Variation of Basal Area Increment in Loblolly Pine

The BAI growth of individual trees typically follows a sigmoidal pattern: BAI increases rapidly from young to middle age, remains at a constant level during a protracted period of middle age and then reduces as trees become old (Weiner and Thomas 2001). In the current study, we observed a similar result. The BAI gradually increased with increasing ring number, reached a maximum at the 22nd ring, and reduced thereafter for stem heights from 0 m to 9.6 m, whereas it initially increased with increasing ring number and remained at a constant level thereafter for stem heights above 9.6 m. This BAI trend may be related to an increasing tree canopy during early age, a constant canopy volume during middle age, and then a physiological decline in old trees (Spiecker *et al.* 1996). Recently, an increasing number of studies have demonstrated that decline of tree growth with tree age and size is closely linked with physiological processes, including declines in gas exchange, photosynthesis, and growth rate (Koch *et al.* 2004; Ryan *et al.* 2006; Greenwood *et al.* 2008). As tree height increases, water must overcome additional gravitational and frictional forces to reach the top. Eventually resistance becomes so great that leaf water stress increases, inducing stomata to close, thereby limiting gas exchange and photosynthesis, and ultimately reducing growth (Delzon and Loustau 2005; Ryan *et al.* 2006). Drake *et al.* (2010) also confirmed that ''hydraulic limitation'' could explain a decline of growth rate with increasing age (or size) in loblolly pine.

The variation of ring width, wood density and BAI in loblolly pine might also be influenced by climate changes (*e.g.* precipitation and temperature) (Rossi *et al.* 2008; Vieira *et al.* 2009; Li *et al.* 2012). However, the climate in the study area did not show great fluctuation during the study period except for a few individual years (Fang and Ji 2008). The knowledge of longitudinal patterns of wood properties in loblolly pine has many useful applications for wood production and wood utilization. For example, pulp wood production and use of wood for furniture and construction could be more accurately evaluated.

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