WOOD DENSITY AND FIBER LENGTH IN YOUNG *POPULUS* STEMS: RELATION TO CLONE, AGE, GROWTH RATE, AND PRUNING

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ABSTRACT

Cross-sectional disks were cut at two stem heights (1.5 m and 3.0 m) from 9-year-old trees of three *Populus* clones grown in an intensively-cultured plantation in western Washington. At age 1.5 years, when the trees averaged 3.4 m tall, half of the trees were pruned by removing all branches below 1.8 m. Ring width, wood density, and fiber length were measured for each ring. Pruning had no effect on mean ring width or wood properties, averaged over the entire disk or on rings produced during the 2nd through the 4th years. Averaged over all trees, wood density of the 1.5-m sample was 0.37 g cm^{-3} during the first 3 years, decreased somewhat at age 4 or 5, and then increased to an average of 0.45 g cm^{-3} at age 9. Fiber length increased from 0.57 mm at age 1 to nearly 1.0 mm at age 9. Averaged over all disks at 1.5 m, clones differed significantly in ring width, wood density, and fiber length. Mean values for the two wood properties at 3.0 m were slightly lower than those at 1.5 m and did not differ significantly among clones. Within clone correlations between ring width and wood density or fiber length or between wood properties were low, and generally nonsignificant or inconsistent.

Keywords: *Populus*, wood density, fiber length, ring width, clones, sampling height, pruning.

INTRODUCTION

Thousands of hectares of clonal plantations of poplar hybrids have been established by industrial firms during the past decade. Initially, the primary purpose of these plantations was fiber for pulp and paper, but objectives have expanded to include solid (Eaton 2000) and composite wood products and, in some cases,

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biomass for energy, carbon sequestration, and phytoremediation of environmental problems (Kuhn and Nuss 2000). Silviculture is intensive and rotations are short: 5 to 8 years for fiber alone and up to 15 years for solid wood products. Thus, a large portion if not all of the wood produced will be in the juvenile core. Wood properties in the juvenile core differ from those of mature wood of most tree species in several ways. Fibers are shorter, wood densities are lower, and microfibril angle and spiral grain are commonly greater in rings near the pith than in rings near the bark in mature trees. Although such differences between juvenile core and mature wood in diffuse-porous hardwoods such as *Populus* are less than differences in conifers and ring-porous hardwoods (Zobel and Sprague 1998), they can affect feedstock quality and uniformity and thereby influence processing operations and product quality. Mature wood of *Populus* has been reported to have wood density values of 0.35 to 0.43 g cm^{-3} and mean fiber lengths from 1.3 to 1.4 mm (cf. various tables in Forest Products Laboratory 1999; Haygreen and Bowyer 1996; Panshin and deZeeuw 1980; Zobel and Sprague 1998).

Information on basic wood properties of *Populus* grown in short-rotation plantations and on opportunities to alter such properties through silvicultural practices and management decisions is limited. Previous research demonstrated that fiber length in species or clones increases with age or distance from the pith (Yanchuk et al. 1984; Bendtsen and Senft 1986; Koubaa et al. 1998). Within a ring at any common age, fiber length seems little affected by growth rate (Bendtsen and Senft 1986; DeBell et al. 1998) though Koubaa et al. (1998) did find a slight negative correlation between fiber length and growth rate at age 6 and 8 in samples collected at 1.5 m but not at lower or greater tree heights. Reports on the relation of wood density or specific gravity to age (or distance from the pith) and growth rate are inconsistent. Some workers have found that density increases with age or distance from pith (Boyce and Kaiser 1961; Curro 1960; Farmer and Wilcox 1966), whereas others suggest a decrease or a decrease followed by an increase (Einspahr et al. 1972; Yanchuk et al. 1983). Reports on the relation of wood density to growth rate are even less conclusive. Peszlen (1998) found no effect of growth on specific gravity or mechanical wood properties of three *Populus* clones growing on two sites in Hungary; Beaudoin et al. (1992) found a slight negative correlation between weighted wood density and stem diameter at breast height but did not examine such relationships within rings of the same age. Moreover, recent studies by Peszlen (1998) and Hernández et al. (1998) showed that mechanical properties of young *Populus* stems are only moderately or weakly correlated with wood density; this is in contrast to the generally strong relationship that exists in mature wood of both conifer and hardwood species. Some of the variance in findings regarding wood density may be associated with differences in species and growing conditions as well as objectives and methods of the researchers. There is a clear need for additional basic information applicable to the clones and regimes now used or under consideration in short-rotation poplar plantings.

Because of increased interest in longer rotations of *Populus* plantations and associated solid wood products, incentives may exist for more extensive pruning to produce additional clear wood. Studies of pruning in young *Populus* stems are few: Keller (1979) showed that pruning of clone I-214 at age 7 did not affect height growth and reduced stem taper; circumference growth, however, was decreased in the more severe treatments (i.e., where pruning was done to 60% or more of the tree height); Polge (1985) showed that pruning of the same clone had no influence on tension wood but increased percentage of heartwood in the more severely pruned trees.

Some evidence suggests for conifers that pruning of branches may accelerate the transition from juvenile wood to mature wood (Polge 1969; Megraw 1985, 1986; Jozsa 1995). Very little work has been done on ef-

TABLE 1. *Characteristics of 9-year-old* Populus *trees analyzed for wood properties.*

Clone	Treatment	n	Height (m)		Diameter (cm)[1]	
			Mean	Range	Mean	Range
Capitol Lake	Unpruned	4	15.2	12.8–16.6	8.7	6.5–11.4
	Pruned	4	14.3	11.4–15.6	7.4	5.6–9.0
11-11	Unpruned	3	17.9	17.4–18.8	9.5	8.9–10.6
	Pruned	5	17.5	16.1–19.1	9.1	8.0–9.6
47-174	Unpruned	10	18.9	14.7–21.2	10.2	6.3–14.7
	Pruned	9	18.0	14.2–21.1	9.4	7.2–12.5

[1] Diameter inside bark calculated by doubling the sum of radial increments from pith to bark at 1.5 m above ground.

fects of pruning on wood anatomy of hardwoods and on *Populus* in particular. Pruning is reported to have no effect on wood density of *Eucalyptus,* even though timing and rate of wood formation are altered (Schonau 1973). Because of the rapid growth rate of poplar, young stems offer an opportunity to see if such accelerated maturation might also occur in this diffuse-porous hardwood species. If it does, managers might achieve unexpected benefits if they prune lower branches in young plantations to make cuttings for additional plantings. Trees remaining after plantations are thinned for pulpwood are commonly destined for solid or laminated wood products where mature characteristics may be more important and valuable than in wood used for pulp or bioenergy.

This paper provides information on the characteristics of stem wood produced in short-rotation *Populus* plantings and how they vary by clone, age, and growth rate. The influence of pruning on the transition from juvenile to mature wood is also examined. Implications of this information in decisions about cultural practices and rotation length are discussed.

MATERIALS AND METHODS

Wood samples

Cross-sectional disks were collected from 9-year-old *Populus* stems grown in a silvicultural research plantation in western Washington. Details on establishment and culture of the entire plantation are given in DeBell and Harrington (1997). In brief, unrooted cuttings of several clones were planted in a thoroughly disked, weed-free area; lime and a mixture of nitrogen, phosphorus, and potassium fertilizer were applied to the soil prior to planting and additional nitrogen was applied after the second growing season; plots were irrigated by a drip system and maintained in a nearly weed-free condition. Work reported in this paper is based on sampling dominant and codominant trees of three clones grown in monoclonal plots planted at 1.5 m by 1.5 m. Two of the clones, 11-11 and 47-174, were hybrids of *P. trichocarpa* Torr. & Gray × *P. deltoides* Bartr. ex Marsh, developed in the University of Washington–Washington State University poplar breeding program (Heilman and Stettler 1985), and had been planted extensively in commercial plantations in western Oregon and Washington. The third clone, Capitol Lake (CL), was a native clone of *P. trichocarpa* collected near Olympia, Washington, and had been planted in research trials only. Characteristics of these trees at time of sampling are shown in Table 1. The two hybrid clones averaged 18 m tall and about 10 cm in diameter (*inside* bark). The native clone (CL) was about 3 m shorter and 1.5 cm smaller in diameter (*inside* bark). Thus, the trees were approaching the size (i.e., 15-cm diameter *outside* bark) generally sought in short-rotation plantations.

We initially sampled 18 to 24 trees of each clone. Half of the trees of each clone were unpruned and half had been pruned to a height of 1.8 m at age 1.5 years (July of the 2nd growing season). Prior to pruning, trees averaged 3.4 m tall and there were no size differences among clones or between trees assigned individually to the pruned and control treatments. Disks were collected at two stem heights—1.5 m (i.e., 0.3 m below the pruned height) and at 3.0 m. The disks were placed in plastic bags and transported to the Oregon State University's Forest Products Laboratory at Corvallis, Oregon. A pith-to-bark strip about 1 cm wide and 1.5 cm thick was sawed along an average radius from each disk; this strip was subsequently separated into two strips: one strip (about 1 cm wide and 1 cm thick) was used to measure fiber length; the remaining portion was reduced to a strip 7 mm wide and 1.5 mm thick that was used to assess wood density and ring width.

Many of the samples were excluded from subsequent measurements of wood properties because they had been damaged by holes and tunnels created by the poplar-and-willow borer (*Chryptorhyncus lapathi*) while the trees were alive. Although this created some imbalance in the design and analyses, the number of intact samples was sufficient to evaluate differences among clones, determine patterns of change in wood properties with age, and test effects of the pruning treatment on clone 47-174.

Wood density and ring width measurement

The 7-mm by 1.5-mm samples were X-rayed using a system developed at Oregon State University's Forest Products Laboratory to determine relative wood density within and between growth rings. The X-ray system was run with a step size of 100 μm, thus providing the greatest resolution possible with this system.

The relative density values of the X-rayed samples were converted to actual oven-dry density by calculating bulk density of each sample based on oven-dry weight and oven-dry volume measurements (the latter determined by immersion in mercury). These data were used to set a baseline density for use in Dendro-Scan (Varem-Sanders and Campbell 1996), a software package that automates summary and analysis of the X-ray data and affords manual manipulation of some variables, such as location of ring boundaries. Because the poplar sections did not show strong differences in X-ray pattern at ring boundaries, we measured growth rings based on visual appearances coupled with knowledge of number of rings present on the section and past diameter measurements. These ring width data were used to set ring boundaries on the X-ray data, and thereby determine average wood density for individual rings. Given the difficulty of determining the annual boundaries with X-ray data alone, we did not attempt to distinguish between earlywood and latewood within each ring.

Fiber length measurements

Growth rings were identified visually on the 1-cm wide by 1-cm thick pith-to-bark strips designated for fiber length measurement, and then separated with a razor blade. Each ring was placed into an individual test tube and submerged by addition of a hydrogen peroxide solution (20% by volume). The test tubes were then placed in a drying oven at 63°C to hasten the chemical maceration process. After several hours, the samples were rinsed three times with de-ionized water and stained with an aqueous solution of safranin-o to improve contrast for microscopic viewing. The stained macerated material from each growth ring was placed on three microscopic slides and mounted in glycerine.

Fiber lengths were measured with a Macintosh-based image analysis system; this system employed a black and white, charge coupled device camera, a dissecting microscope with 0–6.3 magnification, and NIH Image 1.60 software (Rasband 1996). The system was calibrated at the beginning of each measurement session. With a slide's image on the computer monitor, we selected unbroken libriform fibers and used a mouse to locate the two ends of each fiber; the software calculated fiber length. A minimum of 36 fibers were measured on each slide, resulting in at least 108 fibers measured for each growth ring. From these data, an average fiber length was calculated for each ring.

Data analysis

Basic measurements of ring width, wood density, and fiber length were used to determine the mean, maximum, and minimum of these traits for rings of the same age and for various combinations of clone, sample height, and pruning treatment. Values were plotted over ring age to determine changes in traits over time. In addition, we calculated weighted values for wood density and fiber length based on the cross-sectional area of each ring; this value is equivalent to mean values for the disk and approximates relative mean tree values.

Differences among clones and pruning treatments were evaluated by analyses of variance, followed by separation of means by least significant difference. Although the two stem height samples were derived from many of the same trees, some of the samples for each height came from trees only represented at one height; all analyses were therefore done independently for each stem height rather than considering each height as a subplot within an individual tree.

Effects of the pruning treatment were evaluated only for clone 47-174 because it was the only clone with an adequate number of usable (undamaged by the poplar-and-willow borer) samples from pruned and unpruned trees. Fortuitously, the branching habit of clone 47-174 made it the most likely clone to be affected by branch removal; i.e., typically it produces very few sylleptic branches, and after pruning it had fewer remaining branches to compensate for removal of the lower branches. We assessed the influence of pruning the lower crown on transition from juvenile to mature wood by comparing values for fiber length and wood density over the entire cross-sectional disk and for age 2 through 4 years—the period most likely to be affected by the pruning treatment; beyond age 4, natural pruning had lifted the crown above the height of the pruning treatment, and thus would have masked any treatment-related differences in live crown characteristics.

Following the above analysis in which effects of pruning were found to be insignificant (discussed below) and exploratory analyses that demonstrated clone by treatment interactions to be negligible, we combined samples from pruned and unpruned trees for analyses of clonal differences in ring width and wood properties and for examining correlations among ring width, wood density, and fiber length *within clone* for each sample height. Combining the treatments increased the sample size for the additional analysis, which should make them more sensitive. Correlations among variables were calculated for the entire cross-section and within rings of the same age. Differences among clones or pruning treatments and correlations among growth and wood property traits were considered significant if $P \leq 0.10$.

RESULTS AND DISCUSSION

Influence of pruning on ring width and wood anatomy

Averaged over the disk cross-section, mean ring width, wood density, and fiber length at either stem height of clone 47-174 were not affected significantly by pruning (Table 2). Because pruning effects on current wood anatomy might last only as long as treatment-related differences in crown length were maintained and subsequently diminish or disappear, we also analyzed effects on rings laid down during the 2nd through the 4th growing seasons. Even for this presumably more sensitive time period, pruning had no significant effect on ring width or the two wood properties (Table 2). Mean ring width for clone 47-174 was about 10% lower in pruned trees than in unpruned trees but the difference was nonsignificant. Two-year growth data from a larger sample of trees in the same study area (data not shown) also showed no effect of pruning ($P = 0.70$, $n = 88$) so it appears that this level of pruning has no detrimental effects on tree

TABLE 2. *Mean ring width, wood density, and fiber length for unpruned (control) and pruned trees of Clone 47-174 at 1.5 m and 3.0 m height above ground for the entire disk and for rings produced at 2–4 years. Standard deviations shown in parentheses next to each mean.*

Treatment	Ring width	Wood density	Fiber length
	Entire disk		
1.5 m height			
Unpruned	0.57a[1] (0.04)	0.36a (0.01)	0.85a (0.02)
Pruned	0.52a (0.04)	0.36a (0.01)	0.87a (0.02)
3.0 m height			
Unpruned	0.54a (0.04)	0.35a (0.02)	0.82a (0.04)
Pruned	0.53a (0.04)	0.36a (0.02)	0.83a (0.04)
	Mean of rings produced at 2–4 years		
1.5 m height			
Unpruned	0.62a[1] (0.05)	0.35a (0.01)	0.67a (0.02)
Pruned	0.55a (0.05)	0.35a (0.01)	0.68a (0.02)
3.0 m height			
Unpruned	0.60a (0.05)	0.35a (0.02)	0.70a (0.04)
Pruned	0.54a (0.04)	0.36a (0.02)	0.69a (0.04)

[1] Means followed by the same letter within the same column and sample height do not differ significantly (i.e., $P > 0.10$).

growth. For most short-rotation regimes, it therefore appears unlikely that one early pruning would have a significant effect on the transition from juvenile to mature properties. The possibility remains that more severe and/or repeated pruning (consecutively higher lifts) to maintain differences between pruned and unpruned trees in crown length over a longer time period might lead to differences in growth and wood anatomy. Keller (1979) demonstrated reductions in radial (measured by circumference) growth after severe pruning of *Populus* clone I-214 at age 7 years.

General relationship of ring width, fiber length, and wood density to clone and stem height

Differences existed among clones in ring width, wood density, and fiber length (Table 3). For samples taken at 1.5 m above ground, ring width was significantly greater for clone 47-174 than for clone CL; wood density of clone CL was significantly greater than for the two hybrid clones, and mean fiber length differed significantly among all three clones with fibers of clone 11-11 averaging about 7% longer than clone 47-174 and 14% longer than clone CL. In general, mean clonal values in our study for wood density were slightly higher and for fiber length somewhat shorter than mean values reported for young tree sections of other *Populus* clones (Beaudoin et al. 1992; Koubaa et al. 1998; Peszlen 1998), and they were rather similar to values reported by Semen et al. (2001) for wood chips of several hybrids of aspen (*Populus alba*).

General rankings of clones with respect to growth and wood properties in the 3.0-m samples (Table 3) tended to be similar to rankings for the 1.5-m samples, but, with the exception of ring width, the differences were not as great and were not statistically significant. The

TABLE 3. *Means and ranges for ring width, wood density, and fiber length averaged over entire disk as affected by clone at two stem heights: 1.5 m and 3.0 m.*

Clone	Ring width (cm)			Wood density[1] (g cm^{-3})			Fiber length[1] (mm)		
	Mean	Range	SD[2]	Mean	Range	SD	Mean	Range	SD
				1.5 m height					
Capitol Lake	0.45a[3]	0.31–0.63	0.04	0.41a	0.32–0.46	0.03	0.81a	0.37–0.90	0.06
11-11	0.51ab	0.45–0.59	0.04	0.36b	0.29–0.40	0.03	0.92c	0.81–0.97	0.06
47-174	0.55b	0.35–0.82	0.02	0.36b	0.31–0.43	0.02	0.86b	0.77–0.96	0.04
				3.0 m height					
Capitol Lake	0.42a	0.34–0.55	0.04	0.36a	0.31–0.40	0.02	0.85a	0.76–0.92	0.04
11-11	0.53b	0.44–0.67	0.03	0.36a	0.29–0.45	0.02	0.87a	0.78–0.97	0.03
47-174	0.54b	0.38–0.79	0.02	0.36a	0.29–0.47	0.01	0.83a	0.54–0.96	0.02

[1] Weighted by cross-sectional area of each ring.
[2] SD = Standard deviation.
[3] Means followed by the same letter within the same column and sample height do not differ significantly (i.e., $P > 0.10$).

trends in wood properties associated with stem height were similar to expectations given that the 3.0-m sections were one year younger than the 1.5-m sections; mean wood density was somewhat lower, and fiber length was generally shorter at 3.0 m than at 1.5 m. Other workers have identified significant differences among clones in fiber length (Koubaa et al. 1998) and wood density (Beaudoin et al. 1992; Hernández et al. 1998); moreover, Beaudoin et al. (1992) found that wood density was lower in samples collected at 3.0 m height than at 1.5 m and was able to attribute such differences to radial (age) variation in wood density.

Patterns of change in ring width, fiber length and wood density with tree age

General trends in growth and wood properties in relation to age were similar for the 1.5-m and 3.0-m samples. The trends are therefore illustrated in Fig. 1 by clone and for the mean of all samples collected at 1.5 m (*Note:* The two sample heights were not combined for these illustrations because rings in the same position from the pith at the two heights were produced in different years and under different weather conditions.)

Ring width averaged about 0.5 cm but varied substantially by clone and by year (Fig. la). Except for years 2, 3, and 4, the Capitol Lake clone grew much less than the two hybrid clones. The pattern with age, however, was rather similar among clones, notwithstanding exceptions for clone 11-11 in years 6 and 9. But in general (see mean line), ring width increased substantially from age 1 to age 2; was then relatively uniform through age 4; decreased markedly in year 5; and maintained a generally low level in years 6 and 7. In year 8, growth improved substantially in all clones, but then decreased again in year 9. Because of the subsequent improved growth, we suspect that the poor growth in years 5, 6, and 7 was related to environment (most likely, decreased irrigation as patterns in growing-season rainfall do not appear related to growth trends); the decrease in year 9, however, was probably related to both soil moisture reduction and increased inter-tree competition for all resources that developed as trees grew larger, with the competition precluding subsequent growth (ring width) increases.

Wood density averaged 0.37 g cm^{-3} during the first year (Fig. 1b). Though variable from year to year, it was fairly similar among clones for the first three years. Density then decreased for the two hybrid clones, and remained low at ages 4 and 5. Low points ranged from about 0.33 g cm^{-3} in clone 11-11 and 0.32 g cm^{-3} in clone 47-174 to 0.35 g cm^{-3} in clone CL. On average, density began to increase after year 5 and continued to increase each year up to and including the year samples were collected. At age 7, wood density averaged about 0.36 g cm^{-3} among all samples and thus had nearly returned to the initial density of first-year growth. Wood density continued to increase in years 8 and 9, and differences between the native and the hybrid clones became much larger; at ring (or year) 9, wood of clone CL had a density of 0.50 g cm^{-3} whereas wood of clones 11-11 and 47-174 averaged only 0.40 g cm^{-3}. Because both hybrid clones exhibited the same general pattern, and it has been reported in at least some clones by others (e.g., Matyas and Peszlen 1997; Peszlen 1998), we suspect that it may be the norm for many young *Populus* hybrids. The inconsistency noted in some earlier reports could be due in part to sampling a more limited age range (i.e., if fewer than 7 years were examined as in Blankenhorn et al. 1988, some clones might still be in a decreasing phase or on a low plateau) or by sampling fewer more widely separated rings. For example, if 50-year-old trees were sampled only at rings 10 years apart, it would appear that density increased from pith to bark. Moreover, the general pattern exhibited by native clone CL could be characterized as a low, though variable, plateau in early years followed by a steady increase; thus, there may be clonal differences in such patterns. The pattern of decrease, a low plateau, followed by an increase (with the duration of each phase varying

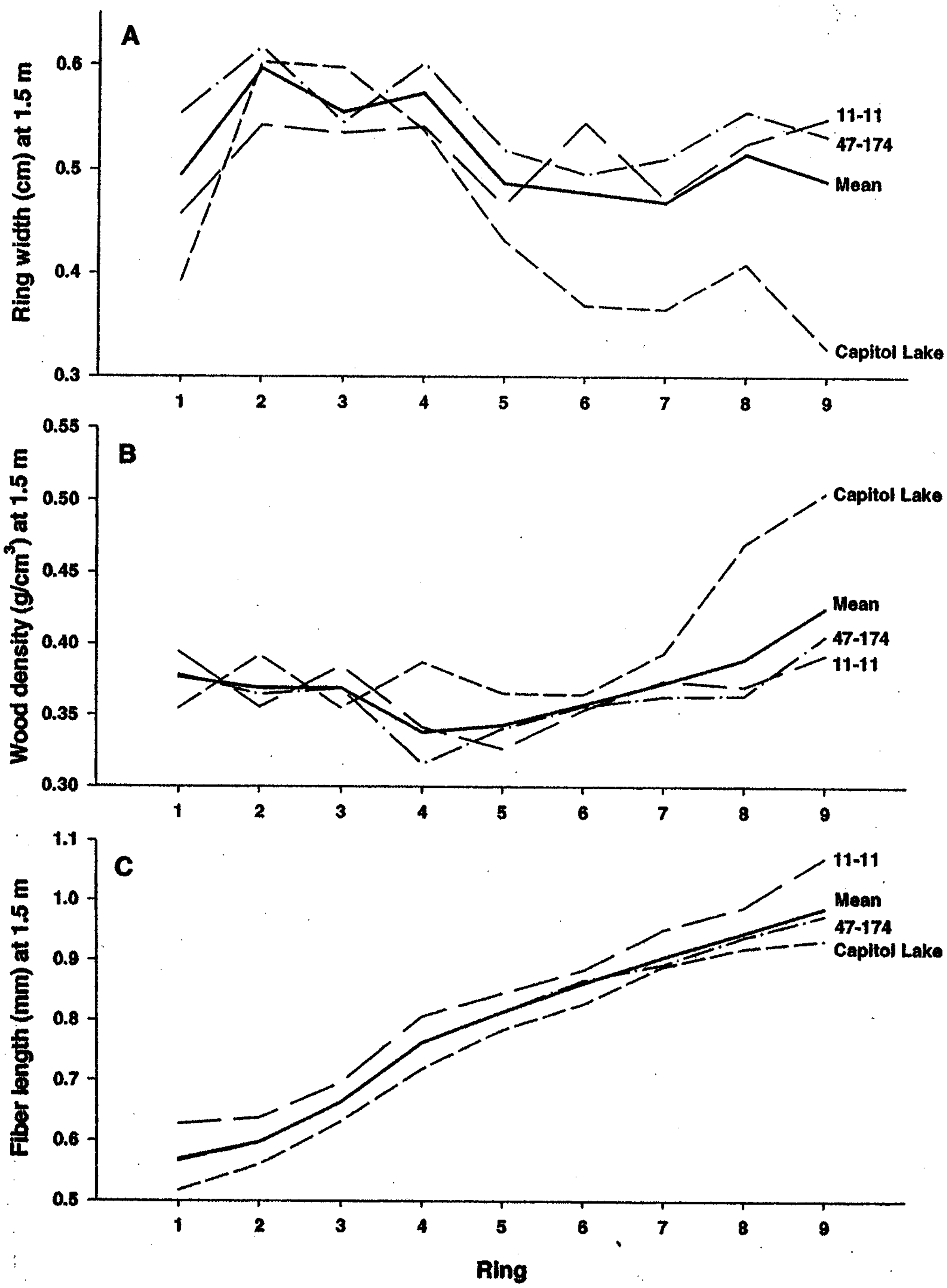

FIG. 1. Growth and wood properties as related to clone and cambial age for samples taken at 1.5 m above ground: (a) ring width, (b) wood density, and (c) fiber length.

among clones), however, will complicate attempts to select for optimal density characteristics—uniformity and average value—of the wood feedstocks produced in short rotation regimes. The lack of significance among clones in wood density or fiber length at 3.0 m, moreover, probably indicates that the clonal differences observed at 1.5 m would overestimate or exaggerate clonal differences for whole trees. Thus, efficient selection of clones for wood properties may require sampling at more than one height.

Trends in fiber length were much more uniform and consistent (Fig. 1c) than the trends in ring width and wood density. At ring one, mean fiber lengths of the three clones ranged from 0.52 mm to 0.63 mm. Fiber length increased each year through age 9 with the largest increases occurring between the 2nd and the 4th or 5th growing seasons. The steady increase with age resulted in fiber lengths in the 9th ring averaging nearly 1.0 mm. In the previous section, it was noted that mean cross-sectional fiber length (i.e., over all ages and weighted by ring basal areas) differed significantly by clone. It also appears that such clonal differences were established at ring 1 and maintained through ring 9; thus, clone 11-11 had the longest mean fiber length (0.63 mm) at ring 1 and this increased to 1.07 mm at age 9, whereas, clone CL had the shortest fibers at age 1 (0.52 mm) and at age 9 (0.93 mm). Such consistent ranking in fiber length over time occurred despite sometimes considerable yearly shifts among clones in both growth (ring width) and wood density, and is promising for organizations interested in selecting or breeding trees for specific fiber lengths. The pattern with age and the range of values observed in the present study are similar to those found by DeBell et al. (1998) and Koubaa et al. (1998) in that fiber length increased consistently during the first 5 or 6 years. Koubaa et al. (1998), however, found that fiber lengths continued to increase albeit at a slower rate through age 8 whereas DeBell et al. (1998) found that fiber lengths were essentially the same at age 7 (the age when that study ended) as at age 6.

It is also noteworthy that the sharp decreases observed in growth rate for rings produced during the 5th growing season (and believed to be associated with inadequate soil moisture) did not appear to be reflected in wood properties in any consistent way.

Correlations among growth (ring width), fiber length, and wood density

We examined correlations of growth rate (ring width and cross-sectional area increase) to wood density and fiber length and correlations between the wood properties within each sample height of each clone for: (1) the whole disk with ring values weighted by ring cross-sectional area, and (2) each ring. For the disk average (three clones × two sample heights = 6 cells), there was one positive correlation between ring width and weighted fiber length (clone 47-174, $r = 0.46$, $P = 0.06$, with 19 observations), but no significant correlations between ring width and wood density, or between wood density and fiber length. Thus, over all growing seasons, there was essentially no influence of growth rate on wood density; little, if any, effect on fiber length; and no relationship between the two wood properties. Results indicating a slightly negative effect or no effect of weighted growth rate on weighted wood density have been reported by Peszlen (1998) and Beaudoin et al. (1992); and a positive relationship between tree diameter and weighted fiber length was documented by DeBell et al. (1998).

We also examined relationships *within rings of the same cambial age* because age has such a major influence on wood properties, particularly in such young trees. For related reasons, we restricted the correlation analyses to include only measurements for the same sample height; that is, rings of the same age from pith would have been produced in different years with different weather regimes at each of the two heights. We also looked within specific clones because the analyses of variance had revealed significant differences among clones. This strategy provided opportunities to examine correlations in 51 different subsets—9 rings at 1.5 m height and 8 rings at 3.0 m height yielded 17 ring-height combinations in each of three clones. Of these, there were only seven significant correlations between ring width and wood density, five of which were negative; eight correlations between ring width and fiber length, four of which were negative; and two correlations between wood density and fiber length, both negative. Earlier studies of relationships between growth rate and fiber length within individual rings showed either no significant relationship through age 7 (DeBell et al. 1998) or a slightly negative relationship at ages 6 and 8 (Koubaa et al. 1998). These results suggest two generalities: (1) growth rate and wood density or fiber length within rings of the same age *in the same clone* are not strongly correlated in any consistent manner, and (2) correlations between wood density and fiber length are negligible.

CONCLUSIONS

Although based only on three clones growing at one location, relationships observed in this study suggest that growth of short-rotation plantations of *Populus* can be increased by silvicultural practices and genetic selection with little likelihood of corresponding reductions in either fiber length or wood density. Similarly, if *Populus* growers wish to select clones for greater wood density or longer fibers, they can do so without decreasing the other property. Selecting clones for wood density or fiber length may need to be based on sampling at more than one height, however.

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