United States
Department of
Agriculture

Forest Service

Forest
Products
Laboratory

General
Technical
Report

FPL–GTR–129

Formation and Properties of Juvenile Wood in Southern Pines

A Synopsis

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Abstract

To satisfy the increasing demand for forest products, much of the future timber supply will be from improved trees grown on managed plantations. This fast-grown resource will tend to be harvested in short age rotations and will contain higher proportions of juvenile wood than that of current harvests. In anticipation of this resource, definitive information is needed on the influence of juvenile wood on lumber properties so that grading rules and the associated allowable design stresses can be modified as needed. This document reports the results of an extensive review of the literature on juvenile wood in southern pines. This report defines and discusses the extent, occurrence, and characteristics of juvenile wood. It reviews the effects that environment and silviculture have on the amount of juvenile wood produced. Finally, the impacts that juvenile wood has on mechanical properties were quantified. The results of this quantification are significant to all producers of fast-grown plantations. Research has clearly shown that juvenile wood will have a detrimental impact on allowable design stresses for visually graded lumber. It is critical that methods are developed to more carefully manage fast-grown plantation wood for its most efficient use. This review should serve as an overall collection of knowledge pertaining to juvenile wood research in southern pines and should help in the decision-making efforts to improve seedling selection techniques and silvicultural practices to maximize the potential for fast-grown plantations of southern pines.

Keywords: juvenile wood, southern pines

September 2001

Larson, Philip R.; Kretschmann, David E.; Clark, Alexander III; Isebrands, J.G. 2001. Formation and properties of juvenile wood in southern pines: a synopsis. Gen. Tech. Rep. FPL-GTR-129. Madison, WI: U.S. Department of Agriculture, Forest Service, Forest Products Laboratory. 42 p.

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The Forest Products Laboratory is maintained in cooperation with the University of Wisconsin.

Acknowledgments

We thank Union Camp Corporation, Savannah, Georgia, for financial assistance to conduct this work.

Preface

This paper is the last scientific writing of Dr. Philip R. Larson's distinguished career as a pioneering scientist and project leader at the USDA Forest Service, North Central Forest Experiment Station, Rhinelander, Wisconsin. Larson grew up in North Branch, Minnesota, and after a 4-year tour of duty as a Navy pilot in the Pacific theater in World War II, he began his career at the University of Minnesota, Department of Forestry. He received his B.S. and M.S. degrees in 1949 and 1952 and took his first professional position with the Southeastern Forest Experiment Station at Lake City, Florida. While in Florida, he conducted research on naval stores production in southern pines before returning to graduate school for a Ph.D. at Yale University, where he studied wood formation in southern pines. He graduated in 1957 and took a position at the North Central Forest Experiment Station in Rhinelander, where his first duties included designing and coordinating the building of the Northern Institute of Forest Genetics completed in 1960. In 1962, he was designated the USDA Forest Service's first pioneering scientist, permitting him freedom of research. He became the world's leading authority on the physiology of wood formation and the Forest Service's first super grade scientist.

Since his retirement in 1986, Larson continued scientific writing by completing a monumental book in which he synthesized the historical aspects of the concept of *The Vascular Cambium: Development and Structure*. It was published in 1994 by Springer–Verlag, Berlin.

His final scientific work was a result of a Cooperative Research and Development Agreement (CRADA) between the Forest Products Laboratory in Madison, Wisconsin, and Union Camp Corporation, Savannah, Georgia. Union Camp managers asked Larson and the Forest Service coauthors to synopsize the current knowledge on juvenile wood formation in southern pines. The CRADA final report was completed in 1998. This document represents our edited version of that report.

Larson and his wife Yvonne are retired and reside in Surprise, Arizona.

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Introduction

To address the problem of juvenile wood quality, one must first address the questions of how wood is formed and why a tree produces juvenile wood. All wood is produced by the cambium, a zone of dividing cells situated between the wood and the inner bark. Cell division by the cambium and differentiation of the wood cells produced by the cambium are, in turn, regulated by physiological processes originating in the foliar organs of the tree crown. Consequently, changes in the characteristics we recognize as wood quality are indirectly controlled by the size, distribution, and efficiency of the foliar organs. This process, which tree physiologists refer to as crown control, is the key to understanding the variability in wood quality.

In pine species, such as loblolly and other southern pines, the beginning of cambial activity in the spring coincides with bursting of the winter buds and new shoot extension. The breaking of winter dormancy is temperature dependent, although in very moderate climates the winter buds might resume growth at any time of year if temperature conditions are favorable. Once activated, the cambium produces springwood (earlywood) during the period of shoot extension and new needle elongation. The transition to summerwood (latewood) approximately coincides with the cessation of terminal shoot extension and reduction of soil moisture. Summerwood formation begins at the base of the tree and proceeds upward in the new growth ring. However, in rapidly growing trees, the transition and its upward progression can be delayed because of vigorous needle growth. Moreover, in multiple flushing species, such as loblolly pine, each new flush of growth produces new springwood, which often occurs before summerwood has been initiated. Therefore, the transition from springwood to summerwood will vary not only with environmental conditions, particularly soil moisture, but also at different height levels within the tree stem.

Springwood and summerwood cells (tracheids in pines) are easily identified in mature wood, but in juvenile wood, the intervening transition zone is often extremely diffuse. The transition zone in juvenile wood consists of cells with large radial diameters typical of springwood but with secondary walls of varying thickness approaching those of summerwood. Radial cell diameter and secondary wall thickness vary independently, and they are controlled by different physiological processes within the crown. Cambial cell division and radial cell expansion respond to hormonal signals emanating primarily from the new shoots and needles of the uppermost crown. Secondary wall thickness, on the other hand, is dependent on the photosynthetic production of the foliage on the older branches of the mid to lower crown.

The foregoing generalizations are obviously subject to numerous interactions too detailed to dwell on here. We do have good knowledge as to how the foliar organs control wood formation on the stem and, if the stand history is known, we can explain with a high degree of confidence how wood quality was affected by past growth conditions. Unfortunately, however, because of the complexity of interacting factors, our confidence level for predicting either wood quality values or changes in these values is greatly diminished.

In the following sections, we define the most important wood quality characteristics and describe how they are affected by external growth conditions. We also explain, to the best of our knowledge, the interacting effect of these growth conditions on tree crown development and wood formation. Emphasis will be placed on loblolly pine with occasional references to the other southern pines and radiata pine.

The objectives of this report are to

1. briefly describe how a tree grows and, in so doing, clarify the relationship between development of the foliage organs in the tree crown and the formation and quality of wood produced in the stem (emphasis will be on juvenile wood characteristics),
2. demonstrate how external growth conditions, both naturally occurring and silviculturally imposed, influence the aforementioned relationship,
3. relate wood quality characteristics of juvenile wood to published values of mechanical strength,
4. suggest what wood quality changes might be anticipated by various silvicultural and management options, based on available knowledge, and
5. suggest what wood quality changes might be anticipated by genetic improvement, based on available knowledge.

Crown–Stem Relationship

A young tree with living branches extending almost to ground level is essentially all crown. Because of the strong regulatory influence of the crown, springwood-type cells are produced throughout most of the growing season. In some trees, the innermost growth rings consist exclusively of springwood-type cells. Springwood cells are produced during the period of terminal shoot extension, and the transition to summerwood production approximately coincides with its cessation. However, in the lower stems of young trees and the upper crowns of older trees, springwood cell production continues while the newly formed needles are elongating.

The springwood–summerwood transition is a complex growth phenomenon. Springwood cells are thin-walled and large in radial diameter with large lumens, whereas summerwood cells are thick-walled and narrow in radial diameter with narrow lumens. Although these changes in cell dimensions occur concomitantly during the transition from springwood to summerwood, radial cell diameter and wall thickness are regulated by entirely different physiological processes highly influenced by environmental factors such as soil moisture. When active shoot extension is underway during high soil moisture, a growth hormone is produced that promotes radial cell expansion characteristic of springwood. When soil moisture is reduced and shoot extension ceases, hormone production diminishes and the narrow-diameter cells characteristic of summerwood begin to form. Cell wall thickening, on the other hand, is regulated by photosynthetic processes occurring in the foliage organs of the crown. In the early part of the season, the photosynthates produced by the older needles are predominantly used in growth of the newly expanding shoot and elongating needles. Thus, relatively little photosynthate is available for wall formation of the rapidly enlarging springwood cells. Later in the season, the photosynthates produced by both the newly matured needles and the older needles become available for wood formation. It is at this time that wall thickening typical of summerwood occurs (Larson 1964, Gordon and Larson 1970).

Because radial cell expansion and cell wall thickening are regulated by different physiological processes, they can and do vary independently. It is this independence that is responsible for the “transition tracheid” characteristic of the growth rings in juvenile wood. Transition tracheids are neither springwood nor summerwood. They consist of large-diameter cells typical of springwood with walls of varying thickness typical of summerwood. Transition tracheids occur in young, vigorously growing trees with full crowns. The vigorous growth of these trees and the short, clear bole lengths permit large-diameter cell production to continue until late in the season while excess photosynthates are simultaneously shunted to cell wall formation. An extreme example of this was observed by Schmidt and Smith (1961) in slash pine growing in southern Queensland, Australia, where growing seasons are exceptionally long. Because wood formation continued almost year round, true summerwood formed for a very short period when terminal growth was dormant. Springwood formed during the remainder of the year, but the cells were essentially all transition tracheids due to the continuous, high level of photosynthetic activity.

As a tree grows in height during the sapling and pole stages, its crown recedes upward and the length of clear bole increases. The increase in distance from the active terminal shoot contributes to more readily recognizable summerwood cells as well as a wider summerwood zone in each successive growth ring of the lower stem. However, the cambium within the crown, which remains in close proximity to the active shoot, continues to produce growth rings with wide zones of springwood and transition wood. With increasing tree age and growth in height, the lower stem becomes farther removed from the most active foliar organs of the crown. Consequently, springwood and summerwood cells become more sharply differentiated and the transition zone[1]

[1]The term transition tracheids refers to the intermediate type cells between true springwood and summerwood. The term transition zone refers to the actual cell boundary between springwood and summerwood. The term transition wood refers to the annual rings produced after the juvenile wood or crown-formed wood but before the rings have the properties of mature wood.

more abrupt. This process of growth ring maturity, which begins at the stem base, progresses upward in the stem with each new increment of growth. However, crown-formed wood, which has characteristics similar to juvenile wood, continues to be produced within the upper crown. The concomitant upward progression of mature wood and the upward regression of juvenile wood result in a core of juvenile wood extending throughout the bole. Although juvenile wood produced by a young tree is not identical to the crown-formed wood produced by an older tree, they are sufficiently similar in characteristics to be considered identical.

The southern pines have inherently adapted to take advantage of the long growing seasons and abundant moisture of the regions in which they naturally occur. This favorable combination contributes not only to rapid juvenile growth but also to the many vagaries in wood formation and quality associated with such growth. Many pines, such as loblolly and slash, produce multiple flushes of growth during the season that are a response to available soil moisture. A succession of strong second or third flushes immediately following the first flush will produce a renewed surge of springwood that might extend to the stem base. In this case, springwood would follow springwood with no intervening summerwood. If, however, the second flush or a later flush is weak, it might extend only part way down the stem. In this case, the cambium responding to the renewed surge of growth would produce a partial growth sheath consisting of springwood at upper stem levels that grades imperceptibly to summerwood in the lower stem. Multiple growth flushes of varying intensity are responsible for the formation of false growth rings that frequently occur in juvenile wood. In older trees, false rings are commonly found in the upper stem but are generally absent at the stem base. As a contrary example, in extremely suppressed trees, even the first flush might be incapable of producing a springwood-forming stimulus sufficient to reach the stem base. In this case, in some parts of the lower stem, summerwood follows summerwood with no intervening springwood (Larson 1956, 1957). In severely suppressed trees, entire growth rings might be absent at the stem base but fully formed in the upper stem.

When one examines how the crown in its development influences wood formation, it becomes clear how changing growth conditions can affect this relationship. As we demonstrate in later sections of this report, stand conditions and silvicultural practices can markedly influence the quality of wood by altering the crown–stem relationship.

Juvenile Wood Defined

Juvenile wood is commonly defined as the zone of wood extending outward from the pith where wood characteristics undergo rapid and progressive changes in successively older growth rings. Older wood beyond the juvenile core has been referred to as mature wood, adult wood, and outer wood. Juvenile wood differs from mature wood in that it has a lower percentage of summerwood, lower specific gravity, shorter tracheids with larger fibril angles, and occasionally disproportionate amounts of compression wood, distorted grain patterns, and pitch deposits.

The term juvenile wood is an unfortunate misnomer. True juvenile wood is produced during the first 1 to 3 years of growth. Thereafter, similar but not identical wood is produced in the central core of wood at all height levels in the stem. This wood has been referred to more appropriately as core wood. It has also been referred to as crown-formed wood because it is produced either within the living crown or in proximity to physiological processes emanating from the living crown. The term juvenile wood will be used in this report as a synonym for core wood, pith-associated wood, and crown-formed wood.

As shown in subsequent sections, the extent of juvenile wood can only be defined by arbitrary criteria. Outward from the pith, identifiable wood characteristics undergo rapid and progressive changes with increasing growth ring age, but the rates of change are not the same within a single stem cross section nor within cross sections from different trees. For example, Bendtsen and Senft (1986) estimated the juvenile period for loblolly pine to be 12 years based on values for specific gravity, modulus of elasticity (MOE), modulus of rupture (MOR), and compressive strength of the wood. However, tracheid length continued to increase rapidly for 18 years, and fibril angle had not yet attained a constant value at 30 years.

Paul (1957, 1960) challenged the concept of juvenile wood. He argued that juvenile wood, or core wood, was not necessarily inherent to tree growth because wood characteristics of these centrally located growth rings were under silvicultural control. His argument was based on the fact that core wood did not contribute to either longitudinal shrinkage or distortion in the southern pines when the growth rings were narrow (1/8 to 1/10 in. (3.2 to 2.5 mm)). On the contrary, both structural defects were excessive when growth rings in the core wood were wide (>1/4 in. (6.4 mm)). Paul’s argument is tempting, and it is supported by numerous studies. However, as proven by so many other studies, slow growth does not eliminate juvenile wood but simply confines it to a smaller core. Both narrow- and wide-core wood rings retain their juvenile characteristics compared with narrow and wide mature rings, respectively.

Paul, however, did correctly interpret the effects of early stand competition on the reduction of springwood formation, hence the increase in summerwood percentage in the juvenile growth rings. Early stand competition reduces crown size and encourages rapid upward retreat of the live crown both of which restrict springwood formation. This silvicultural option is open to forest managers if they are willing to sacrifice volume production for the more favorable small diameter of core-wood growth rings.

Radial Extent and Occurrence

In the southern pines, radial extent of the juvenile wood zone is most commonly based on visual estimates of summerwood percentage, although specific gravity values are sometimes relied on (Hodge and Purnell 1993). As a rule of thumb, McAlister and Powers (1992) judged the transition to mature wood to be those growth rings that consistently attained 50% summerwood. However, in practice they found that 15-year-old loblolly pines growing in seed orchards with average diameter at breast height (DBH) of 10 to 16 in. (254 to 406.4 mm) had still not attained 50% summerwood values. Similar results were obtained by Ying and others (1994).

The transition to mature wood is gradual and therefore arbitrarily defined. In a study of loblolly pines, Zobel and others (1959) estimated the extent of the juvenile zone solely on visual appearance. The number of juvenile growth rings based on this method varied from tree to tree. In most trees, the juvenile zone appeared to consist of the first eight rings, but because of uncertainties, another two rings of transition wood were added to the estimates. Two to four rings of transition wood are now widely recognized as part of the juvenile core, and the ten innermost growth rings, including transition wood, have generally been accepted as the juvenile zone by most investigators of loblolly pine.

As noted in the definition, a juvenile core of wood is produced at all height levels in the stem. Zobel and others (1959) found that the juvenile core in nine 17-year-old loblolly pines was almost cylindrical. Core diameter decreased from 4.4 in. (111.8 mm) at DBH to 3.4 in. (86.4 mm) at the 45-ft (13.7-m) level. The juvenile core averaged 3.6 in. (91.4 mm) in diameter in a larger sample of 670 trees. The amount of juvenile wood in a loblolly pine tree on a volume basis decreased from 85% at age 15 to 55% at age 25 and then to 19% at age 40 (Zobel and others 1972). That is, the older and larger the tree, the lower the volume of juvenile wood even though the size of the juvenile core remains unchanged. Obviously, all these values will vary according to growing conditions of the trees, but they do provide working estimates. According to Franklin (1987), variations in the amount of taper of the juvenile core with height in the tree are insufficient to materially affect sawtimber values.

Despite the many factors that can and do influence the formation of juvenile wood, its radial extent appears to be fairly consistent and developmentally conservative. Szymanski and Tauer (1991) examined the age of transition from juvenile to mature wood in 36 loblolly pine seed sources planted in Arkansas. The seed sources originated from throughout the entire range of loblolly pine. Their analyses were based on wood specific gravity values of 2-year ring segments sampled outward from the pith. Juvenile wood extended to age 6 with a transition period of rapidly increasing specific gravity from ages 6 to 12 and mature wood beyond. The mean transition age averaged for all 36 seed sources was 12.61 years with negligible variation among seed sources. The generally recognized transition age of 10 years for loblolly pine therefore appears to be an acceptable average for most purposes.

Characteristics of Juvenile Wood

The wood of a southern pine tree consists of several kinds of anatomical elements, only one of which, the tracheid, will be of concern in this report. Pine tracheids, sometimes erroneously referred to as fibers, serve two primary functions—to transport water and nutrients from roots to crown and to strengthen tissue for support of the crown. The tracheids that perform these functions are structurally different. Springwood tracheids with their wide lumens and thin walls provide efficient transport pathways between the roots and the newly elongating shoot and needles. The later-formed summerwood tracheids with their narrow lumens and thick walls, on the other hand, provide strength to the new growth sheath and support for the expanding crown. The width of the growth ring, the relative proportions of springwood to summerwood, and the structure of the individual tracheids within the growth ring are regulated in various ways by the foliage organs of the crown and the vigor or health of these organs. Crown vigor, in turn, is entirely dependent on the tree’s growth environment (temperature, soil moisture, nutrients), age, and parentage. Therefore, to understand how wood is formed and how wood quality varies, one must first understand how trees grow.

Wood quality is an arbitrary term that applies to certain wood characteristics that can be quantified and analyzed and then used to evaluate a final wood product. In southern pines, the most meaningful wood characteristics are associated with the tracheids either individually or collectively. Although these wood characteristics are interrelated to varying degrees, they are discussed separately so that their relative importance to the final product can be more readily evaluated.

Growth Ring Width

Growth ring width, often reported as rings per inch of radial growth, is an excellent measure of overall tree health and growing conditions. Growth ring width by itself, however, provides no reliable evidence of wood quality. When sampled at breast height (4 ft (1.2 m)), ring width usually increases radially for an indefinite number of years before either leveling off or decreasing. This pattern reflects both growing conditions and proximity to the living crown. In vigorous trees free of competition, wide rings will be produced until the living crown advances upward beyond a critical level. In trees from closely spaced stands where competition is established early, ring widths are reduced concomitant with the degree of competition. Thus, the radial extent of the juvenile core cannot be estimated on the basis of ring width patterns. Trees freed of competition by early and frequent thinnings or whose growth is enhanced by fertilization and cultivation can maintain wide growth rings well beyond the generally accepted juvenile period. On the contrary, trees subject to competition early in life might exhibit narrow growth ring patterns suggestive of mature wood.

Irrespective of how trees are grown, ring width will eventually decline. As a tree increases in diameter, the wood volume of each annual increment increases. For example, a 1/2-in. (12.7-mm) ring at age 3 produces far less circumferential volume growth than a 1/2-in. (12.7-mm) ring at age 10. It is impossible for a tree to maintain extremely wide growth rings throughout, or much beyond, the juvenile period. However, Burton and Shoulders (1974a,b) grew loblolly pines to sawlog sizes in 27 years. They maintained growth at an average of 3.6 rings per inch (1.4 rings/cm) by frequent thinning.

Although ring widths eventually decline at breast height, they increase at higher levels in the stem. For example, if ring number ten is followed upward in the stem, its width will increase to a maximum and then gradually decrease to the stem top. As a tree ages and the live crown advances upward, the level in the stem where the maximum ring width occurs also advances upward. The point of maximum ring width is often considered to be the base of the live crown. However, this point is more typically found at a slightly higher level where more vigorous branches contribute to stem growth. The fact that maximum ring width shifts progressively upward accounts for changes in stem taper, and as shown in the section Stem Form and Taper, stem taper can be altered by changing growth conditions. Thus, growing conditions not only determine diameter growth at the stem base but also at higher levels in the stem, and consequently they affect yield and quality of the final product.

Obviously, growing conditions dramatically influence growth ring widths, and abrupt changes in these conditions can contribute to nonuniform radial growth rates. Nonuniform growth rates during the juvenile period, although not directly influencing wood quality, are nonetheless associated with other wood characteristics that do contribute to the quality of solid wood products.

Growth Ring Age

The accepted method of determining growth ring age in wood quality investigations is to count the number of growth rings outward from the pith at the level of sampling in the tree. Ring age as determined by this method is not to be confused with chronological age in which case the first growth ring next to the pith would be the oldest.

In most wood quality investigations, ring ages are counted on increment cores or wood disks taken at breast height in the tree. Such determinations do not always accurately reflect the true physiological age of the tree. Most loblolly and slash plantation-grown trees are 3 to 4 years old before a growth ring is discernible at breast height, and in naturally established stands, the true physiological age is often unknown. Moreover, ring counts near the pith are often difficult to identify in trees from stands of unknown age because of false and indistinct growth rings. For most purposes, the physiological age at breast height is perhaps of little or no significance but generally is reliable in planted stands. However, heritability estimates and evaluations of wood quality characteristics have been made on 2- to 3-year-old seedling and clonal material. The question must be raised as to whether such estimates are representative of the generally accepted values for juvenile wood.

Ring age within the juvenile core of wood is a function of annual height increments. At a given height, for example, the 18-ft (5.5-m) level, a tree averaging 3 ft (0.9 m) per year of annual height growth would show more annual growth rings in the juvenile core than one averaging only 2 ft (0.6 m) per year. Again, the physiological ages of the growth rings comprising the juvenile cores of the two trees at the 18-ft (5.5-m) level would be different. Wood quality characteristics within the juvenile core undergo appreciable changes with sampling height in the stem, and some of this change is undoubtedly due to physiological ages of the growth rings.

Growth Ring Uniformity

In wood quality investigations, uniformity refers to consistency in the value of a wood characteristic with increasing growth ring age on a stem cross section. That is, the wood characteristic either maintains a stable pattern or a gradually changing pattern with no abrupt deviations. With regard to juvenile wood, uniformity usually refers to width of the growth rings, the implication being that a uniform growth ring pattern signifies uniformity in the accompanying wood characteristics. Nonuniformity of juvenile wood, on the contrary, implies highly variable wood characteristics and undesirable structural properties. For example, this can result in “lathe chatter” (vibrational forces on a veneer lathe), which increases surface roughness and decreases gluability.

To achieve growth ring uniformity, it is necessary that a uniform growth rate be maintained not only during the juvenile period but also during the juvenile–mature transition and beyond. A uniform growth rate, however, does not mean equal ring widths in successively older growth rings. It is obviously impossible to maintain ring width equality as a tree increases both circumferentially and volumetrically. What uniformity does mean is that despite the inherent decrease in ring width with age, the rate of growth established in the juvenile core should be maintained to the extent possible. One of the main objectives of tree breeding is to increase wood uniformity (Zobel and others 1983).

Authors of a number of spacing studies have suggested how growth ring uniformity can be maintained throughout a rotation in the southern pines (Bassett 1969, Burton and Shoulders 1974a,b). In the case of rapid juvenile growth, ring uniformity requires early and frequent thinning. The alternative is nonuniform wood when competition intensifies and growth rate declines in unthinned stands. Uniformity achieved by judicious thinning will not eliminate the undesirable properties of juvenile wood. Thinning simply minimizes structural problems associated with a juvenile–mature transition exacerbated by a nonuniform growth ring pattern.

Some forest managers have recommended management systems that not only maintain uniformity but also minimize the effects of juvenile wood. Under these systems, juvenile growth would be minimized by close initial spacing and this growth rate would be maintained by frequent, light thinning. Although this method presumably should minimize juvenile wood, rotation length would be increased and volume of production decreased.

Summerwood Percentage

Summerwood percentage is the most easily determined, therefore the most widely used, wood quality characteristic. Because it is highly correlated with wood specific gravity and provides a visual index of strength and structural properties (Koch 1972), it is also an important component of lumber and timber grading rules.

Juvenile wood is inherently low in summerwood. As pointed out in the section Characteristics of Juvenile Wood, springwood formation is favored during juvenile growth because of the predominating influence of the tree crown. In fact, in some trees, the first several juvenile growth rings appear to be all springwood (Hiller 1954). In many other trees, the prevalence of false growth rings combined with a broad, indistinct band of transition tracheids make it impossible to distinguish springwood from summerwood. Consequently, summerwood percentage in the rapidly grown juvenile wood of southern pines is difficult and sometimes impossible to quantify. Most researchers simply make visual estimates based on changes in apparent growth ring density and color changes in the wood (Zobel and others 1959).

The older the growth ring relative to the pith and the greater its distance from the active crown, the more distinct the springwood–summerwood transition and the larger the percentage of summerwood. Beyond the first several growth rings nearest the pith, summerwood percentage increases rapidly within the juvenile core. Selection of 10 years as the arbitrarily defined juvenile period for loblolly pine is based on the assumption that mature summerwood values will be produced thereafter. For example, McAlister and Powers (1992) considered a growth ring with 50% summerwood to be a good rule of thumb for defining the transition. However, loblolly pine in the northern portion of its range may not produce 50% summerwood at any age. Thus, 40% summerwood might be a better rule of thumb for defining the transition to mature wood.

Summerwood percentage in mature growth rings varies widely with environmental conditions and silvicultural practices and, of course, with inherent growth potential. Variations in summerwood percentages attributable to these factors are discussed in the respective sections of this report.

Summerwood percentage is simply an index of wood quality that is more appropriately evaluated by other wood characteristics. The patterns of specific gravity variation discussed in the following section, Specific Gravity, quite accurately reflect similar patterns of variation encountered in summerwood percentage. Specific gravity, in turn, is a fairly reliable index of the combined effect of tracheid radial diameter and wall thickness.

Specific Gravity

Specific gravity is perhaps the oldest and most widely used criterion for evaluating quality of wood and its strength properties. Specific gravity itself is dimensionless. It is the ratio of the weight of a wood sample to the weight of a equal volume of water at a standard temperature. Specific gravity is usually based on the ovendry weight and green volume of the wood sample. Although wood density and basic density are derived differently, the terms are often used synonymously with specific gravity. Because of the utility of specific gravity as a predictor of the quality and strength properties of wood, researchers have searched over the years for some readily definable relation between specific gravity and the growing conditions of trees.

During the early years of research on wood quality, beginning about 1880, it was widely believed that slowly grown, narrow-ringed wood of conifers was superior in quality to that of rapidly grown, wide-ringed wood. In trees from the naturally established stands prevalent at that time, most of the wide rings occurred in the growth zone we now refer to as juvenile wood. Silviculturists therefore recommended planting trees at close spacings followed by frequent stand thinning to maintain uniform ring widths. Most of this research was based on data from natural stands and closely spaced plantations in northern Europe (Larson 1962), although similar recommendations were made for the southern pines in the United States (Paul 1930, 1932a,b). Despite the objections of some, these ideas prevailed until about 1950 when researchers, primarily in South Africa and Australia, began examining fast-grown wood from wide-spaced plantation trees. Results of this and later research proved that growth ring width, per se, was not a valid criterion for evaluating wood quality. The research also demonstrated that close initial spacing of trees simply masked the effects of juvenile wood by confining these growth rings to a small core of wood near the pith where their influence on structural properties was minimized.

Table 1—Variation in specific gravity of merchantable wood with age

Specific gravity[a]					
10 years	15 years	20 years	25 years	30 years	40 years
0.385	0.409	0.425	0.438	0.449	0.466

[a]Values based on a regression equation based upon 100-tree sample

Numerous investigations conducted on the southern pines and other *Pinus* species have conclusively demonstrated that wide growth rings are not necessarily associated with a reduction in wood specific gravity. Summerwood percentage, which is highly correlated with specific gravity, increases radially outward from the pith, and within the juvenile zone, the increase is both progressive and rapid. This age-related pattern in summerwood percentage and specific gravity is inherent, and it occurs in both fast- and slow-grown trees. A typical age-related specific gravity pattern for loblolly pine in the Piedmont of South Carolina, based on data from Zobel and others (1972), is shown in Table 1.

Realistic average values for loblolly pine range from 0.36 to 0.45 for juvenile wood and 0.42 to 0.64 for mature wood (Zobel 1972). In another study of more than 2,000 loblolly pines, Zobel and McElwee (1958) obtained average values of 0.45 and 0.59 for juvenile and mature wood, respectively. Similar specific gravity values have been reported by other researchers.

Although the age-related pattern is inherent, it is not invariable. As shown later in this report, it can be modified by environmental conditions and silvicultural measures that affect crown size and development. In a similar way, the lack of a correlation between ring width and specific gravity requires clarification. Growth rings of the same age from the pith but differing in width do not as a rule differ appreciably in specific gravity. However, when growth rings of approximately equal widths but of widely different ages are compared, for example, from juvenile and mature wood zones, the specific gravity of the older rings will almost always be greatest because of the inherent radial increase in summerwood percentage.

Lack of a correlation between ring width and specific gravity only applies within reasonable limits of comparability. Extremely wide rings are often rich in springwood and extremely narrow rings poor in summerwood. Consequently, wood from trees that had greatly different juvenile growth rates often differ in specific gravity. Comparisons of this nature are illogical when making management decisions. Such an error was sometimes unknowingly committed in past investigations of the southern pines when juvenile wood from open-grown, old field trees was compared with that from close-grown, natural stands (Paul 1929).

The relationship between growth ring width and specific gravity within the juvenile zone can be restated. Within a rather broad range of ring widths, the rate of juvenile growth should exert a negligible effect on wood specific gravity and can be ignored for most end products. However, this conclusion *does not* mean that wide-ringed juvenile wood is comparable in quality with wide-ringed mature wood.

With reference to the relationship between ring width and specific gravity, the weak correlation between these two variables is due not only to variations in the percentage of summerwood but also to the great disparity in the specific gravities of springwood and summerwood. For example, Ying and others (1994) found that summerwood percentage and wood specific gravity in loblolly pines rapidly increased from 15% and 0.39, respectively, at 1 year old, to 53% and 0.51, respectively, at 10 years old. Considering the within-ring variation, Paul (1958) reported that the specific gravity of springwood averaged 0.310, whereas that of summerwood averaged 0.625 for 12- to 13-year-old loblolly pines averaging 3.7 rings per inch (1.5 rings/cm). These values compare favorably with those of Pew and Knechtges (1939), Goggans (1964), Megraw (1985), and Hodge and Purnell (1993). Goggans reported specific gravity values of 0.29 and 0.63 for springwood and summerwood, respectively, in an 8-year-old Georgia progeny test.

The innermost growth rings next to the pith have been found to be atypical by some researchers, and these rings were therefore deleted from their analyses. That is, the rings either lacked recognizable summerwood tracheids or they appeared to possess other unacceptable characteristics such as tendencies for compression wood or spiral grain formation, excessive extractive contents, or extremely short tracheids with high fibril angles. The atypical nature of these growth rings is undoubtedly attributable to physiological age as discussed in the section Growth Ring Age. Again, one might question heritability estimates based on the first one to several growth rings when their physiological ages either have not been accounted for or are unknown.

Within the juvenile zone, specific gravity increases rapidly with increasing ring age. Beyond the juvenile zone, specific gravity continues to increase but the increase is usually more gradual because of a more consistent percentage of summerwood associated with increasing ring maturity. Summerwood percentages are not invariable, however, and mature wood specific gravity values can therefore fluctuate quite widely with seasonal weather patterns and changing stand conditions.

Radial specific gravity patterns observed at breast height are repeated at different heights in the stem. Although the patterns are similar, the values differ because the rings at higher stem levels are both physiologically older and in closer proximity to the living crown. A typical pattern for loblolly pine, as reported by Pearson and Gilmore (1971), is shown in Table 2.

Table 2—Typical pattern for loblolly pine juvenile wood specific gravity with height in stem

	Specific gravity				
Type of wood	3 ft[a]	13 ft	23 ft	33 ft	43 ft
Juvenile wood (10 years)	0.474	0.428	0.408	0.405	0.409
Mature wood	0.525	0.484	0.404	0.434	0.439

[a]Height in stem (1 ft = 0.3048 m).

In most studies of juvenile wood, specific gravity is an average value based on a composite of juvenile growth rings rather than individual rings within the juvenile core. When based on average values, specific gravity will vary with site, geographic location, stand conditions, and silvicultural practices, as will be shown later in this report. Nonetheless, irrespective of the method of group comparison, there is usually more variation between individual trees within a group than there is between group averages. These differences provide the impetus for genetic improvement.

Specific gravity is an excellent index of both the anatomical characteristics and structural properties of dry wood. Anatomically, it is most closely correlated with the percentage of summerwood in the annual growth ring, which in turn is related to characteristics of the springwood and summerwood tracheids. Structurally, specific gravity is a important component of the grading rules for Southern Pine lumber and timbers. However, as we will discuss in the Conclusion of this report, it appears to be of limited usefulness in evaluating the quality of juvenile wood for solid wood products.

Tracheid Diameter and Wall Thickness

Tracheid radial diameter and wall thickness are the primary determinants of summerwood percentage. Springwood tracheids are large in radial diameter with relatively thin cell walls whereas summerwood tracheids are narrow in radial diameter with relatively thick cell walls. The transition from springwood to summerwood in mature growth rings of southern pines is usually abrupt, and often a springwood cell is immediately followed by a distinct summerwood cell. Such a transition occurs either in older trees in which the active crown is far removed from the stem base or in relatively slow-growing trees.

In contrast to mature growth rings, the transition from springwood to summerwood in wide, juvenile growth rings is extremely gradual and diffuse. The difficulty in determining the springwood–summerwood boundary in juvenile rings is due to the transitional nature of the mid-ring tracheids. These so-called transition tracheids, which are neither springwood nor summerwood, often comprise the major part of extremely wide juvenile rings. Transition tracheids are produced when growth conditions are favorable for the prolongation of terminal shoot growth and foliage development and also for the promotion of high levels of photosynthetic activity. Transition tracheids can either gradually decrease in radial diameter, increase in wall thickness, or both. The most common pattern is for tracheid radial diameter to remain essentially constant (that is, wide lumened) and for wall thickness to gradually increase. The measurable decrease in lumen radial diameter, typical of true summerwood, occurs in the outermost part of the juvenile growth ring.

The wide zone of transition tracheids is not only a distinguishing characteristic of juvenile wood but also a major determinant of wood quality. By modifying the structure of these tracheids, dramatic changes can be made in both wood quality and structural properties. As we have repeatedly emphasized, the tree crown regulates wood formation on the stem. Since springwood tracheids are large-lumened, thin-walled, and structurally weak, a reduction in springwood formation should contribute to an improvement in quality of the wood. Minimizing juvenile ring width can reduce springwood. A reduction in ring width always affects springwood more drastically than summerwood. A reduction in ring width, however, will not necessarily increase the amount of summerwood, although it will increase the percentage of summerwood.

Reduction of juvenile springwood occurs primarily by reduction in the width of transition tracheids, which are usually classified as springwood. The more drastic the decrease in growth rate and ring width, the narrower the width of transition tracheids in the growth ring. In relatively narrow rings, such as those produced by close initial tree spacing, transition wood might be absent in the outer rings of the juvenile core. These rings often have the outward appearance and visual characteristics of mature rings, suggesting to some workers that the juvenile core consists of only the innermost six to eight rings.

It is difficult to generalize as to how the springwood–summerwood relationship will be affected by either an increase or decrease in ring width. Although both radial tracheid diameter and wall thickness are used to differentiate springwood from summerwood, the two characteristics vary independently during growth ring formation. That is, radial tracheid diameter and wall thickness have been found to be under the control of entirely different physiological processes (Larson 1964). Therefore, an environmental factor or a silvicultural practice might either increase or decrease wall thickness while having no effect on radial lumen diameter. However, both the springwood–summerwood ratio and wood specific gravity values would be significantly altered, as Bethel (1950) pointed out in his work on loblolly pine. Tangential tracheid diameter does not vary significantly within a growth ring nor appreciably within a tree, and it is therefore of no concern in wood quality investigations.

This digression into the relative structures of springwood and summerwood, and especially of transition tracheids, in juvenile growth rings is necessary to place specific gravity in proper perspective. Variations in wood specific gravity are frequently related back to variations in percentage of summerwood. But both of these wood characteristics are arbitrary indices dependent almost entirely on the radial diameter and wall thickness of the individual tracheids comprising a growth ring. Because of the importance of these interrelations to our final conclusions, two highly pertinent studies will be briefly summarized.

In the first study, Pew and Knechtges (1939) examined the variation in tracheid diameter and wall thickness in fast- and slow-grown loblolly pines. Neither the cross-sectional dimensions nor wall thickness of springwood tracheids varied appreciably between the fast- (2.9 rings per inch (1.1 rings/cm)) and slow- (10 rings per inch (3.9 rings/cm)) grown trees either at breast height or at several height levels in the stems. Similarly, the cross-sectional dimensions of summerwood tracheids did not vary greatly between fast- and slow-grown trees, but in the slow-grown trees, summerwood tracheids had slightly thicker walls and wall thickness decreased with sampling heights in the stems.

These authors also examined two loblolly pine upper-stem logs, both about 8 years old and of comparable growth rates but varying significantly in wood specific gravity. The data revealed little variation in cross-sectional dimensions but large variations in wall thickness between the high and low specific gravity wood samples (Table 3).

In all samples tested by Pew and Knechtges, specific gravity of springwood remained rather constant at 0.28 whereas that of summerwood varied widely with variations in wall thickness. They concluded that woods with high and low specific gravity values often appear strikingly similar in visual appearance and the underlying differences cannot be detected with the naked eye, for example, by grading rules.

In the second example, McMillan (1968) approached the problem differently but arrived at somewhat similar conclusions. His data, based on 40 loblolly pine trees, is summarized in Table 4. Again, it can be seen that the most important variable is summerwood wall thickness. McMillan concluded that since springwood wall thickness remained constant with distance from the pith while radial tracheid diameter increased, the amount of wood substance per unit area decreased. Therefore, specific gravity of a unit volume of springwood must decrease with distance from the pith. In contrast, radial diameters of summerwood tracheids remained essentially constant with increasing distance from the pith while wall thickness increased. Therefore, because the amount of wood substance per unit cross-sectional area increased, the specific gravity of summerwood must increase with distance from the pith.

The main point to be gained from this exercise is that springwood and summerwood are independently related to specific gravity. Therefore, the characteristic increase in wood specific gravity with distance from the pith is determined not only by the relative amounts of springwood and summerwood in the growth rings but more importantly by

Table 3—Variation of specific gravity and cell wall thickness with high and low specific gravity

	Entire disk				½-in. (13-mm) test samples			
					Specific gravity		Wall thickness (μm)	
Specific gravity	Rings per inch[a]	Specific gravity	Rings per inch	Summerwood (%)	Springwood	Summerwood	Springwood	Summerwood
High	2.7	0.460	2.5	54	0.28	0.68	4.1	8.7
Low	2.1	0.38	1.8	60	0.28	0.49	3.0	5.8

[a]1 ring per inch = 0.4 ring/cm.

Table 4—Radial tracheid diameter and cell wall thickness as a function of growth ring

	Growth ring number					
	1–10		11–20		21–30	
	Springwood	Summerwood	Springwood	Summerwood	Springwood	Summerwood
Radial tracheid diameter (μm)	52.8	32.8	55.3	33.6	56.7	33.8
Wall thickness (μm)	4.5	9.4	4.6	9.4	4.6	10.0

the wall thickness of the individual tracheids and to a lesser extent their radial diameters. These conclusions can be reinforced by referring back to the section on specific gravity.

Tracheid Length

Tracheid length is of special importance to the pulp and paper industry, and for this reason, extensive literature exists concerning its variation within and among trees. As a general rule, tracheid length increases rapidly from rings nearest the pith to the outer rings of the juvenile core. Thereafter, it might continue to increase rapidly, do so more slowly, or vary unpredictably. Similar patterns occur in rings of the juvenile core at different height levels in the stem, although the actual length values often differ.

Tracheid lengths are quite closely correlated with growth ring width. In the juvenile core, tracheid length increases more rapidly in narrow than in wide growth rings. In mature wood, tracheids are generally longer in narrow than in wide rings.

Within a growth ring, summerwood tracheids are longer than springwood tracheids. In radiata pine, tracheid length has been found to increase rather abruptly at the springwood–summerwood transition, attain a maximum in the mid- to late-summerwood zone, and then decrease sharply at season's end (Nicholls and others 1964). The wider the growth ring, the more gradual the increase at the springwood–summerwood transition, particularly in juvenile rings with broad bands of transition tracheids. Similar patterns have been observed in other conifers, including loblolly pine (Ifju and Labosky 1972).

Reported values for tracheid lengths within and among loblolly pine trees are extremely variable. Because of the manner in which cambial cells divide and the new wood cells then elongate, a population of tracheids is produced that varies widely in length. Research has shown how this population of tracheids originates and why it is so variable. Briefly, the changes are related to how rapidly the cambial cells must divide to accommodate the circumferential growth of the tree. The process is complex and is of no immediate concern in this report. The subject has been thoroughly covered in Larson (1994, chap. 6).

In addition to variation with age and position within stems of individual trees of loblolly pine, tracheid length has also been found to vary among trees according to stand density, site, geographic location (Zobel and others 1960), and different silvicultural practices. Tracheid length also varies widely among individual trees and is considered a highly heritable trait.

Although tracheid length has been found to be correlated with summerwood percentage, possibly due to the within-ring pattern, it is either poorly or sometimes negatively correlated with wood specific gravity according to Zobel and others (1960).

Tracheid length, by itself, is of little or no importance in evaluating strength or structural properties of products made from mature wood. However, longer tracheids in juvenile wood appear to impart increased MOE and tensile strength. Longer tracheids are also associated with smaller fibril angles (Megraw 1985). Some typical tracheid length values for loblolly pine are given in Table 5.

Microfibrillar Angle

The secondary, or S_2, layer is the main wall layer comprising the bulk of a pine tracheid. Research has shown that the compound middle lamella and the S_1 and S_3 layers remain essentially fixed, while variation in volume of the S_2 is solely responsible for change in total cell wall thickness (Cave 1976). The secondary wall is not solid wood substance. Rather, it consists of helically arranged cellulose microfibrils oriented in the long axis of the tracheid. Orientation of the microfibrils in juvenile wood tracheids varies widely both within the same tree and among different trees.

Table 5—Tracheid lengths for loblolly pine

Reference	Tracheid length (mm)			
	Juvenile wood		Mature wood	
	Springwood	Summerwood	Springwood	Summerwood
McMillan (1968)	3.52	3.79	3.91	4.13
Taylor and Moore (1981)	2.92	3.14	4.15	4.17
Cole and others (1966)	2.58[a]		3.45[a]	
Zobel and Blair (1976)	2.56[a]		3.41[a]	
Kellison (1981)	2.98[a]		4.28[a]	

[a]These values were average values for both springwood and summerwood.

In mature loblolly pines, the microfibrillar or fibril angle is small, averaging about 5° to 10° as measured by deviation from the vertical. In juvenile wood, the fibril angle is large, averaging 25° to 35° and often up to 50° in rings next to the pith, then decreasing outward in the juvenile core. However, the decrease in fibril angle often continues well beyond the juvenile core. For example, Ying and others (1994) found that fibril angles in tracheids of fast-grown loblolly pines decreased from 33° at age 1, to 23° at age 10, and to 17° at age 22. Bendtsen and Senft (1986) reported that loblolly pines had not yet attained stable fibril angles at age 30.

Within the juvenile zone, fibril angle varies with growth rate. As a general rule, fibril angles are larger in wide than in narrow growth rings. Pillow and others (1953), for example, found that fibril angles in the juvenile wood of open-grown loblolly pines averaged almost 20° larger than those in a closely spaced natural stand. Fibril angles of springwood tracheids are also larger than those of summerwood. This difference between springwood and summerwood fibril angles accounts for the fact that fibril angles have been reported to be negatively correlated with both summerwood percentage and specific gravity, although not always so. The negative correlation is much stronger between fibril angle and wall thickness. The angle of orientation of the microfibrils tends to increase from the inner to outer parts of the secondary wall. And so, the thicker the secondary wall, the smaller the fibril angle. Hiller (1964) found that wall thickness accounted for 64% to 81% of the variation in fibril angle.

Fibril angle is negatively and strongly correlated with tracheid length in growth rings of mature wood (the longer the tracheid, the smaller the fibril angle). Although this relationship also holds in the juvenile growth rings, the correlation is weaker and it is for this reason that fibril angles often continue to decline in slope outward in the stem long after tracheid length values have stabilized.

A strong relationship exists between fibril angle and longitudinal shrinkage. Tests by Harris and Meylan (1965) on juvenile wood of radiata pine showed that longitudinal shrinkage increased sharply while tangential shrinkage decreased at fibril angles greater than 25°. More specifically, longitudinal shrinkage was low as fibril angles decreased below 25°, whereas tangential shrinkage increased as fibril angles decreased below 15°. Ying and others (1994) confirmed these data by showing that fibril angles of 25° or greater corresponded to the outer boundary of the 10-year juvenile core in loblolly pine.

Compression wood tracheids, which are both abnormally short and thick-walled, also have excessively large fibril angles. Compression wood growth rings with extremely large fibril angles show a higher degree of longitudinal and a lower degree of tangential shrinkage than normal wood for comparable fibril angles (Harris 1977). For example, at a fibril angle of 40°, longitudinal shrinkage of radiata pine compression wood was 2.5%, whereas that of normal wood was only 1%. In trees with strongly expressed compression wood in the juvenile core, longitudinal shrinkage of summerwood was 3% to 5% and that of springwood was 2%. This apparent contradiction, with summerwood shrinking more than springwood, is due to the fact that compression wood is essentially a summerwood phenomenon.

Shrinkage is due to several interrelated factors but is primarily due to the removal of moisture from between the microfibrils and from within the cellulosic microfibrillar matrix. From a practical standpoint, wood shrinkage can be related to microfibril angle with a high degree of certainty.

Other Wood-Related Properties

Branches, Knots, and Knotwood

Loblolly pine has relatively small branches and exhibits good self-pruning, especially for lower stem branches. According to von Wedel and others (1967), branches in the lower crowns of loblolly pines 8 to 11 years old, planted 7.8 by 7.8 ft (2.4 by 2.4 m) apart, essentially stopped growing after the third year. Reduced growth, however, does not necessarily mean branch death. For example, Paul (1957) estimated that loblolly branches remain alive for about 7 years in the lower 20 ft (6.1 m) of stem, although a more reliable estimate might be 4 or 5 years.

This pattern of branch death and senescence continues upward in successive branches as long as height growth remains strong and crown competition persists. However, when height growth begins to slow, branches of the upper crown remain alive longer because of the reduced competition for sunlight. These upper-crown branches are usually larger in diameter and have steeper branch angles relative to the main stem than lower-crown branches. In general, fast-growing trees have steeper branch angles than slow-growing trees, although all branch angles tend to flatten as a branch ages.

Both branch longevity and branch size can be controlled to a large degree by stand density. Close initial spacing encourages small branches and early mortality, whereas wide initial spacing encourages large, persistent branches. Close initial spacing significantly reduces radial stem growth, but it also confines knotwood to a smaller juvenile core. Any management practice that stimulates overall crown and foliage development, such as thinning or fertilization, will prolong the life and invigorate the growth of existing branches (de Villiers 1965, 1966). For example, Burton and Shoulders (1974a) observed that lower branches developing in heavily thinned loblolly pine stands were so large that artificial pruning was required to ensure an outer cylinder of clear wood. Another closely related effect of heavy thinning or fertilization in young stands is the stimulation of height growth. An increase in height growth can be accomplished by an increase in the number of branch whorls (growth flushes), by an increase in the distance between whorls, or both. An increase in the number of whorls would, of course, increase branch number and knot volume.

Another important branch characteristic is the number of branches per whorl. Paul (1957) considered two to four, sometimes five, branches per whorl to be typical of loblolly pine. von Wedel and others (1967) arrived at a similar conclusion, although they observed differences among selected progenies. Apparently, a tree can satisfy its foliage needs by either producing a small number of relatively large branches per whorl or a larger number of small branches.

Branch death is not the same as self-pruning, which is the elimination of dead branches from the stem. Loblolly is a fairly efficient self-pruning species. Nonetheless, the propensity for self-pruning decreases upward on the stem as branch sizes and branch angles increase. The longer the dead branch remains intact on the stem, the larger the core of knotty wood. Retention of dead branches with acute branch angles are especially deleterious because the resulting knots not only are larger but also pass through a larger volume of stem wood.

Publications by von Wedel and others (1967, 1968) contain a wealth of information, including knot sizes, volumes, and distributions, on loblolly pine. Knot volume is considered a better measure of potential lumber degrade than knot size. Knot volume includes the effects of branch or knot angle as well as associated defects such as compression wood, grain distortions, and pitch deposits.

Knots in the juvenile core contribute to serious degrade of solid wood products. Large knots are sites of weakness in an already substandard wood, particularly if the wood is rapidly grown. Trees with high knot volumes also have high amounts of compression wood (von Wedel and others 1967). The volume occupied by knotwood and compression wood increases upward in the stem, contributing to lesser value of upper-stem logs. On a total tree basis, the compression wood associated with knotwood averaged 7.1% of the stem volume of 11-year-old loblolly pine trees (von Wedel and others 1967).

Pearson (1988) examined knotty and knot-free stud samples cut from the juvenile cores of loblolly pines. Knotty studs had slightly higher specific gravities than clear studs because of the higher density of knots. Nonetheless, the mean maximum crushing strength of the knotty studs was only 41% of the species mean value compared with 52% for the clear studs. Interestingly, he found that the continuity of grain and swelling of the trunk around large knots in loblolly pine stemwood tended to counteract, to some extent, the reduction in crushing strength caused by the knots. Other structural properties were similarly reduced by the presence of knots. For example, MOR in upper-stem logs was reduced outward from the pith due to the larger knots.

Compression Wood

Compression wood, or reaction wood, occurs on the lower sides of leaning coniferous stems, on the undersides of branches, and below the level of branch insertion on a stem. It is a gravitational response, and its formation tends either to return a leaning stem to an upright position or to maintain the position of a branch within the crown. Tree lean in young pines can be attributed to many causes such as poor planting procedures, spongy soils with poor root holding ability, persistent prevailing winds or wind storms, and heavy thinning or sudden release cutting (see Timell 1986 for an exhaustive review of compression wood).

All degrees of compression wood can be encountered in the juvenile cores of southern pines. When lean is excessive and tree growth is vigorous, the stem cross sections will appear eccentric because of the unusually wide growth rings that develop on the underside of the lean. Compression wood is produced primarily during summerwood formation, and the extra-wide summerwood zone is preceded by a broad band of transition tracheids that resemble summerwood. Compression wood is easily recognized in eccentric growth rings. However, it can also be present in growth rings that show little or no eccentricity. In such cases, compression wood can only be visually detected by the dark coloration of transition tracheids that appear as a crescent or eccentric arc in an otherwise normal appearing growth ring. It is most easily detected by its greater opacity when viewed with transmitted light.

Young loblolly pines are highly susceptible to compression wood formation, especially during the first few years of growth (Zobel 1961, 1976; Bendtsen and Senft 1986). In some rapidly grown trees, compression wood arises without any observable cause and it often appears in young trees showing no evidence of lean (Cown 1974, Harris 1977). Compression wood is known to be caused by an excess of growth hormones produced by elongating shoots and foliage organs of the crown, and the combination of rapid growth and short branch-free stems in young, upright trees accentuates the response. Anatomically, the innermost rings of the juvenile core in fast-grown trees resemble compression wood, and physiologically, the processes responsible for both types of wood are remarkably similar.

Compression wood often occurs in the wood of young pines after heavy fertilization and/or thinning even in trees that are apparently free of lean (de Villiers 1965, 1966; Smith 1968). For example, in radiata pine, heavy thinning increased the incidence of compression wood by 20% in butt logs that showed no evidence of eccentricity (Cown 1974).

The specific gravity of compression wood is usually reported as being higher than that of normal wood, possibly because of the higher proportion of summerwood in the growth rings. According to Shelbourne and Ritchie (1968), the specific gravity of springwood compression wood was the same as normal wood after extraction. However, the specific gravity of summerwood compression wood was slightly lower than normal due to intercellular spaces, larger tracheid lumens, and spiral checking in the secondary wall layer. These tracheid characteristics are typical of compression wood. The intercellular spaces are formed by the circular rather than hexagonal-shaped tracheids when viewed as cross sections, and the spiral checking is related to the high fibril angle. Tracheids of both springwood and summerwood are shorter than normal in compression wood.

Physical properties of compression wood are similar to those of juvenile wood but are more extreme due to the accentuated tracheid characteristics. For example, normal, green Southern Pine lumber shrinks longitudinally about 15 parts in 10,000; compression wood is often 10 times that (Manwiller 1966). Stresses in boards with both juvenile and compression wood may be so severe as to cause splitting. This combination can be particularly damaging in boards or planks consisting of only a few growth rings as often encountered in the juvenile core. Compression wood is also associated with warp, bowing, and other distortions in lumber that appear during drying. In radiata pine with strongly expressed compression wood, longitudinal shrinkage in summerwood of the juvenile core was about 3% to 5% in contrast to almost zero shrinkage in normal summerwood (Harris 1977). Longitudinal shrinkage of springwood was about 2%, not appreciably different than normal springwood.

Longitudinal shrinkage has been found to be highly correlated with fibril angle. Compression wood tracheids have abnormally large fibril angles. But for the same fibril angle, compression wood shrinks longitudinally more than normal wood. The difference is believed to be related to the thicker secondary wall layers, lower cellulose content, higher hemicellulose content, and the spiral checking in the secondary wall of compression wood. Longitudinal shrinkage results during drying when moisture is removed from between the microfibrils and the spiral checks in the secondary wall.

Transverse shrinkage responds differently to changes in fibril angle. Again, in radiata pine, longitudinal shrinkage increased sharply at fibril angles greater than 25° while tangential shrinkage decreased with increasing fibril angles just as it did in normal juvenile wood (see Microfibrillar Angle section). Longitudinal shrinkage was low at fibril angles less than 25°, whereas tangential shrinkage was highest below 15° (Harris and Meylan 1965).

Spiral Grain

Spiral grain is a defect in which the tracheids within a growth ring are aligned at an angle to the vertical, that is, the normal stem axis. It is not to be confused with fibril angle, which involves the orientation of the microfibrils comprising the tracheid walls. When severe, spiral grain can exert an adverse effect on solid wood products because of differential drying resulting in warping, checking, and cracking.

Spiral grain is an inherited characteristic, and it therefore varies considerably among trees. It also varies among species with slash and loblolly being affected to a much lesser degree than radiata pine. However, in all species, certain trees express a proclivity for spiral grain formation in juvenile growth rings nearest the pith. The tendency usually disappears in older rings, although it might persist if growth is exceptionally rapid.

The occurrence of spiral grain in the innermost rings of the juvenile core might be difficult to silviculturally control in rapidly growing young trees. However, because of the strong inherited potential, trees with excessive spiral grain in the juvenile core should be eliminated as parents.

Extractives

Extractives in southern pines are essentially resin acids in turpentine. They often saturate growth rings near the pith to varying extents. When present in large amounts in solid wood products, extractives can create problems in painting, finishing, and the penetrability of preservatives. Although extractives exert little or no influence on either the strength or physical properties of wood, they do significantly affect specific gravity values. For this reason, alcohol–benzene extraction is recommended before specific gravity determinations are made.

Typically, specific gravity in the juvenile core of southern pines increases rapidly in the radial direction. However, in unextracted wood, specific gravity values of the first several rings nearest the pith are abnormally high because of resin or pitch deposits. These growth rings not only have an abundance of resin ducts but the ducts are well distributed throughout the growth rings (Larson 1994, chap. 9). Wildfires or controlled burns that severely scorch the bark can cause release of the resin. Stem swaying by strong winds can have a similar effect. For some unknown reason, pitch deposition increases in growth rings of the juvenile core as trees increase in size and age. Such depositions are unpredictable, and large tree to tree variations have been reported for the southern pines (Goggans 1961).

Taras and Saucier (1967) estimated that unextracted increment cores overestimated specific gravity by 6.0% to 7.5%. Similar values were obtained by Cole and others (1966) in a 10-tree sample of loblolly pine. The extractive content averaged 3.06% for juvenile wood and 2.67% for mature wood. Unextracted and extracted specific gravities were 0.430 and 0.413 for juvenile wood and 0.553 and 0.540 for mature wood, respectively.

Heartwood

Heartwood formation, like extractives content, exerts little or no influence on both the strength and physical properties of solid wood products. However, the deposition of minerals and other biochemical constituents associated with the death and dissolution of ray cells during heartwood formation can significantly affect specific gravity values. Heartwood deposits also serve as preservatives for certain solid wood products.

Alcohol–benzene extraction removes most heartwood deposits along with the resins. However, in older trees with significant heartwood formation, specific gravity values for rings in the juvenile zone often remain high even after extraction (Zobel and others 1959). Although the cause is unknown, these higher values are probably due to residual minerals and other insoluble constituents.

The time of heartwood initiation varies among the southern pines. In slash pine, it might begin as early as 8 years, whereas it might be delayed until age 30 in loblolly pine (Zobel and Blair 1976). Zobel and others (1959) concluded that heartwood in loblolly pine was of little significance during a rotation age of 25 to 45 years. Paul (1952) reported that heartwood is initiated earlier in weak or suppressed trees than in co-dominant or dominant trees. Moreover, it can first appear at an isolated position on a stem cross section or at varying height levels in the lower stem. Once initiated, heartwood formation gradually spreads outward in rings of the juvenile core and beyond. The denser the stocking and slower the growth, the larger the inner core of heartwood relative to the outer sapwood. Consequently, rapidly grown trees often retain wide sapwood bands well into maturity. Based on analysis of increment cores from 577 loblolly and 519 longleaf pine trees sampled across the South, Clark (1994) also reported that the more rapid growing trees contained a wider band of sapwood than the slower growing trees. However, he also found that the faster growing trees on the good sites contained a wider core of heartwood at an earlier age than the slower growing trees on the poorer sites.

Stem Form and Taper

Stem form generally relates to straightness of the stem. In this sense, defects include stem crooks, bowing, and other deformities. Such defects, unless severe, have little effect on most wood quality characteristics other than the possibility of induced compression wood. However, any deviation in stem straightness will affect not only the total yield of solid wood products but also the lengths of straight boards cut from logs. In one study, separation of 165 loblolly pines into five straightness categories resulted in 5% more lumber recovery from straight trees than from the average tree in the stand (Kellison and others 1985). Tree straightness is one of the easiest qualities to improve genetically, and estimated gains of 24% have been attained in one generation.

Another interpretation of stem form involves stem taper, a measure of the degree of cylindricity of a stem (Larson 1963). Lumber yield of strongly tapered stems is decreased because of the diameter difference between the log bottom and top. Strongly tapered stems also produce shorter poles of lesser quality.

Stem taper is related to crown size and its distribution on the stem and also to rate of growth. In general, rapidly growing trees with deep, full crowns have greater stem taper than slower growing trees with high-setting crowns. Thus, artificial pruning, which reduces crown length, tends to increase cylindricity and decrease stem taper. On the contrary, heavy thinning or sudden tree release, which retards branch decline and increases crown size, tends to decrease cylindricity and increase stem taper. In the former case, growth would shift upward toward the new crown base, whereas in the latter case, growth would shift downward in response to renewed crown vigor. Loblolly pine growing on a good site and expressing strong height growth would undoubtedly show minimal taper in the first log. Consequently, changes in stem taper following judicious thinning should be negligible.

Effects of Environment

Stand Density

Stand density regulation is the most powerful tool available to the silviculturist for controlling wood formation and quality. Stand density regulation is, in essence, a form of crown control, as mentioned in the Introduction.

In plantation management, stand density is determined by initial stocking density and thereafter by the frequency and intensity of thinning, if any. Initial stocking densities are management decisions with important consequences relative to both the quantity and quality of the final product. Once a plantation is established, silvicultural practices can modify the initial stocking level in a desired direction but they are expensive to employ and of limited effectiveness.

The effect of stocking levels on crown competition can be illustrated by contrasting the growth response of loblolly pines at two widely different initial spacings. At a 12- by 12-ft (3.7- by 3.7-m) spacing, tree crowns develop unimpeded to their full potential. Lack of competition permits vigorous foliar development and the formation of large, persistent lower-stem branches. These crown attributes continue until crown closure eventually causes the lower branches to decline and then die for lack of sunlight. Up to this time, however, the large, vigorous crowns will have contributed to large juvenile cores of wide-ringed, knotty wood that tapers upward in the stem. Irrespective of how the stand is managed in later years, these juvenile core attributes will persist.

The wide-ringed wood that forms in the juvenile core of these trees typically has high proportions of springwood and transition wood, low specific gravity, short tracheids with relatively large fibril angles, and in some trees, abnormal amounts of compression wood and extractives. Collectively, these wood characteristics contribute to substandard grades of solid wood products.

At the other extreme, for example, a 4- by 4-ft (1.2- by 1.2-m) spacing on a good site, noticeable crown competition might begin within a few years after planting. As competition intensifies, the lower, shaded branches die and branch senescence gradually advances upward on the stem. These dead, lower-stem branches, which are small in diameter, will be confined to a relatively small juvenile core. The small juvenile core is the result of the narrow growth rings produced by restricted crown development not the tendency for close spacing to accelerate the transition to mature wood formation. The influence of initial spacing on the date of transition from juvenile to mature wood of loblolly pine was examined at breast height for loblolly pine planted at 6 by 6, 8 by 8, 10 by 10, and 12 by 12 ft (1.8 by 1.8, 2.4 by 2.4, 3.1 by 3.1, and 3.7 by 3.7 m) in the Piedmont of Georgia and slash pine planted at 6 by 6, 8 by 8, 10 by 10, and 15 by 15 ft (1.8 by 1.8, 2.4 by 2.4, 3.1 by 3.1, and 4.6 by 4.6 m) in the Coastal Plain of Georgia (Clark and Saucier 1989). Results show that planting density does not significantly affect the age of transition from juvenile to mature wood but does affect the diameter of the juvenile core.

The narrow-ringed wood that forms the juvenile core of loblolly pine planted at close spacing typically has a relatively narrow band of transition tracheids. However, because summerwood formation is also restricted, the specific gravity of these narrow rings seldom differs from that of growth rings produced at wider spacings. Yet, the summerwood tracheids usually will be longer and fibril angles smaller compared with tracheids in the much wider growth rings.

The differences in the wood produced at extremely wide and narrow initial spacings is less a matter of quality than quantity. As emphasized previously, juvenile wood quality characteristics are inherent to the species examined. They can be modified only to a limited extent. Thus, narrow spacing simply confines the juvenile growth rings to a smaller central core. But, as we will discuss later, it is the size of the core that is important during conversion to a final product. For example, Clark and others (1994) found that loblolly pines planted at 6- by 6-ft (1.8- by 1.8-m) spacing and thinned to 100 ft^2 (9.3 m^2) basal area at age 18 yielded 60% No. 2 and better lumber when harvested at age 38. A stand planted at 12- by 12-ft (3.7- by 3.7-m) spacing, thinned to the same basal area, yielded 42% No. 2 and better lumber. The lumber value for trees at the narrower spacing was about 10% higher than those at the wider spacing.

In most spacing studies of loblolly pine, the close-spaced stands have been thinned because of the excessive per-tree volume reduction caused by carrying such stands through a short rotation. If thinning is not conducted on time, nonuniform wood and additional wood quality problems can develop.

Site

Site quality, which causes variations in overall growth and wood formation, is next in importance to stand density. Site quality varies greatly within a species range, but in every case, wood quality can be related to the growth response. That is, good sites will produce trees with wood quality characteristics associated with fast growth and poor sites with slow growth. Poor sites are usually those with either nutrient deficiencies or poor soil moisture conditions. Like the effects of stand density, which can be modified by thinning, the effects of site can be ameliorated to some extent by fertilization, irrigation, and drainage.

Most commercial plantations are established on moderate to good sites, and differences in wood quality due to the site are in most cases insignificant. This does not mean, however, that site differences are inconsequential. Zobel and others (1960), for example, found highly significant site differences in all wood characteristics studied in an extensive investigation of loblolly pine. Lantz and Hofmann (1969) and Zobel and others (1972) also found that local site and environment had a greater effect on wood quality than the source of seed in several progeny tests.

Geographic Location

Geographic location refers to the differences in tree growth and wood quality throughout a species range. Geographic location differs from site. Site differences are due to local environmental effects, whereas geographic location differences are due primarily to broad climatic effects, although edaphic and other regional factors cannot be ruled out.

Several studies have demonstrated a general trend for wood specific gravity values to decrease from south to north and east to west within the species range of loblolly pine. This south–north trend is particularly evident in stands in the western part of the range and along the Atlantic Coast, but it is not present in the Piedmont region. These regional differences strongly coincide with seasonal rainfall patterns and length of the growing season. Regional climatic influences are presumably responsible for the finding of Clark and Saucier (1989). They reported that the period of juvenile wood formation in loblolly and slash pines increased from 6 years in the Gulf Coastal Plain to 14 years in the Piedmont.

Juvenile wood is apparently influenced to a lesser degree than mature wood by geographic location of the planting site. For example, Talbert and Jett (1981) concluded that the range in specific gravity values for loblolly pine juvenile wood was smaller than that of mature wood, and geographic trends in the former were not evident. In an earlier study, Zobel and others (1959) could detect no trends in the specific gravity of corewood due to geographic location.

Effects of Silviculture

Thinning

The effect of stand thinning on wood quality is variable. It depends on initial stocking, tree age, time of year, site, and many other growing conditions. The main purpose of thinning at any age is to enhance growth rate by promoting crown expansion. To maximize wood quality characteristics in a young stand, an optimal balance must be struck between stem growth rate and a degree of crown expansion sufficient to promote competition and self-pruning. Thus, heavy or frequent early thinnings will promote lower branch growth, delay self-pruning, increase stem taper, increase the proportion of springwood in the growth ring, increase the tendency for compression wood formation, as well as other characteristics associated with rapid juvenile growth. Light or delayed early thinnings of closely stocked stands will produce essentially opposite growth and wood quality responses. From the wood quality standpoint, some of these responses are beneficial but at the expense of volume growth.

The response to thinnings conducted at older ages, such as the pole stage, are less predictable because of the many interrelated variables. Thinning cannot revive decadent lower-crown branches, but it can rejuvenate living branches thereby increasing their size and longevity. Most thinnings tend to favor early season crown development. Thus, as the crown expands, it not only promotes wider growth rings but also the proportion of springwood and transition tracheids in the growth rings. In some situations, thinning can also favor late-season growth processes. That is, in addition to increasing crown foliage mass, thinning can also increase foliage efficiency and extend the seasonal duration of wood formation. These conditions would enhance summerwood production, and the growth rings produced after thinning, although wider, would not show any appreciable decrease in the percentage of summerwood or wood specific gravity.
A good example of the latter condition would be closely stocked stands in which reduced root competition alleviated late-season soil moisture stress (Bassett 1969, Smith 1968). This, again, would be an indirect effect with the greater availability of water promoting late-season foliage efficiency.

The duration of thinning response depends on initial stocking and stand conditions, intensity of thinning, and response of the trees to thinning. The response as measured by enhanced growth ring widths can be short-lived, usually lasting for 2 or 3 years (Szymanski and Tauer 1991), but sometimes longer. It will continue until either crown or root competition, whichever becomes limiting, is reestablished.

In general, judicious thinning schedules have a negligible effect on wood specific gravity. The response is usually short-lived, and a reduction in summerwood production for a few years is minimized when averaged across all rings in a juvenile core or across a rotation. For example, Burton and Shoulders (1974a,b) demonstrated that it was possible to grow 18- to 20-in. (457.2- to 508-mm) diameter loblolly pines averaging 3 rings per inch (1.2 rings/cm) by periodic heavy thinning. However, the trees had large, persistent branches requiring pruning to produce merchantable sawlogs. Although wood specific gravity at DBH averaged 0.53 for all 27 growth rings, specific gravity for the juvenile core was presumably much below this level. Several additional examples of thinning studies have been described by MeGraw (1986).

The benefits of thinning in terms of growth promotion are many and obvious. However, the negative effects must also be recognized and balanced against the positive in keeping with the product objective.

Pruning

Pruning involves the artificial removal of branches from a tree. Dead branch pruning simulates natural self-pruning by removing dead branches or branch stubs that would otherwise extend outward in the juvenile core. Green or live branch pruning eliminates branches that would otherwise continue growing. Their removal ensures a smaller knot size and a smaller knotty core.

The effect of green pruning is to reduce the crown of an open-grown tree to that of a simulated stand-grown condition. Severe green pruning, in which many lower-stem branches are removed at one time, causes pronounced readjustments in tree growth. Because of the smaller residual crown, height growth might be temporarily reduced. Meanwhile the lower branches at the new crown base become larger and more vigorous. Radial growth at the stem base is reduced in heavily pruned trees, and the height level in the stem at which maximum ring width occurs shifts upward to the new crown base. Concomitant with these changes in ring width, the percentage of summerwood and the specific gravity values increase in the lower stem. All these responses can be associated with a smaller, less vigorous crown and a long, branch-free stem. In young trees, pruning tends to accelerate the transition from juvenile to mature wood characteristics in growth rings below the new crown base. In many respects, the growth responses after pruning are opposite those caused by stand thinning. But, as in thinning, the effects are usually short-lived. Depending on the degree of live branch removal, the growth pattern returns to normal within a few years.

The aforementioned growth responses are typical of what might be anticipated with moderate to severe green pruning. Light green pruning might elicit either a negligible or insignificant response. Green pruning is labor-intensive and relatively costly, although it is routinely performed in the fast-growing pine plantations of New Zealand and South Africa and in some loblolly pine plantations in the southern United States.

The benefits of green pruning are to produce lower-stem bolts or logs with small, tight knots and short branch-free stubs confined to a small knotty core. Ancillary benefits are reduced stem taper and increased percentage of summerwood and specific gravity in the lower stem, depending on the growth response. In addition to economic considerations, another negative effect of pruning is the increased growth of branches at the new crown base, which often drastically reduces the grade of the lumber from upper logs.

Fertilization

The purpose of fertilization is to increase tree growth by artificially supplying one or more mineral nutrients that are limiting to growth in the natural environment. In one sense, fertilization provides a temporary boost in site quality.

It is difficult to generalize regarding the effect of fertilization on wood quality because of the large number of influencing variables and the fact that no two studies were conducted under similar conditions. General statements can be made, however, as to the anticipated growth responses of tree stem and crown. The effects of fertilization are somewhat akin to those observed after thinning. If height growth and overall crown development are promoted, increased wood growth will usually be accompanied by a increase in springwood and transition tracheid formation, hence a decrease in summerwood percentage and specific gravity. If, on the other hand, foliage mass and photosynthetic efficiency are promoted or the duration of seasonal growth prolonged, then the percentage of summerwood might be maintained despite the increase in growth ring width. Under some circumstances, increased photosynthetic efficiency can significantly increase cell wall thickness of the summerwood tracheids.

Tree age at the time of fertilizer application apparently has a pronounced effect on the nature of the response. Fertilization either at the time of planting or during the first few years of growth, especially if combined with cultivation, increases both height growth and crown development. Decreases in summerwood percentage and specific gravity usually accompany these growth responses. In older trees, particularly beyond the juvenile stage, the response is less dramatic. Although a modest decrease in the percentage of summerwood often occurs during the first few years after fertilization, it is usually short-lived. A curve of summerwood percentage compared with age will therefore show a several-year decline followed by a return to normal values. This temporary decline in summerwood percentage has a negligible effect on specific gravity. In fact, most studies conducted on southern pines growing on reasonably good sites indicate that summerwood percentage and wood specific gravity are not adversely affected by site fertilization (MeGraw 1986, Blanche and others 1992, Jokela and Stearns-Smith 1993). If, however, fertilizer treatments are either heavy or frequently repeated, as in Posey's (1964) studies on loblolly pine, then significant reductions can occur in both summerwood percentage and specific gravity. These values return to normal gradually over a period of years. Posey (1964) and Rockwood and others (1985) noted tree to tree variation, suggesting a genetic response to fertilization.

Irrigation and Drainage

The growth responses due to irrigation are similar to those brought about by fertilization. That is, the response depends on the time of year in which water is artificially applied. Consequently, early-season irrigation will favor height growth and overall crown development, which promotes springwood formation, whereas late-season irrigation will prolong seasonal cambial activity, which promotes summerwood formation. In most irrigation studies, water is supplied throughout the growing season resulting in greater growth and wider growth rings. Because both springwood and summerwood formation are promoted under this irrigation schedule, the effect on wood specific gravity is usually negligible.

In practice, water might more realistically be supplied when needed. Because soil moisture is most commonly limiting during late-season growth, irrigation at this time of year would promote summerwood formation and increase specific gravity.

Cultivation

Cultivation involves the removal of competition by herbaceous weeds, grasses, and woody undergrowth. In newly planted stands, cultivation removes plants that not only overtop and "smother" small seedlings but also compete for soil moisture and nutrients. Cultivation is often continued in young sapling stands as a growth enhancement practice.

Schmidtling (1973) reported that cultivation of a loblolly pine plantation during the first 3 years of growth resulted in a 6-ft (1.9-m) growth advantage compared with uncultivated controls by the 9th year. In addition to a much greater growth rate by trees in the cultivated stand, the size distribution among trees was more uniform. Despite the increase in growth rate, specific gravity values were not appreciably less than that of uncultivated controls. Again, one of the anticipated effects of cultivation is to prolong summerwood formation by increasing the late-season availability of soil moisture.

Clark and others (1991) examined the effect of cultivation on wood formation of slash pine when growing on moderately well-drained and poorly drained soils in the lower Coastal Plain of Georgia. On study plots that received no cultivation, the length of juvenility was 8 years on both the moderately well-drained and poorly drained sites. On intensively cultivated plots, juvenile wood was produced 2 years longer on moderately well-drained soil than on poorly drained soil. However, the specific gravity of the juvenile wood from the trees on the cultivated, moderately well-drained site was 6% higher than that of the trees on the control sites or poorly drained cultivated sites.

Mechanical and Strength Properties

Shrinkage

Longitudinal shrinkage is the defect most frequently associated with juvenile wood. Although wood sometimes expands during the early stages of drying, most wood shrinks longitudinally to some degree as moisture is removed from within the cells and cellular matrix. If compression wood is present, longitudinal shrinkage will be greatly accentuated (Harris 1977). Differential shrinkage also contributes to warp, which compounds the effect of the defect (Beard and others 1993).

Shrinkage of juvenile wood is closely correlated with specific gravity. The lower the specific gravity, the greater the longitudinal shrinkage, and the higher the specific gravity, the greater the radial, tangential, and volumetric shrinkage (Yao 1969). Low density springwood shrinks to a far greater degree than high density summerwood in juvenile wood. The lower density of the springwood can be attributed to shorter tracheids with larger radial diameters and thinner walls. As moisture is removed from the interstices between microfibrils and finally from within the cellulose matrix, anisotropic shrinkage progressively increases. Fibril angle, in turn, is negatively correlated with both tracheid length and wall thickness. McAlister and Clark (1992) have pointed out that there is no single, easily measurable property related to longitudinal shrinkage. Similarly, Beard and others (1993) concluded that there are no readily observable growth characteristics to identify lumber with a proclivity to warp. However, available evidence suggests that shrinkage might be most closely related to fibril angle (Ying and others 1994).

MOR and MOE

Modulus of rupture (MOR) and modulus of elasticity (MOE) are mechanical properties of wood that are highly correlated with specific gravity. Both properties are therefore strongly influenced by the age patterns of specific gravity typically found in the juvenile core. The relatively few studies that have compared the strength properties of juvenile and mature wood have consistently shown lower values for juvenile wood. Data from a study by Pearson and Ross (1984) based on wood from a 15-year-old loblolly pine progeny test (six 4-ft (1.2-m) logs) and a 25-year-old commercial plantation (three 4-ft (1.2-m) logs) are given in Table 6.

Data from another study by Bentdsen and Senft (1986) based on a 30-year-old loblolly pine plantation (six 6-ft (1.8-m) logs) are given in Table 7.

Table 6—Average value of specific gravity, modulus of elasticity (MOE), and modulus of rupture (MOR) at average number of rings from pith for two different age trees

Number of rings from pith	Specific gravity		MOE ($\times 10^6$ lb/in^2)[a]		MOR (lb/in^2)[a]	
	25-yr-old tree	15-yr-old tree	25-yr-old tree	15-yr-old tree	25-yr-old tree	15-yr-old tree
0+	0.4	0.38	0.88	0.64	9,080	7,260
2+	0.43	0.39	1.31	1.04	10,600	8,980
5+	0.47	0.44	1.53	1.36	13,100	11,400
10+	0.5	0.517	2.08	1.64	16,700	13,900

[a]1 lb/in^2 = 6.9 kPa.

Table 7—Average properties by age for loblolly pine

Age (years)	Specific gravity	MOR (lb/in^2)[a]	MOE ($\times 10^6$ lb/in^2)[a]	Maximum crush (lb/in^2)[a]	Tracheid length (mm)	Fibril angle (deg)	Ring width (in.)[b]
1	0.412	4,200	0.289	2,020	1.57	36.5	0.394
2	0.384	4,240	0.294	1,880	1.73	39.0	0.508
3	0.400	3,800	0.293	1,620	1.95	39.3	0.360
4	0.400	4,400	0.349	1,730	2.14	37.0	0.367
5	0.436	5,470	0.498	2,160	2.37	31.0	0.348
6	0.423	5,490	0.514	2,100	2.53	33.7	0.312
7	0.467	6,470	0.642	2,550	2.68	33.2	0.260
8	0.502	6,848	0.710	2,960	2.82	29.5	0.223
9	0.514	8,160	0.904	3,190	3.03	24.5	0.181
10	0.531	9,820	1.120	3,430	3.16	27.3	0.164
15	0.582	11,570	1.541	4,140	3.51	22.0	0.138

[a]1 lb/in^2 = 6.9 kPa.
[b]1 in. = 25.4 mm.

In the latter study, there was a fivefold increase in the average MOE (0.3 to 1.6 $\times 10^6$ lb/in^2 (2.1 to 11 GPa)) and about a threefold increase in MOR (4,000 to 12,000 lb/in^2 (27.6 to 82.7 MPa)) from early juvenile wood to late mature wood (23+ years). Pearson (1988) found that maximum crushing strength and MOE of clear loblolly pine nominal 2- by 4-in. (standard 38- by 89-mm) lumber (2 by 4's) cut from juvenile wood, on average, were only 52% and 37%, respectively, of the corresponding means for mature wood. To appreciate the significance of these differences in both wood quality characteristics and physical properties, imagine a 6-in. (15.2-cm) radially cut board extending inward to the pith. Even at a growth rate of 3 rings per inch (1.2 rings/cm), such a board would encompass 18 growth rings.

Although these data are revealing, it must be recognized that the sampling base in all such studies is small and rarely are comparisons made for juvenile and mature wood obtained from the same tree. Moreover, in relatively few studies did the authors relate strength properties to wood characteristics other than specific gravity. Yet, available data suggest that the differences in strength properties between juvenile and mature wood cannot be accounted for solely by differences in specific gravity (Bendtsen 1978). The actual volume of springwood and the large fibril angles of the springwood tracheids in the early juvenile growth rings might be far more important than previously realized. In support of this suggestion, Cave and Walker (1994) concluded that fibril angle was the only factor that alone could account for the pronounced decrease in stiffness (MOE) of radiata pine wood.

Tensile Strength

Tensile strength of juvenile wood has been of increasing concern in recent years because of its effect when used in laminated beams and finger joints in lumber. In the latter case, finger joints in nominal 2- by 6-in. (standard 38- by 140-mm) lumber containing juvenile wood from southern pines were 34% lower in tensile strength than those without juvenile wood (Moody 1970). Tensile strength values of 2 by 4's composed entirely of loblolly pine juvenile wood were from 45% to 59%, depending on lumber grade, of those composed entirely of mature wood (Kretschmann and Bendtsen 1992). As in the case of other strength properties, the large fibril angles of juvenile wood tracheids appear to strongly influence the tensile strength values.

Shear Parallel to Grain and Compression and Tension Perpendicular to Grain

Most information developed on juvenile wood to date has concentrated on ultimate tensile stress, MOR, and MOE. Little work has been done looking at the effect of juvenile wood content on less important properties. In one study, the effect of ring orientation and percentage of juvenile wood was investigated on shear parallel to grain and compression and tension perpendicular to grain strength (D.E. Kretschmann, unpublished report). The data indicate that the average of all three properties decreased with increasing amounts of juvenile wood in the cross section. Shear strength was insensitive to annual ring orientation and followed the expected shear strength density relationship. Compression and tension perpendicular to grain strength was very sensitive to annual ring orientation. Also, tension and compression perpendicular to grain, with loads applied to the radial face, were more sensitive to changes in juvenile wood content than expected.

Conclusion

Two main conclusions can be drawn from a review of the extensive literature on juvenile wood and wood quality characteristics in loblolly pine and related species:

1. Wood formation and the interrelations among various wood quality characteristics are exceedingly complex.

2. The existing literature provides few identifiable clues as to how to deal with this complexity.

Discussion

We consider the second conclusion first. The literature on juvenile wood, although extensive and filled with valuable information and data, has never been synthesized from the standpoint of solid wood products and structural wood-based composites. That is, each published report focused on a particular objective and addressed an isolated part of the juvenile wood problem. In addition, the variables in the studies, such as tree growth and stand conditions, differed so widely that few data yielded valid comparisons.

Most investigations provided average values for the selected characteristics based on either several to many growth rings or the entire juvenile core. Average values are perhaps legitimate for analyzing wood quality characteristics for pulpwood, and pulpwood has been the main objective of juvenile wood research over the years. When pulped, juvenile wood has good paper properties except for significantly low tear strength because of short tracheids. When juvenile wood is processed in the mill, it is mixed with mature wood and the low tear properties become less critical. That is, wood quality is averaged out.

Average values for juvenile wood characteristics are essentially meaningless for solid wood products and structural wood-based composites. For example, summerwood percentage and wood specific gravity are often used to define the size of the juvenile core. Yet, the average specific gravity of a board containing wide juvenile growth rings provides little or no information as to how the board will respond to drying. A board cut through the juvenile core might have a perfectly acceptable average specific gravity, but within that board, one to several substandard growth rings would be sufficient to cause unacceptable shrinkage or warp. That is, individual boards do not shrink on the basis of average values but only on the characteristics of the annual rings that comprise them. Although present grading rules based on growth ring width and summerwood percentage would perhaps downgrade such boards, the rules are admittedly subjective. The main point of this discussion is not to criticize grading rules. Rather, it is to emphasize that average juvenile wood quality characteristics derived from investigations with pulpwood as an objective are not directly applicable to solid wood products.

For the same reasons cited above, we might argue against a juvenile wood zone of 10-year duration because it has been reported to vary with geographic location. Again, this value was established for pulpwood and it, too, is based on an average tree, growing in an average stand, on an average site for loblolly pine. Criteria for identifying a juvenile core are needed that are more appropriate for solid wood products. However, since we do not at present have such a model, we will continue to refer to the 10-year juvenile core in this discussion.

Juvenile wood quality is indeed exceedingly complex. In the main body of this report, we have briefly summarized how juvenile wood is formed, the important wood characteristics associated with juvenile wood, and how these wood characteristics vary with environmental conditions and silvicultural practices. Like all previous reports on the subject, this review provides few clues as to how to deal with this complexity. Admittedly, there is no simple solution to the problems confronting the utilization of juvenile wood, but it is possible to narrow the scope of the problem and confine the extent of future investigations.

We know what characteristics of juvenile wood contribute to undesirable solid wood properties. Above all are the inherent changes in wood characteristics that occur with increasing growth ring age within the juvenile core. These changes are greatly accentuated in the extremely wide growth rings found in rapidly grown plantation trees. Wide juvenile growth rings have relatively low summerwood percentages and low wood specific gravity values compared with those of mature wood. However, both summerwood percentage and specific gravity are simply indices that reflect anatomical differences of the individual tracheids such as radial diameter and wall thickness. Although these indices provide valuable rules of thumb, for example, grading rules, the indices by themselves do not provide an answer to the juvenile wood problem.

We also know that within a growth ring, springwood differs greatly from summerwood. In juvenile wood of loblolly pine, springwood specific gravity averages about 0.29 and that of summerwood about 0.63. Again, these differences are due to the larger radial diameters and thinner walls of the springwood tracheids relative to those of summerwood. The specific gravity of juvenile springwood is not significantly different from that of mature springwood, both of which fall within the range of 0.29 to 0.40. However, the specific gravity of juvenile summerwood is significantly different from that of mature summerwood, which might range from 0.65 to 0.85 (Koch 1972). One might therefore conclude that efforts should be made to increase juvenile summerwood specific gravity. However, summerwood with a specific gravity of 0.50 to 0.55 or higher does not shrink or warp excessively. In fact, growth rings consisting entirely of juvenile summerwood would undoubtedly be acceptable from the strength standpoint for most solid wood products.

On the basis of the foregoing analysis, one might argue that a high proportion of springwood is the major problem in juvenile wood. Wide juvenile growth rings that contain a high proportion of springwood and transition tracheids have springwood tracheids that are shorter with larger fibril angles than summerwood tracheids and have larger radial diameters and thinner cell walls. It would appear that a high proportion of juvenile springwood is the characteristic of greatest impact, which is more specifically the thickness of the walls and the fibril angles of the tracheids that comprise the springwood.

Two possibilities exist for rectifying this imbalance between juvenile springwood and summerwood: silvicultural and genetic practices.

A first step in an evaluation program would be to establish meaningful parameters for juvenile wood characteristics and physical properties applicable to solid wood products. A suggested procedure would be to analyze individual growth rings throughout the stem of planted loblolly pine growing under a wide range of silvicultural practices across the geographic range of the species. Minimal data to be obtained from each growth ring would be ring width, springwood specific gravity, summerwood specific gravity, summerwood percentage, springwood and summerwood tracheid radial diameters, tracheid lengths, double wall thickness, and fibril angles. Additional data might include springwood and summerwood MOE and longitudinal shrinkage where feasible on small samples.

From these data, it should be possible to estimate at what ages physical properties attain acceptable values for different growth ring widths. It should also be possible to determine which wood characteristics, alone or in combination, contribute most strongly to the physical properties of juvenile wood and which characteristics might be susceptible to genetic improvement.

With the above database, if based on a sufficiently large and diverse sample, it should be possible to develop models for predicting ring widths, specific gravity, tracheid lengths, microfibrillar angle of springwood and summerwood, and ring MOE based on ring age, height in stem, geographic location, site productivity, and silvicultural practice. These models would then be used to determine the wood properties for specific silvicultural practices applied to specific sites in various geographic regions of the South. Knowing the wood properties would facilitate processing of timber into its optimum product application.

To test for the effect of growth rate on physical properties, analyses could be confined to juvenile growth ring numbers four through eight. The rational is as follows. The first three rings are truly juvenile, with wood quality characteristics well below acceptable values. Any improvement of rings four through eight might also, but not necessarily, benefit these rings. Any improvement in wood quality characteristics of rings four through eight would naturally benefit rings nine and older because of the inherent increase in wood quality characteristics with age. Confining analyses to rings four through eight would not only simplify sampling but also minimize any effect of averaging.

This exercise should provide information as to whether or not, and to what extent, wood quality characteristics and physical properties can be modified by silvicultural practices that, in turn, modify growth rate. It would provide information not now available, such as whether a reduction in juvenile ring width would reduce springwood percentage, and if so, whether it would result in an improvement in physical wood properties. This exercise would not provide information as to the practical and economic feasibility of silvicultural control of juvenile wood formation.

Another possibility for using the foregoing database and prediction models is manipulating the growth rate of genetically improved trees by silvicultural practices such as stand density control. For example, modifying growth rate by stand density alone might be uneconomical because of reduced volume production. However, the combination of genetically improved trees and judicious stand density regulation might result in higher physical properties that would offset any reduction in volume growth.

A second suggestion that might warrant consideration relates to site and geographic location. We know that wood specific gravity of loblolly pine varies from site to site and also regionally within the species range. It might be feasible to harvest from predetermined regions for solid wood products with specific strength and stiffness requirements.

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Appendix—References

Extensive literature exists on the anatomical characteristics of juvenile wood and the effects of juvenile wood on wood properties. This reference list is confined to the southern pines, primarily to loblolly and slash pines. Numerous references to radiata pine, grown mainly in Australia and New Zealand, have also been included because of its close resemblance to the southern pines and the extensive research conducted on this species. Not all listed references are cited in the report.

Key Words

Species

General overview

Wood characteristics

Ring width (includes ring per inch and growth rate)

Ring age (includes growth ring age from pith, length of juvenile period, and juvenile–mature comparisons)

Specific gravity (includes wood density, basic density, and dry weight yields)

Uniformity (applies to growth ring width and specific gravity values)

Summerwood percentage

Springwood vs. summerwood (Springwood–summerwood comparison of wood characteristics)

Tracheid length

Tracheid diameter (includes radial and tangential lumen diameter)

Wall thickness (refers to radial and tangential tracheid wall thickness)

Fibril angle (also microfibrillar angle and micellar angle)

Position in stem (refers to variation in wood characteristics at different stem heights)

Other wood-related properties

Branchiness (includes branch size, angle, and position)

Knots (includes associated knotwood)

Compression wood (includes reaction wood)

Extractives (includes pitch, resin, mineral deposits, and lignification)

Heartwood

Spiral grain (includes twisted grain)

Bark (bark thickness and volume)

Tree characteristics

Crown size (includes crown length and width and tree height)

Foliage efficiency (includes needle mass, net assimilation, and contribution of different-aged needles)

Tree age (includes juvenile compared with mature trees)

Tree diameter (includes tree class — suppressed compared with dominant)

Stem form (twist, torsion, crook, sweep, etc.)

Stem taper

Stand characteristics

Stand density (initial tree spacing trials as opposed to thinning; includes stocking based on basal area and trees per acre)

Site (site quality, site index, local environment)

Geographic location (includes climatic differences)

Silvicultural modification

Thinning (includes release cutting)

Pruning (includes partial defoliation — natural and artificial)

Fertilization

Irrigation

Drainage

Cultivation (postplanting disking, weeding, mowing, other than fertilization)

Inheritance

General heredity

Provenance tests

Clonal tests

Progeny tests

Heritability estimates

Parental specific gravity (evaluation or selection for trees with high and low specific gravity or identification of such trees)

Structural properties

Shrinkage (longitudinal, radial, tangential, and volumetric)

Warp (includes twist, bow, and other distortions)

Brashness

Modulus of rupture (parallel and perpendicular to grain)

Modulus of elasticity (parallel and perpendicular to grain)

Compressive strength (parallel and perpendicular to grain)

Tensile strength (parallel and perpendicular to grain)

Shear strength

Sawlog yield (refers also to lumber yield and sawtimber quality)

Other structural (structural mechanical properties other than above)

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(general overview, specific gravity, tracheid length)

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(*P. radiata*, specific gravity, branching, general heredity, progeny tests)

Bannister, M.H.; Vine, M.H. 1981. An early progeny trial in Pinus radiata 4. Wood density. New Zealand Journal of Forest Science. 11: 221–243.
(*P. Radiata*, ring width, ring age, specific gravity, branchiness, tree diameter, stem form, progeny tests, heritability estimates)

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(*P. taeda*, specific gravity, crown size, tree diameter, stand density, sawlog yield)

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(general overview, southern pines, specific gravity, tracheid length, fibril angle, general heredity, shrinkage, other structural)

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(*P. taeda*, *P. elliottii*, *P. palustris*, *P. echinata*, specific gravity, geographic location, modulus of rupture, modulus of elasticity, compressive strength, other structural)

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(*P. taeda*, ring age, tracheid length, position in stem)

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(*P. taeda*, xylem formation, inner bark chemistry, fertilization)

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(*P. caribaea*, specific gravity, compression wood, site, shrinkage, modulus of rupture, modulus of elasticity, compressive strength)

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(wall thickness, fibril angle, extractives, shrinkage)

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(*P. radiata*, ring width, specific gravity, wall thickness, fibril angle, modulus of elasticity, compressive strength)

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(*P. taeda*, tree form, general heredity, sawlog yield)

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(*P. taeda*, stem taper, stand density, thinning, sawlog yield)

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(*P. taeda*, ring width, specific gravity, branchiness, tree diameter, stem taper, thinning, pruning, cultivation, sawlog yield)

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(*P. radiata*, fibril angle, modulus of elasticity)

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(*P. radiata*, specific gravity, wall thickness, fibril angle, extractives, shrinkage)

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(*P. taeda*, ring age, specific gravity, tracheid length, extractives, tree diameter, fertilization, irrigation cultivation)

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(*P. taeda*, *P. elliottii*, red-cockaded woodpecker, heartwood formation)

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(*P. taeda*, *P. elliottii*, ring age, specific gravity, summerwood percentage, wall thickness, tree diameter, stand density, geographic location, shrinkage)

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(*P. taeda, P. palustris, P. echinata*, ring width, shrinkage)

Cole, D.E.; Zobel, B.J.; Roberds, J.H. 1966. Slash, loblolly, and longleaf pine in a mixed natural stand; a comparison of their wood properties, pulp yields, and paper properties. TAPPI Journal. 49: 161–166.
(*P. taeda, P. elliottii*, *P. palustris*, specific gravity, tracheid length, extractives)

Collicott, L.V.; Strickland, J.R.; Stonecypher, R.W. 1968. Dry-weight yields of slash pine plantations. Tech. Note 27. Bainbridge, GA: Southlands Experiment Forest International Paper Company. 17 p.
(*P. elliottii*, ring width, specific gravity, position in stem, branchiness, tree age, tree diameter, thinning)

Cown, D.J. 1973. Effects of severe thinning and pruning treatments on the intrinsic wood properties of young radiata pine. New Zealand Journal of Forestry Science. 3: 379–389.
(*P. radiata*, ring width, ring age, specific gravity, summerwood percentage, springwood vs. summerwood, tracheid length, position in stem, thinning, pruning)

Cown, D.J. 1974a. Wood density of radiata pine: Its variation and manipulation. New Zealand Journal of Forestry Science. 4: 84–92.
(*P. radiata*, general overview, ring age, specific gravity, tracheid length, fibril angle, position in stem, tree diameter, stand density, site)

Cown, D.J. 1974b. Comparison of the effects of two thinning regimes on some wood properties of radiata pine. New Zealand Journal of Forestry Science. 4: 540–551.
(*P. radiata*, ring width, ring age, specific gravity, tracheid length, position in stem, compression wood, heartwood, stem form, thinning, pruning)

Cown, D.J. 1977. Partial defoliation and wood properties of 5-year-old Pinus radiata. New Zealand Journal of Forestry Science. 7: 192–198.
(*P. radiata*, ring width, ring age, specific gravity, summerwood percentage, springwood vs. summerwood, tracheid length, foliage efficiency, pruning)

Cown, D.J. 1989. Wood characteristics of New Zealand *radiata* pine and Douglas fir: Suitability for processing. New Zealand Forest Research Institute Rep. Commissioned by New Zealand Forestry Coop. Ltd. 85 p.
(*P. radiata*, general overview, ring width, ring age, specific gravity, summerwood percentage, springwood vs. summerwood, tracheid length, position in stem, branchiness, compression wood, extractives, heartwood, spiral grain, thinning, pruning, fertilization, shrinkage)

Cown, D.J.; McConchie, D.L. 1983. *Radiata* pine wood properties survey (1977–1982). FRI Rep. 50. New Zealand Forest Service. 42 p.
(*P. radiata*, ring width, ring age, specific gravity, tracheid length, position in stem, extractives, heartwood, tree age, site, geographic location, shrinkage, sawlog yield)

Cown, D.J.; Love, J.G.; McConchie, D.L.; Colbert, C. 1984. Wood properties of *radiata* pine in some forests of the Bay of Plenty/Taupo region. FRI Rep. 81. New Zealand Forest Service. 23 p.
(*P. radiata*, ring age, specific gravity, position in stem, heartwood, site, geographic location, sawlog yield)

Cregg, B.M.; Dougherty, P.M.; Hennessey, T.C. 1988. Growth and wood quality of young loblolly pine trees in relation to stand density and climatic factors. Canadian Journal of Forest Research. 18: 851–858.
(*P. taeda*, specific gravity, summerwood percentage, tracheid diameter, wall thickness, foliage efficiency, thinning)

Cromer, R.N.; Barr, N.J.; Williams, E.R.; McNaught, A.M. 1985. Response to fertilizer in a *Pinus radiata* plantation. New Zealand Journal of Forestry Science. 15: 59–70.
(*P. radiata*, specific gravity, branchiness, bark, crown size, foliage efficiency, stem taper, fertilization)

Cubbage, F.W. 1990. Economic impacts of southern pine wood quality changes. Gen. Tech. Rep. SE–63. Asheville, NC: U.S. Department of Agriculture, Forest Service, Southeastern Station. 70: 57.
(general overview, southern pines, sawlog yield)

Dadswell, H.E.; Nicholls, J.W.P. 1959. Assessment of wood qualities for tree breeding. I. In: *Pinus elliottii* var. Elliottii from Queensland, Australia. For. Prod. Tech. Pap. CSIRO Division Forest Products Laboratory. 4: 1–16.
(*P. elliottii*, ring width, specific gravity, summerwood percentage, tracheid length, fibril angle, compression wood, spiral grain, general heredity, shrinkage)

Dadswell, H.E.; Fielding, J.M.; Nicholls, J.P.; Brown, A.G. 1961. Tree-to-tree variations and the gross heritability of wood characteristics of *Pinus radiata*. TAPPI Journal. 44(3): 174–179.
(*P. radiata*, ring width, ring age, summerwood percentage, springwood vs. summerwood, compression wood, spiral grain, clonal tests, heritability estimates, shrinkage)

de Villiers, A.M. 1965. Silvicultural, exploitation and conversion methods that affect timber quality. Pt. 1. South African Forestry Journal. 55: 21–31.
(*P. taeda, P. elliottii, P. patula*, ring width, ring age, specific gravity, tracheid length, branchiness, compression wood, extractives, spiral grain, stand density, thinning, pruning, other structural, sawlog yield)

de Villiers, A.M. 1966. Silvicultural, exploitation and conversion methods that affect timber quality. Pt. 2. South African Forestry Journal. 56: 5–10.
(*P. taeda, P. elliottii, P. patula*, ring width, ring age, specific gravity, tracheid length, branchiness, compression wood, extractives, spiral grain, stand density, thinning, pruning, other structural, sawlog yield)

Dinwoodie, J.M. 1975. Timber—a review of the structure-mechanical property relationship. Journal of Microbiology. 104: 3–32.
(general overview)

Echols, R.M. 1960. Effects of growing space on wood specific gravity in loblolly pine. In: Proceedings, Society of American Forestry; 1959: 140–143.
(*P. taeda*, specific gravity, tree diameter, stand density, thinning)

Einspahr, D.W.; Goddard, R.E.; Gardner, H.S. 1964. Slash pine, wood and fiber property heritability study. Silvae Genetica. 13: 103–109.
(*P. elliottii*, specific gravity, summerwood percentage, tracheid length, compression wood, extractives, clonal tests, heritability estimates)

Elliott, G.K. 1970. Wood density in conifers. Commonwealth Forestry Bureau of Technical Communications 8. 44 p.
(general overview, ring width, ring age, specific gravity, summerwood percentage, springwood vs. summerwood, tracheid length, tracheid diameter, wall thickness, position in tree, stand density, site, geographic location, fertilization, progeny tests)

Fenton, R.I. 1973. Profitability of second log pruning. New Zealand Journal of Forestry Science. 3: 313–322.
(*P. radiata*, pruning, sawlog yield)

Fielding, J.M. 1967. Influence of silvicultural practices on wood properties. International Review of Forest Research. 2: 95–126.
(general overview, ring age, specific gravity, tracheid length, compression wood, spiral grain, stand density, thinning, pruning, fertilization, general heredity)

Fielding, J.M.; Brown, A.G. 1961. Tree-to-tree variations in the health and some effect of superphosphate on the growth and development of Monterey pine on a low quality site. Forest Timber Bureau Australia Leaflet 79. 19 p.
(*P. radiata*, ring width, specific gravity, crown size, fertilization, clonal tests)

Frampton, L.J., Jr.; Jett, J.B. 1989. Juvenile wood specific gravity of loblolly pine tissue culture plantlets and seedlings. Canadian Journal of Forest Research. 19: 1347–1350.
(*P. taeda*, specific gravity, uniformity, site, clonal tests, progeny tests)

Franklin, E.C. 1987 Economics of forest management options: influence on wood properties. In: TAPPI Research and Development conference; 1987 April; Atlanta, GA: 43–48.
(*P. taeda*, tree age, stand density, site, thinning, sawlog yield)

Franklin, E.C.; Bridgwater, F.E. 1981. Genetics of fast growth and wood properties. In: Proceedings, TAPPI annual meeting; 1981 March 2–5; Chicago IL: 445–448.
(*P. taeda, P. elliottii*, specific gravity, tracheid length, tree form, general heredity)

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(*P. caribaea* var. hondurensis, ring width, ring age, specific gravity, position in stem, extractives, site)

Gentle, S.W.; Bamber, R.K.; Humphreys, F.R. 1968. Effect of two phosphate fertilizers on yield, financial yield, and wood quality of *radiata* pine. Forest Science. 14: 282–286.
(*P. radiata*, specific gravity, summerwood percentage, tracheid length, fertilization, sawlog yield)

Gerry, E. 1916. Fiber measurement studies: A comparison of tracheid dimensions in longleaf pine and Douglas fir, with data on the strength and length, mean diameter and thickness of wall of the tracheids. Science. 43 (1106): 360.
(*P. palustris*, ring age, springwood vs. summerwood, tracheid length, tracheid diameter, wall thickness)

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(*P. taeda*, ring width, ring age, specific gravity, summerwood percentage, tree diameter, stand density)

Gilmore, A.R.; Metcalf, G.E.; Bogess, W.R. 1961. Specific gravity of shortleaf pine and loblolly pine in southern Illinois. Journal of Forestry. 59: 894–896.
(*P. taeda, P. echinata*, specific gravity, geographic location)

Gilmore, A.R.; Boyce, S.G.; Ryker, R.A. 1966. The relationship of specific gravity of loblolly pine to environmental factors in southern Illinois. Forest Science. 12: 399–405.
(*P. taeda*, specific gravity, summerwood percentage, site, geographic location)

Goddard, R.E.; Cole, D.E. 1966. Variation in wood production of six-year-old progenies of select slash pine. TAPPI Journal. 49: 359–362.
(*P. elliottii*, specific gravity, extractives, geographic location, progeny tests, parental specific gravity)

Goddard, R.E.; Strickland, R.K. 1962. Geographic variation in wood specific gravity of slash pine. TAPPI Journal. 45: 606–608.
(*P. elliottii*, specific gravity, site, geographic location)

Goggans, J.F. 1961. The interplay of environment and heredity as factors controlling wood properties in conifers with special emphasis on their effects on specific gravity. Sch. For. Tech. Rep. 11. Raleigh, NC: University of North Carolina. 56 p.
(*P. taeda*, general overview, ring width, ring age, specific gravity, summerwood percentage, springwood vs. summerwood, tracheid length, tracheid diameter, wall thickness, extractives, site, general heredity)

Goggans, J.F. 1964. Correlation and heritability of certain wood properties in loblolly pine (*Pinus taeda*.) TAPPI Journal. 47: 318–322.
(*P. taeda*, ring width, specific gravity, summerwood percentage, springwood vs. summerwood, tracheid length, tracheid diameter, wall thickness, site, progeny tests, heritability estimates)

Gordon, J.C.; Larson, P.R. 1970. Redistribution of reserve food in young red pines during shoot elongation. Forest Science. 16: 14–20.
(foliage efficiency)

Gorman, T.M. 1985. Juvenile wood as a cause of seasonal arching in trusses. Forest Products Journal. 35: 35–40.
(*P. taeda*, shrinkage)

Grant, R.K. 1978. Predicting the impact of silvicultural treatment on wood characteristics of *Pinus radiata*. New Zealand Journal of Forestry Science. 8: 277–287.
(*P. radiata*, tree diameter, tree age, stand density, thinning, sawlog yield)

Greene, J.T. 1966. Selection for tracheid length in loblolly pine (*Pinus taeda* L.). Georgia Forest Research Council. Rep. 18. 30 p.
(*P. taeda*, ring age, tracheid length, position in stem, progeny tests, heritability estimates)

Greene, J.T.; Carmon, J.L. 1962. Variation of tracheid length in clonal lines of shortleaf pine. Georgia Forest Research Council. Res. Pap. 13. 6 p.
(*P. echinata*, tracheid length, clonal tests)

Hallock, H. 1968. Observations on form of juvenile core in loblolly pine. Res. Note FPL–0188. Madison, WI: U.S. Department of Agriculture, Forest Service, Forest Products Laboratory. 6 p.
(*P. taeda*, ring width, ring age, compression wood, warp)

Hamilton, J.R.; Harris, J.B. 1965. Influence of site on specific gravity and dimensions of tracheids in clones of *Pinus elliottii* Engelm. and *Pinus taeda* L. TAPPI Journal. 48: 330–333.
(*P. taeda, P. elliottii*, specific gravity, tracheid length, tracheid diameter, wall thickness, site, clonal tests)

Hamilton, J.R.; Matthew, R.M. 1965. Wood characteristics of planted loblolly and shortleaf pine. Res. Pap. 27. Georgia Forest Research Council. 5 p.
(*P. taeda, P. echinata*, ring width, ring age, specific gravity, summerwood percentage, crown size, tree diameter, stand density)

Harris, J.M. 1965. A survey of the wood density, tracheid length and latewood characteristics of *radiata* pine grown in New Zealand. For. Serv. Tech. Pap. 47. New Zealand Forest Research Institute. 31 p.
(*P. radiata*, ring width, ring age, specific gravity, uniformity, summerwood percentage, springwood vs. summerwood, tracheid length, branchiness, extractives, heartwood, stem form, site, geographic location, general heredity, parental specific gravity)

Harris, J.M. 1977. Shrinkage and density of *radiata* pine compression wood in relation to its anatomy and mode of formation. New Zealand Journal of Forestry Science. 7: 91–106.
(*P. radiata*, ring age, specific gravity, tracheid length, wall thickness, fibril angle, compression wood, stem form, general heredity, provenance tests, shrinkage)

Harris, J.M. 1981. Wood quality of *radiata* pine. Appita. 35: 211–215.
(*P. radiata*, ring age, specific gravity, tracheid length, tracheid diameter, wall thickness, site, general heredity)

Harris, J.M.; Meylan, B.A. 1965. The influence of microfibril angle on longitudinal and tangential shrinkage in *Pinus radiata*. Holzforschung. 19: 144–153.
(*P. radiata*, springwood vs. summerwood, fibril angle, compression wood, clonal tests, shrinkage)

Harris, J.M.; James, R.N.; Collins, M.J. 1976. Case for improving wood density in *radiata* pine. New Zealand Journal of Forestry Science. 5: 347–354.
(*P. radiata*, ring width, specific gravity, branchiness, thinning, general heredity, parental specific gravity, modulus of rupture, modulus of elasticity)

Hiller, C.H. 1954. Variations in fibril angles in slash pine. FPL Rep. 2003. Madison, WI: U.S. Department of Agriculture, Forest Service, Forest Products Laboratory. 6 p.
(*P. elliottii*, ring width, ring age, fibril angle, crown size, tree diameter, general heredity)

Hiller, C.H. 1964a. Correlation of fibril angle with wall thickness of tracheids in summerwood of slash and loblolly pine. TAPPI Journal. 47: 125–128.
(*P. taeda, P. elliottii*, ring age, wall thickness, fibril angle, position in stem)

Hiller, C.H. 1964b. Estimating size of the fibril angle in latewood tracheids of slash pine. Journal of Forestry. 62: 249–252.
(*P. elliottii*, ring width, ring age, summerwood percentage, tracheid length, wall thickness, fibril angle, crown size)

Hiller, C.; Brown, R.S. 1967. Comparison of dimensions and fibril angle of loblolly pine tracheids formed in wet or dry growing seasons. American Journal of Botany. 54: 453–460.
(*P. taeda*, ring width, summerwood percentage, springwood vs. summerwood, tangential diameter, wall thickness, fibril angle, position in stem)

Hodge, G.R.; Purnell, R.C. 1993. Genetic parameter estimates for wood density, transition age, and radial growth in slash pine. Canadian Journal of Forest Research. 23: 1881–1891.
(*P. elliottii*, ring width, specific gravity, summerwood percentage, springwood vs. summerwood, uniformity, site, progeny tests, heritability estimates)

Hsu, J.K.; Walters, C.S. 1975. Effect of irrigation and fertilization on selected physical and mechanical properties of loblolly pine (*Pinus taeda*). Wood and Fiber. 7: 192–206.
(*P. taeda*, ring width, specific gravity, summerwood percentage, springwood vs. summerwood, fertilization, irrigation, modulus of rupture, modulus of elasticity, other structural)

Ifju, G. 1969 Within-growth-ring variation in some physical properties of Southern Pine wood. Wood Science. 2: 11–19.
(southern pines, ring width, ring age, specific gravity, summerwood percentage, modulus of elasticity, tensile strength, other structural)

Ifju, G.; Labosky, P. 1972. A study of loblolly pine growth increments. Pt. 1. Wood and tracheid characteristics. TAPPI Journal. 55: 524–529.
(*P. taeda*, specific gravity, tracheid length, wall thickness, springwood vs. summerwood)

Jackson, L.W.R. 1959. Loblolly pine tracheid length in relation to position in tree. Journal of Forestry. 57: 366–367.
(*P. taeda*, ring age, springwood vs. summerwood, tracheid length, position in stem, branchiness, general heredity)

Jackson, L.W.R. 1962. Effects of size of forest openings on morphology of pine seedlings. Ecology. 43: 768–770.
(*P. taeda, P. echinata*, specific gravity, tracheid length, foliage efficiency, tree diameter, thinning)

Jackson, L.W.R.; Greene, J.T. 1957. Hereditary variations in slash pine tracheids. In: Proceedings, 4th southern conference on forest tree improvement: 23–26.
(*P. elliottii*, ring age, springwood vs. summerwood, tracheid length, position in stem, branchiness, progeny tests)

Jackson, L.W.R.; Greene, J.T. 1958a. Tracheid length variation and inheritance in slash and loblolly pine. Forest Science. 4: 316–318.
(*P. taeda, P. elliottii*, tracheid length, progeny tests)

Jackson, L.W.R.; Greene, J.T. 1958b. Slash pine tracheid length as related to position in stem and branch. Naval Stores Review. 68(4): 6,8.
(*P. elliottii*, ring age, tracheid length, springwood vs. summerwood, position in stem)

Jackson, L.W.R.; Morse, W.E. 1965a. Tracheid length variation in single rings of loblolly, slash, and shortleaf pine. Journal of Forestry. 63: 110–112.
(*P. taeda, P. elliottii, P. echinata*, ring width, springwood vs. summerwood, tracheid length)

Jackson, L.W.R.; Morse, W.E. 1965b. Variation in fibril angle of slash and loblolly pine. Res. Pap. 43. Georgia Forest Research Council. 5 p.
(*P. taeda, P. elliottii*, specific gravity, fibril angle, progeny tests)

Jackson, L.W.R.; Strickland, R.K. 1962. Geographic variation in tracheid length and wood density of loblolly pine. Res. Pap. 8. Georgia Forest Research Council. 4 p.
(*P. taeda*, ring width, specific gravity, tracheid length, springwood vs. summerwood, position in stem, geographic location, provenance tests)

Jackson, L.W.R.; Warren, B.J. 1962. Variation and inheritance in specific gravity of slash and loblolly pine progeny. Res. Pap. 14. Georgia Forest Research Council. 4 p.
(*P. taeda, P. elliottii*, specific gravity, progeny tests, parental specific gravity)

Jett, J.B.; Talbert, J.T. 1982. Place of wood specific gravity in the development of advanced-generation seed orchards and breeding programs. Southern Journal of Applied Forestry. 6: 177–180.
(*P. taeda*, specific gravity, progeny tests, heritability estimates, parental specific gravity)

Jokela, E.J.; Stearns–Smith, S.C. 1993. Fertilization of established southern pine stands: effects of single and split nitrogen treatments. Southern Journal of Applied Forestry. 17(3): 135–138. (August)
(*P. Elliottii, P. taeda*, nitrogen fertilizers, phosphorus fertilizers, application methods, growth, basal area, volume, split dressing)

Jurbergs, K.A. 1963 Determining fiber length, fibrillar angle, and springwood-summerwood ratio in slash pine. Forest Science. 9: 181–187.
(*P. elliottii*, specific gravity, summerwood percentage, tracheid length, fibril angle, position in stem)

Jurbergs, K.A. 1968. Transverse dimensions of slash pine tracheids. TAPPI Journal. 51: 389–394.
(*P. elliottii*, tracheid diameter, wall thickness, springwood vs. summerwood)

Kellison, R.C. 1981. Characteristics affecting quality of timber from plantations, their determinations and scope for modification. In: Proceedings, 17th IUFRO Division 5 forest products world congress; Japan: 77–88.
(*P. taeda*, general overview, specific gravity, tracheid length, springwood vs. summerwood, wall thickness, spiral grain, general heredity)

Kellison, R.C.; Deal, E.; Pearson, R.H. 1985. More plantation wood means quality problems. Forest Industries. 112(7): 24–26.
(general overview, specific gravity, tracheid length, wall thickness, fibril angle, shrinkage)

Kelsey, K.E. 1963. A critical review of the relationship between the shrinkage and structure of wood. For. Prod. Tech. Pap. 28. Queensland, Australia: CSIRO Division. 35 p.
(*P. taeda*, specific gravity, modulus of rupture, modulus of elasticity, other structural)

Kerr, J. 1931. Summerwood formation in southern pines dependent on capacity of soil to retain moisture. Forest Worker. 7(4): 17.
(*P. palustris*, summerwood percentage, fertilization, irrigation)

Kirk, D.G.; Breeman, L.G.; Zobel, B.J. 1972. A pulping evaluation of juvenile loblolly pine. TAPPI Journal. 55: 1600–1604.
(*P. taeda*, specific gravity, tracheid length, tracheid diameter, wall thickness)

Koch, P. 1972a. Three rings-per-inch dense southern pine—should it be developed. Journal of Forestry. 70: 332, 334, 336.
(southern pines, ring width, specific gravity, summerwood percentage, uniformity, compression wood, spiral grain, stem taper, general heredity, warp)

Koch, P. 1972b. Utilization of the southern pines. Vol. I. The raw material. Agric. Handb. 420. Washington, DC: U.S. Department of Agriculture. 734 p.
(southern pines, general overview)

Koehler, A. 1938. Rapid growth hazards usefulness of southern pine. Journal of Forestry. 36: 153–158.
(*P. taeda*, *P. elliottii*, ring width, specific gravity, uniformity, fibril angle, compression wood, shrinkage, warp, compressive strength, other structural)

Koehler, A. 1939. Heredity versus environment in improving wood in forest trees. Journal of Forestry. 37: 683–687.
(general overview, general heredity)

Kramer, P.R. 1957. Tracheid length variation in loblolly pine. Tech. Rep. 10. Texas Forest Service. 22 p.
(*P. taeda*, ring width, ring age, specific gravity, tracheid length, springwood vs. summerwood, general heredity)

Kretschmann, D.E. [In press]. Impact of juvenile wood on tension and compression perpendicular and shear parallel to grain strength for loblolly pine. Wood and Fiber Science.
(*P. taeda*, compression perpendicular to grain, tension perpendicular to grain, shear parallel to grain)

Kretschmann, D.E.; Bendtsen, B.A. 1992. Ultimate tensile strength and modulus of elasticity of fast-grown plantation loblolly pine lumber. Wood and Fiber Science. 24(2): 189–203.
(*P. taeda*, ring width, ring age, specific gravity, summerwood percentage, modulus of elasticity, tensile strength)

Kromhout, C.P.; Basman, D.L. 1981. The influence of short rotation forestry on wood production for sawnwood and veneer. In: Proceedings, 17th IUFRO Division 5 forest products world congress; Japan: 60–75.
(*P. taeda*, *P. elliottii*, *P. radiata*, ring width, ring age, compression wood, spiral grain, stand density, thinning, pruning, warp, sawlog yield)

Lantz, C.W.; Hofmann, J.G. 1969. Geographic variation in growth and wood quality of loblolly pine in North Carolina. In: Proceedings, 10th Southern forest tree improvement conference; Houston TX: 175–188.
(*P. taeda*, *P. elliottii*, ring width, specific gravity, geographic location, provenance tests)

Larson, P.R. 1956. Discontinuous growth rings in suppressed slash pine. Tropical Woods. 104: 80–99.
(ring width, summerwood percentage, crown size)

Larson, P.R. 1957. Effect of environment on the percentage of summerwood and specific gravity of slash pine. Sch. For. Bull. 63. New Haven, CT: Yale University. 78 p.
(*P. elliottii*, ring width, ring age, specific gravity, summerwood percentage, tree diameter, stand density, site, geographic location)

Larson, P.R. 1960. A physiological consideration of the springwood-summerwood transition in red pine. Forest Science. 6: 110–122.
(summerwood percentage, tracheid diameter, wall thickness, compression wood, foliage efficiency)

Larson, P.R. 1962a. A biological approach to wood quality. TAPPI Journal. 45: 443–448.
(ring width, ring age, specific gravity, summerwood percentage, crown size, tree diameter, site, geographic location, thinning, pruning)

Larson, P.R., ed. 1962b. The influence of environment and genetics on pulpwood quality: an annotated bibliography. Monog. 24. TAPPI. 316 p.
(specific gravity, summerwood percentage, tracheid length, tracheid diameter, wall thickness, fibril angle, compression wood, extractives, heartwood, spiral grain, tree diameter, stand density, site, geographic location, thinning, pruning, fertilization, irrigation, general heredity)

Larson, P.R. 1963a. Evaluating the environment for studies of the inheritance of wood properties. In: Proceedings, World Consultation of Forest Genetic & Tree Improvement; 1963 August; Stockholm, Sweden. Vol. II. 7/1:1–6.
(summerwood percentage, crown size, stand density, general heredity)

Larson, P.R. 1963b. Microscopic wood characteristics and their variations with tree growth. In: Proceedings, IUFRO Sect. 41; 1963 September 11–13; Madison, WI: Forest Products Laboratory: 24 p.
(summerwood percentage, springwood vs. summerwood, tracheid length, tracheid diameter, wall thickness, crown size, foliage efficiency)

Larson, P.R. 1963c. Stem form development of forest trees. Forest Science. Monogram 5. 42 p.
(specific gravity, crown size, stem taper, stand density, thinning, pruning, general heredity)

Larson, P.R. 1964. Contribution of different-aged needles to growth and wood formation of young red pine. Forest Science. 10: 224–238.
(ring width, specific gravity, tracheid diameter, wall thickness, foliage efficiency)

Larson, P.R. 1968. Assessing wood quality of fertilized coniferous trees. In: Bengtson, G.W., ed. Forest fertilization. Proceedings, symposium, forest fertilization; 1967 April; Gainesville FL: 275–280.
(specific gravity, summerwood percentage, springwood vs. summerwood, wall thickness, branchiness, crown size, foliage efficiency, site, fertilization)

Larson, P.R. 1969 Wood formation and the concept of wood quality. Sch. For. Bull. 74. New Haven, CT: Yale University. 54 p.
(specific gravity, summerwood percentage, uniformity, tracheid diameter, wall thickness, compression wood, crown size, foliage efficiency, stem taper, stand density, thinning, pruning, general heredity)

Larson, P.R. 1972. Evaluating the quality of fast-grown coniferous wood. In: Proceedings, 63rd Western Forest Conference; 1972 December 6–8; Seattle, WA: 146–152.
(*P. taeda*, *P. elliottii*, ring width, ring age, specific gravity, crown size, stand density, thinning , fertilization, irrigation)

Larson, P.R. 1973. The physiological basis for wood specific gravity in conifers. In: Proceedings. IUFRO Division 5, Forest Products; 1973 September–October 12; Stellenbosch, South Africa. 2: 672–679.
(specific gravity, summerwood percentage, tracheid length, tracheid diameter, wall thickness, crown size, foliage efficiency, stand density)

Larson, P.R. 1994. The vascular cambium: Development and structure. Berlin: Springer–Verlag. 725 p.
(general overview)

Lindgren, R.M. 1949. Density and moisture relations in slash pine wood. For. Notes 63. New Orleans LA: U.S. Department of Agriculture, Forest Service. 2 p.
(*P. elliottii*, ring width, specific gravity, position in stem)

Lodewick, J.E. 1933. Some summerwood percentage relationships in the southern pines. Journal of Agricultural Research. 46: 543–556.
(*P. taeda*, *P. palustris*, ring width, specific gravity, summerwood percentage, springwood vs. summerwood, wall thickness, position in stem, stand density)

Loo, J.A.; Tauer, C.G.; van Buijtenen, J.P. 1984. Juvenile–mature relationships and heritability estimates of several traits in loblolly pine (*Pinus taeda*). Canadian Journal of Forest Research. 14: 822–825.
(*P. taeda*, ring age, specific gravity, tracheid length, tree diameter, progeny tests, heritability estimates, parental specific gravity)

Loo, J.A.; Tauer, C.G.; McNew, R.W. 1985. Genetic variation in the time of transition from juvenile to mature wood in loblolly pine (*Pinus taeda*). Silva Genetica. 34: 14–19.
(*P. taeda*, ring age, specific gravity, tracheid length, site, progeny tests, heritability estimates, parental specific gravity)

Lulay, R.; Galligan, W.L. 1981. The impact of juvenile and compression wood on lumber from small logs. In: Proceedings, 32nd annual meeting, West Dry Kiln Clubs; 1981 May 6–8; Corvallis OR: 106–116.
(southern pines, general overview, specific gravity, fibril angle, shrinkage, warp, other structural)

MacPeak, M.D.; Burkart, L.F.; Weldon, D. 1990. Comparison of grade, yield, and mechanical properties of lumber produced from young fast-grown and older slow-grown planted slash pine. Forest Products Journal. 40(1): 11–14.
(*P. elliottii*, ring width, specific gravity, modulus of rupture, modulus of elasticity)

Manwiller, F.G. 1966. Southern pine cell walls and shrinkage. Southern Lumberman. 213(2656): 184–186.
(southern pines, fibril angle, compression wood, shrinkage, warp)

Manwiller, F.G. 1972. Wood and bark properties of spruce pine. Res. Pap. SO–78. Asheville, NC: U.S. Department of Agriculture, Forest Service. 25 p.
(*P. glabra*, ring width, ring age, specific gravity, summerwood percentage, springwood vs. summerwood, tracheid length, tracheid diameter, wall thickness, fibril angle.

Martin, J.W. 1984. Forest management practices that will influence product characteristics of the changing wood resource. In: Proceedings, Symposium utilization of changing wood resource in the Southern United States; 1984 June 12–14. Sch. For. Resources. Raleigh, NC: North Carolina State University: 115–123.
(*P. taeda*, specific gravity, knots, tree form, stand density, general heredity)

Marts, R.O. 1949. Effect of crown reduction on taper and density in longleaf pine. Southern Lumberman. 179(2249): 206–209.
(*P. palustris*, specific gravity, springwood vs. summerwood, crown size, stem taper, pruning)

Marts, R.O. 1951. Influence of crown reduction on springwood and summerwood distribution in longleaf pine. Journal of Forestry. 49: 183–189.
(*P. palustris*, specific gravity, summerwood percentage, springwood vs. summerwood, tracheid diameter, position in stem, crown size, tree taper, pruning)

Massey, J.G.; Reeb, J.E. 1989. A method for estimating juvenile wood content in boards. Forest Products Journal. 39(2): 30–32.
(ring width, sawlog yield)

Matziris, D.I.; Zobel, B.J. 1973. Inheritance and correlations of juvenile characteristics in loblolly pine (*Pinus taeda*). Silvae Genetica. 22: 38–45.
(*P. taeda*, ring age, specific gravity, tracheid length, bark, crown size, tree diameter, stem form, progeny tests, heritability estimates, parental specific gravity)

McAlister, R.H.; Clark, A., III. 1991. Effect of geographic location and seed source on the bending properties of juvenile and mature loblolly pine. Forest Products Journal. 41(9): 39–42.
(*P. taeda*, ring age, specific gravity, geographic location, provenance tests, modulus of rupture, modulus of elasticity)

McAlister, R.H.; Clark, A., III. 1992. Shrinkage of juvenile and mature wood of loblolly pine from three locations. Forest Products Journal. 42(7/8): 25–28.
(*P. taeda*, specific gravity, tree diameter, geographic location, provenance tests, shrinkage)

McAlister, R.H.; Powers, H.R., Jr. 1992. Physical and mechanical properties of half-sib families of rust-resistant loblolly and slash pine. Forest Products Journal. 42(11/12): 15–20.
(*P. taeda*, *P. elliottii*, specific gravity, summerwood percentage, progeny tests, shrinkage, modulus of rupture, modulus of elasticity, other structural)

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(*P. taeda*, ring age, specific gravity, progeny tests, shrinkage, modulus of rupture, modulus of elasticity)

McKinnell, F.H.; Rudman, P. 1972. Potassium fertilizer and wood density of *Pinus radiata*. Appita. 26: 283–286.
(*P. radiata*, ring width, ring age, specific gravity, tree diameter, stand density, thinning, fertilization)

McMillan, C.W. 1968. Morphological characteristics of loblolly pine wood as related to specific gravity, growth rate and distance from pith. Wood Science and Technology. 2: 166–176.
(*P. taeda*, ring width, ring age, specific gravity, springwood vs. summerwood, tracheid length, tracheid diameter, wall thickness)

Megraw, R.A. 1985. Wood quality factors in loblolly pine. TAPPI Press. 88 p.
(*P. taeda*, general overview)

Megraw, R.A. 1986. Effect of silvicultural practices on wood quality. In: Proceedings, TAPPI research and development conference; 1986 September 28–October 1; Raleigh, NC: 27–34.
(*P. taeda*, general overview, ring width, specific gravity, fibril angle, position in stem, compression wood, stand density, site, thinning, pruning, fertilization)

Meier, R.J.; Goggans, J.F. 1977. Heritabilities of height, diameter, and specific gravity on young Virginia pine. Forest Science. 23: 450–456.
(*P. virginiana*, specific gravity, crown size, site, progeny tests, heritability estimates)

Meylan, B.A. 1968. Cause of high longitudinal shrinkage in wood. Forest Products Journal. 18(4): 75–78.
(*P. radiata, P. Jeffreyi*, wall thickness, fibril angle, shrinkage)

Meylan, B.A. 1972. The influence of microfibril angle on the longitudinal shrinkage–moisture content relationship. Wood Science Technology. 6: 293–301.
(*P. radiata*, specific gravity, tracheid diameter, wall thickness, fibril angle, compression wood, shrinkage)

Miller, S.R. Jr. 1959. Variation in inherent wood characteristics in slash pine. In: Proceedings, 5th. Southern forest tree improvement conference: 97–105.
(*P. elliottii*, specific gravity, position in stem, bark, tree diameter, site)

Mitchell, H.L. 1964. Patterns of variation in specific gravity of southern pines and other coniferous species. TAPPI Journal. 47: 276–283.
(general overview, southern pines, ring width, ring age, specific gravity, geographic location)

Moehring, D.M. 1964. Speeding up growth of the loblolly. Forest Farmer. 23(6): 9, 13–14.
(*P. taeda*, specific gravity, tree diameter, fertilization, irrigation)

Moody, R.C. 1970. Tensile strength of fingerjoints in pith-associated and non-pith-associated Southern Pine lumber. Res. Pap. FPL–138. Madison, WI: U.S. Department of Agriculture, Forest Service, Forest Products Laboratory. 20 p.
(southern pines, ring width, specific gravity, modulus of elasticity, tensile strength)

Moschler, W.W., Jr.; Woods, F.W.; Vincent, L.W. 1985. Fiber length in normal and foxtail *Pinus caribaea*. Mor. Wood & Fiber Science. 17: 290–293.
(*P. caribaea*, ring age, tracheid length, position in stem, crown size)

Namkoong, G.; Barefoot, A.C.; Hitchings, R.G. 1969. Evaluating control of wood quality through breeding. TAPPI Journal. 52: 1935–1938.
(*P. taeda*, specific gravity, tracheid length, heritability estimates)

Nicholls, J.W.P. 1967. Preliminary observations on the change with age of the heritability of certain wood characters in *Pinus radiata* clones. Silvae Genetica. 16: 18–20.
(*P. radiata*, ring width, ring age, specific gravity, summerwood percentage, tracheid length, spiral grain, clonal tests, heritability estimates)

Nicholls, J.W.P. 1971. The effect of environmental factors on wood characteristics. Pt. 1: The influence of irrigation on *Pinus radiata* from South Australia. Silvae Genetica. 20: 26–33.
(*P. radiata*, ring width, ring age, specific gravity, summerwood percentage, springwood vs. summerwood, tracheid length, site, fertilization, irrigation)

Nicholls, J.W.P. 1984. Tracheid cell dimensions and density relationships for normal and abnormal wood of *Pinus radiata* D. Don. Australian Forest Research. 14: 85–98.
(*P. radiata*, specific gravity, tracheid diameter, wall thickness, springwood vs. summerwood, compression wood)

Nicholls, J.W.P.; Dadswell, H.E. 1962. Tracheid length in *Pinus radiata* D. Don. For. Prod. Tech. Pap. 24. Australian CSIRO Division. 19 p.
(*P. radiata*, tracheid length, springwood vs. summerwood, position in stem)

Nicholls, J.W.P.; Fielding, J.M. 1965. The effect of growth rate on wood characteristics. Appita. 19: 24–30.
(*P. radiata*, ring width, ring age, specific gravity, summerwood percentage, tracheid length, position in stem, spiral grain, clonal tests, shrinkage)

Nicholls, J.W.P.; Waring, H.D. 1977. The effect of environmental factors on wood characteristics. IV. Irrigation and partial droughting of *Pinus radiata*. Silvae Genetica. 26: 107–111.
(*P. radiata*, ring width, ring age, specific gravity, summerwood percentage, spiral grain, irrigation)

Nicholls, J.W.P.; Dadswell, H.E.; Fielding J.M. 1964. The heritability of wood characteristics of *Pinus radiata*. Silvae Genetica. 13: 68–71.
(*P. radiata*, ring width, ring age, specific gravity, summerwood percentage, tracheid length, spiral grain, clonal tests, heritability estimates, shrinkage)

Nicholls, J.W.P.; Morris, J.D.; Pederick, L.A. 1980. Heritability estimates of density characteristics in juvenile *Pinus radiata* wood. Silvae Genetica. 29: 54–61.
(*P. radiata*, ring width, specific gravity, summerwood percentage, springwood vs. summerwood, site, progeny tests, heritability estimates)

Page, D.H.; El–Hosseiny, F.; Winkler, K.; Bain R. 1972. The mechanical properties of single wood-pulp fibres. Pt. 1: A new approach. Pulp and Paper Magazine of Canada. 73(8): T198.
(black and white spruce, fibril angle, pulp, tensile strength, fibers)

Paul, B.H. 1913. Variation in weight of slash pine wood and its proportion of heartwood. Forest Worker. 8(2): 6–7.
(*P. elliottii*, specific gravity, position in stem, heartwood, tree age)

Paul, B.H. 1929. Relation of growth factors to wood quality growing space—longleaf pine. Southern Lumberman. 1768: 53–54.
(*P. palustris*, ring width, ring age, specific gravity, summerwood percentage, stand density)

Paul, B.H. 1930. The application of silviculture in controlling the specific gravity of wood. Tech. Bull. 168. U.S. Department of Agriculture. 20 p. Reprinted as Tech. Bull. 1288. 1963. 97 p.
(*P. taeda, P. elliottii, P. palustris, P. echinata*, ring width, ring age, specific gravity, crown size, stand density, site, geographic location, thinning)

Paul, B.H. 1932a. Quality versus size as an index of a profitable tree: loblolly pine. Journal of Forestry. 30: 831–833.
(*P. Taeda*, stand density, thinning)

Paul, B.H. 1932b. Some properties of slash pine. Pulp & Paper Magazine of Canada. 2 p. (January)
(*P. elliottii*, ring age, specific gravity, position in stem, heartwood, stand density)

Paul, B.H. 1938. Reducing bowing and crooking of lumber cut from southern yellow pine. Southern Lumberman. 156: 48–50.
(*P. taeda, P. elliottii*, ring width, uniformity, shrinkage, warp)

Paul, B.H. 1939. Variation in specific gravity of the springwood and summerwood of four species of southern pines. Journal of Forestry. 37: 478–482.
(*P. taeda, P. elliottii, P. palustris, P. echinata*, specific gravity, springwood vs. summerwood, position in stem)

Paul, B.H. 1952. Variability of wood of southern pines as influenced by silviculture. FPL Rep. R 1923. Madison, WI: U.S. Department of Agriculture, Forest Service, Forest Products Laboratory. 10 p.
(general overview, ring width, specific gravity, springwood vs. summerwood, compression wood, heartwood, site, pruning, shrinkage)

Paul, B.H. 1955. Importance of wood quality in tree breeding. Journal of Forestry. 53: 659–661.
(southern pines, ring width, ring age, fibril angle, general heredity, shrinkage, other structural)

Paul, B.H. 1957. Juvenile wood in conifers. FPL Rep. 2094. Madison, WI: U.S. Department of Agriculture, Forest Service, Forest Products Laboratory. 6 p.
(southern pines, ring width, ring age, specific gravity, crown size)

Paul, B.H. 1958. Specific gravity changes in southern pines after release. Southern Lumberman. 197(2465): 122–124.
(*P. taeda, P. palustris, P. echinada*, specific gravity, summerwood percentage, position in stem, crown size, stand density, site, thinning)

Paul, B.H. 1960. The juvenile core in conifers. TAPPI Journal. 43: 1–2.
(*P. elliottii*, *P. palustris*, ring width, ring age, stand density, shrinkage, warp)

Paul, B.H.; Marts, R.O. 1931. Controlling the proportion of summerwood in longleaf pine. Journal of Forestry. 29: 784–796.
(*P. palustris*, ring width, springwood vs. summerwood, foliage efficiency, fertilization, irrigation)

Pawsey, C.K.; Brown, A.G. 1970. Variation in properties of breast height wood samples of trees of *Pinus radiata*. Australian Forest Research. 4: 15–25.
(*P. radiata*, specific gravity, tracheid length, compression wood, tree form, site, clonal tests)

Pearson, R.G. 1984. Characteristics of structural importance of clear wood and lumber from fast-grown loblolly pine stands. In: Proceedings, symposium on the changing wood resource in the southern United States; 1984 June 12–14. Sch. For. Resources. Raleigh, NC: North Carolina State University: 66–70.
(*P. taeda*, ring age, specific gravity, position in stem, knots, modulus of rupture, modulus of elasticity)

Pearson, R.G. 1986. Effect of the changing wood resource on solid wood products. In: Proceedings, TAPPI research and development conference; 1986 September 28–October 1; Raleigh NC: 35–37.
(general overview, ring age, specific gravity, modulus of rupture, modulus of elasticity, compressive strength)

Pearson, R.G. 1988. Compressive properties of clear and knotty loblolly pine juvenile wood. Forest Products Journal. 38(7/8): 15–22.
(*P. taeda*, ring age, specific gravity, knots, site, progeny tests, modulus of elasticity, compressive strength)

Pearson, R.G.; Gilmore, R.C. 1971. Characterization of the strength of juvenile wood of loblolly pine (*Pinus taeda* L.) Forest Products Journal. 21(1): 23–31.
(*P. taeda*, ring age, specific gravity, position in stem, shrinkage, modulus of rupture, modulus of elasticity)

Pearson, R.G.; Gilmore, R.C. 1980. Effect of fast growth rate on the mechanical properties of loblolly pine. Forest Products Journal. 30(5): 47–54.
(*P. taeda*, ring width, ring age, specific gravity, progeny tests, modulus of rupture, modulus of elasticity, compressive strength, other structural)

Pearson, R.G.; Ross, B.E. 1984. Growth rate and bending properties of selected loblolly pines. Wood and Fiber Science. 16: 37–47.
(*P. taeda*, ring width, ring age, specific gravity, progeny tests, modulus of rupture, modulus of elasticity)

Perry, T.O.; Wang, C.W. 1958. Variation in the specific gravity of slash pinewood and its genetic and silvicultural implications. TAPPI Journal. 4: 178–180.
(*P. elliottii*, ring width, ring age, specific gravity, geographic location, general heredity)

Pew, J.C.; Knechtges, R.G. 1939. Cross-sectional dimensions of fibers in relation to paper-making properties of loblolly pine. Paper Trade Journal. 109(15): 46–48.
(*P. taeda*, ring width, specific gravity, summerwood percentage, springwood vs. summerwood, tracheid diameter, wall thickness, position in stem, parental specific gravity)

Pillow, M.Y. 1954. Specific gravity relative to characteristics of annual rings in loblolly pine. FPL Rep. 1989. Madison, WI: U.S. Department of Agriculture, Forest Service, Forest Products Laboratory. 8 p.
(*P. taeda*, ring width, ring age, specific gravity, summerwood percentage, position in stem, crown size)

Pillow, M.Y.; Terrell, B.Z.; Hiller, C.H. 1953. Patterns of variation in fibril angles in loblolly pine. Mimeo. D1953. Washington, DC: U.S. Department of Agriculture, Forest Service. 11 p.
(*P. taeda*, ring width, ring age, fibril angle, position in stem, crown size, stand density, thinning)

Posey, C.E. 1964. The effects of fertilization upon wood properties of loblolly pine (*Pinus taeda* L.). Sch. For. Tech Rep. 22. Raleigh, NC: North Carolina State College. 62 p.
(*P. taeda*, ring width, ring age, specific gravity, summerwood percentage, springwood vs. summerwood, tracheid length, tracheid diameter, wall thickness, fertilization)

Ralson, R.A.; McGinnes, E.A. 1964. Shortleaf pine wood density unaffected by ring growth. Southern Lumberman. 208(2592): 17–19.
(*P. echinata*, ring width, specific gravity, tracheid length, tree diameter, thinning)

Rendle, B.J. 1958. A note on juvenile and adult wood. International Association of Wood Anatomists. News Bull. 2: 1–6.
(general overview, specific gravity, tracheid length)

Rendle, B.J. 1960. Juvenile and adult wood. Journal of Institute of Wood Science. 5: 58–61.
(general overview, tracheid length)

Rink, G.; Thor, E. 1973. Inheritance and gains of three wood properties in Virginia pine. In: Proceedings, 12th southern forest tree improvement conference: 24–30.
(*P. virginiana*, specific gravity, extractives, tree diameter, progeny tests, heritability estimates, parental specific gravity)

Rockwood, D.L.; Windsor, C.L.; Hodges, J.F. 1985. Response of slash pine progenies to fertilization. Southern Journal of Applied Forestry. 9: 37–40.
(*P. elliottii*, specific gravity, fertilization, progeny tests)

Rudman, P.; NcKinnell, F.H. 1970. Effect of fertilizers on wood density of young *radiata* pine. Australian Forestry. 34: 170–178.
(*P. radiata*, ring width, specific gravity, summerwood percentage, compression wood, fertilization)

Saucier, J.R. 1981. Effects of fast growth on wood quality and product yields. In: Proceedings, TAPPI annual meeting.
(general overview, southern pines, other structural)

Saucier, J.R. 1990. Forest management and wood quality. Gen. Tech. Rep. SE–63. Asheville, NC: U.S. Department of Agriculture, Forest Service, Southeastern Station: 47–56.
(*P. taeda*, *P. elliottii*, ring width, ring age, specific gravity, springwood vs. summerwood, stand density, geographic location, thinning)

Saucier, J.R.; Taras, M.A. 1966. Wood density variation among six longleaf pine seed sources grown in Virginia. Journal of Forestry. 64: 463–465.
(*P. palustris*, specific gravity, provenance tests)

Saucier, J.R.; Taras, M.A. 1967. Wood density and percent summerwood variation among nine loblolly pine seed sources grown in Alabama. In: Proceedings, southern forest tree improvement conference; 1967 June 8–9; Knoxville TN: 9: 115–119.
(*P. taeda*, specific gravity, summerwood percentage, geographic location, provenance tests)

Saucier, J.R.; Taras, M.A. 1969. Regional variation in specific gravity of seven pines in the southern United States. Res. Pap. SE–45. Asheville, NC: U.S. Department of Agriculture, Forest Service, Southeastern Station: 16 p.
(*P. taeda. P. elliottii*, *P. palustris*, *P. echinata*, specific gravity, geographic location)

Schafer, E.R. 1949. The influence of volume of summerwood and rate of growth on the specific gravity of southern pine pulpwood. Southern Pulp & Paper Manufacturing. 12(10A): 166–168.
(*P. taeda*, *P. elliottii*, *P. palustris*, *P. echinata*, ring width, ring age, specific gravity, summerwood percentage, springwood vs. summerwood)

Schmidt, J.D.; Smith, W.J. 1961. Wood quality evaluation and improvement in *Pinus caribaea* Morelet. For. Serv. Res. Note 15. Queensland, Australia. 69 p.
(*Pinus caribaea*, ring width, ring age, specific gravity, summerwood percentage, tracheid length, fibril angle, stem form, compression wood, shrinkage)

Schmidtling, R.C. 1973. Intensive culture increases growth without affecting wood quality of young southern pines. Canadian Journal of Forest Research. 3: 565–573.
(*P. taeda*, *P. elliottii*, *P. palustris*, specific gravity, summerwood percentage, tracheid length, crown size, fertilization, cultivation, progeny tests, parental specific gravity)

Schmidtling, R.C.; Amburgey, T.L. 1977. Growth and wood quality of slash pines after early cultivation and fertilization. Wood Science. 9: 154–159.
(*P. elliottii*, ring width, specific gravity, crown size, fertilization, cultivation, parental specific gravity)

Scott, M.H. 1952. The quality of the wood of young trees of *Pinus caribaea* grown in South Africa. Journal of South African Forestry Association. 22: 38–47.
(*P. caribeaea*, specific gravity, branchiness, shrinkage, warp, modulus of rupture, compressive strength)

Sellers, T. 1962. Factors influencing the wood quality of plantation-grown slash pine. Forest Products Journal. 12: 443–446.
(*P. elliottii*, ring width, ring age, specific gravity, summerwood percentage, position in stem, tree age)

Senft, J.F.; Bendtsen, B.A. 1984. Juvenile wood: Processing and structural products considerations. In: Proceedings, symposium on utilization of the changing wood resource in the Southern United States; 1984 June 12–14. Sch. For. Res. Raleigh, NC: North Carolina State University: 102–108.
(general overview, specific gravity, fibril angle, knots, shrinkage, warp)

Senft, J.F.; Bendtsen, B.A. 1985. Measuring microfibrillar angles using light microscopy. Wood & Fiber Science. 17: 564–567.
(*P. taeda*, fibril angle)

Senft, J.F.; Bentsen, B.A.; Galligan, T.M. 1985. Weak wood. Fast-grown trees make problem lumber. Journal of Forestry. 83: 477–484.
(southern pines, ring width, ring age, specific gravity, tracheid length, fibril angle, fertilization, general heredity, shrinkage, warp, modulus of rupture, modulus of elasticity, compressive strength, sawlog yield)

Shelbourne, C.J.A.; Ritchie, K.S. 1968. Relationships between degree of compression wood development and specific gravity characteristics in loblolly pine. Holzforschung. 22: 185–190.
(*P. taeda*, ring age, specific gravity, springwood vs. summerwood, tracheid length, position in stem, compression wood, extractives, stem form)

Shupe, T.F.; Choong, E.T.; Stokke, D.D.; Gibson, M.D. 1996. Variation in cell dimensions and fibril angle for two fertilized even-aged loblolly pine plantations. Wood and Fiber Science. 28(2): 268–275.
(*P. taeda*, cell wall thickness, fiber length, microfibril angle, specific gravity, fertilized plantation)

Smith, D.M. 1968. Wood quality of loblolly pine after thinning. Res. Pap. FPL–89. Madison, WI: U.S. Department of Agriculture, Forest Service, Forest Products Laboratory. 10 p.
(*P. taeda*, ring width, specific gravity, summerwood percentage, springwood vs. summerwood, tracheid diameter, compressive wood, thinning, pruning)

Smith, D.M.; Wilsie, M.C. 1961. Some anatomical responses of loblolly pine to soil-water deficiencies. TAPPI Journal. 44: 179–185.
(*P. taeda*, ring width, specific gravity, summerwood percentage, position in stem)

Smith, D.M.; Wahlgren, H.; Bengtson, G.W. 1972. Effect of irrigation and fertilization on wood quality of young slash pine. In: Proceedings, symposium on the effect of growth acceleration on the properties of wood. Madison, WI 1971: D1–D14
(*P. elliottii*, ring width, ring age, specific gravity, summerwood percentage, position in stem, branchiness, extractives, spiral grain, fertilization, irrigation)

Smith, W.D. 1986. Evaluation of a loblolly pine plantation thinning model. Southern Journal of Applied Forestry. 10: 52–63.
(*P. taeda*, stand density, thinning, sawlog yield)

Smith, W.J. 1967. The heritability of fibre characteristics and its application to wood quality improvement in forest trees. Silvae Genetica. 16: 41–50.
(*P. taeda, P. elliottii, P. radiata*, springwood vs. summerwood, tracheid length, tracheid diameter, wall thickness, fibril angle, heritability estimates)

Smith, W.J. 1970. Improvement in yield and wood quality through selection criteria and indices. Research Committee, Australian Forest Council, 2nd meeting. Research Workers Group 1, Queensland, Australia. 21 p.
(*P. elliottii*, specific gravity, summerwood percentage, tracheid length, fibril angle, compression wood, branchiness, tree form, provenance tests, progeny tests, heritability estimates)

Snyder, E.B.; Jamaker, J.M. 1970. Specific gravity and fiber length of loblolly and spruce pines on the same site. Res. Note SO–103. Asheville, NC: U.S. Department of Agriculture, Forest Service, Southern Research Station. 3 p.
(*P. taeda, P. glabra*, specific gravity, summerwood percentage, tracheid length, site)

Sprague, J.R.; Talbert, J.T.; Jett, J.B.; Bryant, R.L. 1983. Utility of the Pilodyn in selection for mature wood specific gravity in loblolly pine. Forest Science. 29: 696–701.
(*P. taeda*, specific gravity, heritability estimates)

Squillace, A.E.; Echols, R.M.; Dorman, K.W. 1962. Heritability of specific gravity and summerwood percent and relation to other factors in slash pine. TAPPI Journal. 45: 599–601.
(*P. elliottii*, specific gravity, summerwood percentage, crown size, clonal tests, progeny tests, heritability estimates)

Stonecypher, R.W.; Zobel, B.J. 1966. Inheritance of specific gravity in five-year-old seedlings of loblolly pine. TAPPI Journal. 49: 303–305.
(*P. taeda*, tracheid diameter, extractives, progeny tests, heritability estimates)

Stonecypher, R.W.; Cech, C.C.; Zobel, B.J. 1964. Inheritance of specific gravity in two and three-year-old seedlings of loblolly pine. TAPPI Journal. 47: 405–407.
(*P. taeda*, specific gravity, progeny tests, heritability estimates)

Strickland, R.K.; Goddard, R.E. 1966. Correlation studies of slash pine tracheid length. Forest Science. 12: 54–62.
(*P. elliottii*, ring width, specific gravity, springwood vs. summerwood, tracheid length, tree form, site, geographic location, general heredity)

Sutton, W.P.J.; Harris, J.M. 1974. Effect of heavy thinning on wood density in *radiata* pine. New Zealand Journal of Forestry Science. 4: 112–115.
(*P. radiata*, ring width, ring age, specific gravity, thinning)

Szymanski, M.B.; Tauer, C.G. 1991. Loblolly pine provenance variation in age of transition from juvenile to mature wood specific gravity. Forest Science. 37: 160–174.
(*P. taeda*, ring width, ring age, specific gravity, summerwood percentage, geographic location, thinning, provenance tests, heritability estimates)

Talbert, J.T.; Jett, J.B. 1981. Regional specific gravity values for plantation grown loblolly pine in the southeastern United States. Forest Science. 27: 801–807.
(*P. taeda*, specific gravity, tree age, geographic location, general heredity)

Talbert, J.T.; Bridgwater, F.E.; Jett, J.B.; Jabromi, S. 1982. Genetic parameters of wood specific gravity in a control pollinated loblolly pine genetic test. In: Proceedings, TAPPI research and development conference; 1982 August 29–September 1; Asheville NC: 179–182.
(*P. taeda*, specific gravity, progeny tests, heritability estimates, parental specific gravity)

Talbert, J.T.; Jett, J.B.; Bryant, R.L. 1983. Inheritance of wood specific gravity in an unimproved loblolly pine population: 20 years of results. Silvae Genetica. 32: 33–37.
(*P. taeda*, ring age, specific gravity, progeny tests, heritability estimates)

TAPPI. 1970. Fifth forest biology conference; 1970 May 11–13; Raleigh, NC. Abstract of papers.

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Taras, M.A.; Saucier, J.R. 1967. Influence of extractives on specific gravity of Southern Pine. Forest Products Journal. 17: 97–99.
(*P. taeda*, *P. elliottii*, *P. palustris*, *P. echinata*, specific gravity, extractives)

Taylor, F.W.; Moore, J.S. 1981. A comparison of earlywood and latewood tracheid lengths in loblolly pine. Wood and Fiber. 13: 159–165.
(*P. taeda*, ring age, springwood vs. summerwood, tracheid length, tracheid diameter)

Taylor, R.W.; Burton, J.D. 1982. Growth ring characteristics, specific gravity, and fiber length of rapidly grown loblolly pine. Wood and Fiber. 14: 204–210.
(*P. taeda*, specific gravity, summerwood percentage, thinning, pruning)

Thomas, R.J. 1984. The characteristics of juvenile wood. In: Proceedings on utilization of the changing wood resource in the Southern United States; 1984 June 12–14. Sch. For. Res. Raleigh, NC: North Carolina State University: 40–52.
(southern pines, specific gravity, summerwood percentage, tracheid length, tracheid width, wall thickness, fibril angle)

Thor, E. 1964. Variation in Virginia pine. Pt. 1. Natural variation in wood properties. Journal of Forestry. 62: 258–262.
(*P. virginiana*, ring width, ring age, specific gravity, tracheid length, extractives, geographic location)

Thor, E.; Bates, A.L. 1970. Relationships of some wood properties of shortleaf pine with radial growth and site factors. TAPPI Journal. 53: 290–294.
(*P. echinata*, ring width, ring age, specific gravity, tracheid length, extractives, site)

Timell, T.E. 1986. Compression wood in gymnosperms. Vol. I–III. Berlin: Springer–Verlag. 2,150 p.
(general overview, compression wood)

Turnbull, J.M. 1937. Variations in strength of pine timbers. South African Journal of Science. 33: 653–682.
(*P. taeda*, ring width, specific gravity, summerwood percentage, springwood vs. summerwood, position in stem, general heredity, parental specific gravity)

Turnbull, J.M. 1947. Some factors affecting wood density in pine stem. Publ. 82. Union South African Forestry Department.
(*P. taeda*, ring width, ring age, specific gravity, summerwood percentage, springwood vs. summerwood, modulus of rupture)

van Buijtenen, J.P. 1958. Experimental control of environmental factors and their effects upon some aspects of wood anatomy in loblolly pine. TAPPI Journal. 41: 175–178.
(*P. taeda*, tracheid diameter, springwood vs. summerwood, wall thickness, irrigation)

van Buijtenen, J.P. 1962. Heritability estimates of wood density in loblolly pine. TAPPI Journal. 45: 602–605.
(*P. taeda*, ring age, specific gravity, tree age, clonal tests, progeny tests, heritability estimates)

van Buijtenen, J.P. 1964. Anatomical factors influencing wood specific gravity of slash pines and the implications for the development of a high-quality pulpwood. TAPPI Journal. 47: 401–404.
(*P. elliottii*, summerwood percentage, springwood vs. summerwood, tracheid length, tracheid diameter, tall thickness, parental specific gravity)

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(*P. taeda, P. elliottii*, ring width, ring age, specific gravity, site, clonal tests)

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(*P. taeda*, ring width, specific gravity, summerwood percentage, crown size, tree diameter, fertilization)

von Wedel, K.W.; Zobel, B.J.; Shelbourne, C.J.A. 1967. Knotwood in loblolly pine. Sch. For. Tech Rep. 36. Raleigh, NC: North Carolina State College. 45 p.
(*P. taeda*, branching, knots, compression wood, tree diameter, progeny tests)

von Wedel, K.W.; Zobel, B.J.; Shelbourne, C.J.A. 1968. Prevalence and effects of knots in young loblolly pine. Forest Products Journal. 18: 97–103.
(*P. taeda*, position in stem, branching, knots, compression wood, tree diameter, progeny tests)

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(*P. taeda, P. elliottii, P. palustris, P. echinata*, specific gravity, position in stem)

Wheeler, E.Y.; Zobel, B.J.; Weeks, D.L. 1966. Tracheid length and diameter variation in the bole of loblolly pine. TAPPI Journal. 49: 484–490.
(*P. taeda*, ring age, tracheid length, tracheid diameter, position in stem, site, general heredity)

White, J.F.; Saucier, J.R. 1966. A comparison of the specific gravity of two slash pine varieties grown in south Florida. TAPPI Journal. 49: 230–232.
(*P. elliottii*, *P. elliottii* var. *densa*, ring width, ring age, specific gravity, summerwood percentage, provenance tests)

Whitesell, C.D.; Zobel, B.J.; Roberds, J. 1966. Specific gravity and tracheid length of loblolly pine in Maryland and Delaware. Sch. For. Tech. Rep. 29. Raleigh, NC: North Carolina State University. 11 p.
(*P. taeda*, specific gravity, tracheid length, site, geographic location, general heredity)

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(*P. caribaea*, specific gravity, tree diameter, stand density, site)

Williams, C.G.; Megraw, R.A. 1994. Juvenile–mature relationships for wood density in *Pinus taeda*. Canadian Journal of Forest Research. 24: 714–722.
(*P. taeda*, ring age, specific gravity, crown size, progeny tests, heritability estimates, parental specific gravity)

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(*P. elliottii*, ring width, specific gravity, summerwood percentage, wall thickness, tree diameter, fertilization)

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(*P. echinata*, ring age, specific gravity, tracheid length, provenance test, progeny tests, heritability estimates)

Wood, G.B.; Siemon, G.R. 1981. Effect of thinning on wood properties of *radiata* pine. Australian Forest Research. 11: 149–159.
(*P. radiata*, ring width, ring age, specific gravity, summerwood percentage, position in stem, stand density, thinning)

Yandle, D.O. 1956. Statistical evaluation of the effect of age on specific gravity in loblolly pine. FPL Rep. 2049. Madison, WI: U.S. Department of Agriculture, Forest Service, Forest Products Laboratory. 15 p.
(*P. taeda*, ring width, specific gravity)

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(*P. taeda*, ring age, specific gravity, springwood vs. summerwood, position in stem, shrinkage)

Yao, J. 1970. Influence of growth rate on specific gravity and other selected properties of loblolly pine. Wood Science and Technology. 4: 163–175.
(*P. taeda*, ring width, ring age, specific gravity, summerwood percentage, springwood vs. summerwood, position in stem)

Ying, L.; Kretschmann, D.E.; Bendtsen, B.A. 1994. Longitudinal shrinkage in fast-grown loblolly pine plantation wood. Forest Products Journal. 44(1): 58–62.
(*P. taeda*, ring age, specific gravity, summerwood percentage, fibril angle, site, shrinkage)

Zobel, B.J. 1956. Genetic, growth, and environmental factors affecting specific gravity of loblolly pine. Forest Products Journal. 6: 442–447.
(*P. taeda*, ring width, ring age, specific gravity, summerwood percentage, site, general heredity)

Zobel, B.J. 1961. Inheritance of wood properties in conifers. Silvae Genetica. 10: 65–70.
(general overview, specific gravity, tracheid length, fibril angle, spiral grain, general heredity)

Zobel, B.J. 1970. Developing trees in the southeastern United States with wood properties most desirable for paper. TAPPI Journal. 53: 2320–2325.
(*P. taeda*, specific gravity, position in tree, extractives, bark, tree age, site, general heredity, parental specific gravity)

Zobel, B.J. 1971. Genetic manipulation of wood of the southern pines, including chemical characteristics. Wood Science Technology. 5: 255–271.
(southern pines, ring width, ring age, specific gravity, wall thickness, tracheid length, branchiness, compression wood, stem form, fertilization, general heredity)

Zobel, B.J. 1972. Three rings-per-inch dense southern pine—can it be developed. Journal of Forestry. 70: 333, 335.
(*P. taeda*, ring width, specific gravity, uniformity, geographic location, fertilization, general heredity, parental specific gravity)

Zobel, B.J. 1974. Increasing productivity of forest lands through better trees. The S. J. Hall Lectureship in Industrial Forestry. April 18, 1974. Berkeley, CA: University of California, School of Forestry and Conservation.
(southern pines, forestry, increasing timber supplies, southern pines breeding program)

Zobel, B.J. 1976. Wood properties as affected by changes in the wood supply of southern pines. TAPPI Journal. 59: 126–128.
(*P. taeda*, specific gravity, tracheid length, tracheid width, wall thickness, position in tree, thinning)

Zobel, B.J.; Blair, R. 1976. Wood and pulp properties of juvenile wood and topwood of the southern pines. Applied Polymers Symposia. 28: 421–433.
(*P. taeda*, *P. elliottii*, specific gravity, tracheid length, wall thickness, fibril angle, position in stem, compression wood, progeny tests)

Zobel, B.J.; McElwee, R.L. 1958. Natural variation in wood specific gravity of loblolly pine, and an analysis of contributing factors. TAPPI Journal. 41: 158–161.
(*P. taeda*, ring age, specific gravity, position in stem, tree diameter, stand density, site, geographic location)

Zobel, B.J.; Rhodes, R.R. 1955. Relationship of wood specific gravity in loblolly pine to growth and environmental factors. Tech Rep. 11. Texas Forest Service. 32 p.
(*P. taeda*, ring width, ring age, specific gravity, summerwood percentage, compression wood, stand density, site, general heredity)

Zobel, B.J.; Rhodes, R.R. 1956. Specific gravity estimations of mature loblolly pine from juvenile wood and seedling limb sections. Forest Science. 2: 107–112.
(*P. taeda*, ring age, specific gravity, branchiness, general heredity, parental specific gravity)

Zobel, B.J.; Rhodes, R.R. 1957. Specific gravity indices for use in breeding loblolly pine. Forest Science. 3: 281–285.
(*P. taeda*, specific gravity, branchiness, site, progeny tests, parental specific gravity)

Zobel, B.J.; van Buijtenen, J.P. 1989. Wood variation: Its causes and control. Berlin: Springer–Verlag. 363 p.
(general overview)

Zobel, B.J.; Webb, C.; Henson, F. 1959. Core or juvenile wood of loblolly and slash pine trees. TAPPI Journal. 42: 345–356.
(*P. taeda*, *P. elliottii*, ring age, specific gravity, position in stem, extractives, heartwood, geographic location, general heredity, parental specific gravity)

Zobel, B.J.; Thorbjornsen, E.; Henson, F. 1960. Geographic, site and individual tree variation in wood properties of loblolly pine. Silvae Genetica. 9: 149–158.
(*P. taeda*, ring width, specific gravity, tracheid length, compression wood, geographic location)

Zobel, B.J.; Goggans, J.F.; Maki, T.E.; Henson, F. 1961a. Some effects of fertilizers on wood properties of loblolly pine. TAPPI Journal. 44: 186–192.
(*P. taeda*, specific gravity, tracheid length, tree diameter, fertilization)

Zobel, B.J.; McElwee, R.L.; Brown, C. 1961b. Interrelationship of wood properties of loblolly pine. In: Proceedings, tree improvement conference, Gainesville, FL. 18 p.
(*P. taeda*, ring width, ring age, specific gravity, tracheid length, tracheid diameter, wall thickness, compression wood, extractives, parental specific gravity)

Zobel, B.J.; Ralston, J.; Roberds, J.A. 1965. Wood yields from loblolly pine stands of different age, site, and stand density. Sch. For. Tech. Rep. 26. Raleigh, NC: North Carolina State University. 23 p.
(*P. taeda*, ring width, ring age, specific gravity, position in stem, extractives, tree age, tree diameter, stand density, site, geographic location)

Zobel, B.J.; Kellison, R.C.; Matthias, M.F. 1969. Genetic improvement in forest trees—growth rate and wood characteristics in young loblolly pine. In: Proceedings, Southern forest tree improvement conference: 59–75.
(*P. taeda*, specific gravity, tracheid length, site, progeny tests, parental specific gravity)

Zobel, B.J.; Kellison, R.C.; Matthias, M.F.; Hatcher, A.V. 1972. Wood density of the southern pines. Tech. Bull. 208. North Carolina Agricultural Experiment Station. 56 p.
(*P. taeda, P. elliottii, P. palustris, P. virginiana*, ring age, specific gravity, position in stem, extractives, bark, tree age, site, geographic location, fertilization, general heredity)

Zobel, B.J.; Jett, J.B.; Hutto, R. 1978. Improving wood density of short-rotation southern pine. TAPPI Journal. 61: 41–44.
(*P. taeda*, specific gravity, compression wood, site, thinning, progeny tests, heritability estimates, parental specific gravity)