Geographic, Site and Individual Tree Variation in Wood Properties of Loblolly Pine

By Bruce Zobel, Eyvind Thorbjornsen, and Faye Henson[1])

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Loblolly pine (P. *taeda* L.), a species of high commercial value, has a wide geographic range and grows under many different site and environmental conditions. Its morphological and physiological characteristics have been observed in a general way to vary considerably, both regionally and locally, throughout its natural range. The observed variation has led to both speculation and effort concerning the possibility of finding and breeding improved strains of loblolly pine.

The feasibility of breeding trees for wood properties has been discussed without much unanimity for many years. Some have expressed opinions similar to Koehler's (1939) that wood is a „conservative character," and that it gives small hope for discovering pronounced inherent wood differences between varieties, races and strains of a species. Others have been more optimistic about breeding for wood properties and have looked forward to the time when „strains" with special wood could be developed (Schreiner, 1935). Schütt (1959) analyzes briefly the potential development of trees with different woods through natural selection. One thing is clear, however; — before genetic studies of wood properties can be efficiently undertaken, the variation pattern from tree to tree, site to site, as well as throughout the range of the species, must be known. In addition, the interrelationships among the various wood characteristics and growth factors need to be determined.

The present study was initiated to determine the extent of variation in several wood properties in seven southeastern states in which this species is important. It concerns the variation patterns of specific gravity, tracheid length and cellulose yields. It also includes some characteristics of a tree that can affect wood properties, such as growth rate and compression wood. Tracheid wall thickness and tracheid diameter are currently being investigated, although results are not yet available. It must be emphasized that the variations studied are phenotypic and nothing is known about the genotypes of the trees from which wood samples were taken. Research results should be interpreted in that light.

Our Present State of Knowledge

Although several studies on variation of wood qualities have been initiated on loblolly pine and closely related species, such as slash pine (P. *elliottii* var. *elliottii)*, it is still too early to tell much about variation patterns or relationships of wood properties. Considerable information is being accumulated through the efforts of industry cooperative tree inmprovement programs with universities in Florida, Texas and North Carolina, and with the Institute of Paper Chemistry in Wisconsin. In recent years the Forest Survey of the U. S. Forest Service has taken wood properties into account, and their widespread studies, complete in one southern state and underway in several others, will yield valuable information on variation in specific gravity of wood.

There is a large body of literature referring to wood characteristic variability among trees, among sites and among different geographic areas. Reference will be made here only to studies on conifers and will emphasize information available on pines. Most research of this nature can be placed in either of two categories: (1) investigations involving seed collection from a number of different geographic regions and sites, followed by growing the trees from these sources under relatively uniform conditions, and (2) sampling of natural wild stands to assess wood differences under different environmental conditions, as well as individual tree differences.

In the past, especially in Europe, many studies of geographic seed source influence and effects have been made. The original objectives of investigations seldom were designed to assess wood properties, but rather to determine such things as site adaptability, growth rate, volume yields and resistance to insects and diseases. As interest in wood variation developed, the trees were assessed for this characteristic also, and much valuable information on wood is now becoming available.

Specific Gravity

The most intensive investigations have been on specific gravity. This complex wood characteristic has been emphasized because of its obvious economic importance with its effects on yield and quality of the final product, and because of the relative ease with which it can be determined.

Geographic variation in specific gravity of loblolly pine wood has long been recognized because lower yields were obtained from wood grown in certain parts of the species range. Although exact data have not been published, Wakeley[2]) reports that there appears to be considerable difference in specific gravity of wood among the seed sources from Louisiana, Texas, Arkansas, and Georgia when these sources are grown in Louisiana. Under Louisiana conditions the Georgia sourceproduced theheaviest wood. The provenances tested were the same as reported in the account of the original seed source study of southern pines (Wakeley, 1950). In contrast to Wakeley's results on loblolly, Knudsen (1956) found that among eight different provenances of Norway spruce (Picea *abies)* there was no marked variation in either ring width or density (specific gravity). Unreplicated studies on red pine (P. *resinosa)* by Rees and Brown (1954) showed that 18 of their 19 sources exhibited no differences in specific gravity, but the 19th source from Bay City, Michigan, was significantly more dense than the other sources. Kramer and Smith (1956), in sampling wood properties of slash pine plantations, suggested that a portion of the variation they observed was attributable to seed source. In South African trials, Rycroft and Wicht (1947) found wood of *Pinus pinaster* varied with source of seed, the Portugese sources being the heaviest in each of two trial areas. The differences among sources were large. In reporting on a study of 13 provenances of white spruce (*Picea glauca),* Holst (1958) found that apparent differences in wood specific gravity are present, and that one provenance was consistently high, one

[1]) Professor of Forest Genetics, N. C. State College; Forest Geneticist, Agricultural Experiment Station, University of Tennessee; and Research Assistant, N. C. State College, respectively.

[2]) Personal communication.

consistently low. For Norway spruce, KLEM (1957) found higher specific gravity in spruce of German origin than that of Norwegian origin. HARRIS and KRIPAS (1959) report from New Zealand that the California provenance of Ponderosa pine *(P. ponderosa)* has considerably lower specific gravity than that from British Columbia.

There are many reports dealing with specific gravity variation in natural stand growing in different geographic areas. ZOBEL and RHODES (1955) describe variations among 15 plots taken from native loblolly pines in East Texas. No geographical trends were evident. They attempted to relate wood properties to growth and environmental factors with poor success. PERRY and WANG (1958) reported regional variation in specific gravity for slash pine, obtaining the lowest averages in the western part of the species range. These findings confirmed those of LARSON (1957), who reported the lowest specific gravities in the northern and western portions of the species range. LARSON attributes plot differences to moisture and soil characteristics. ZOBEL and MCELWEE (1958 a) showed a similar northerly and westerly trend for loblolly pine in the southeastern states, while MITCHELL and WHEELER (1959) found very definite trends with latitude and longitude for all four major species of the Southern pines in the State of Mississippi. Geographic area was found to be important for Douglas fir *(Pseudotsuga menziesii)* and DROW (1957) gives regional differences for samples from more than 40 areas within its natural range. FIELDING and BROWN (1960), in reporting on heritabilities of Montery pine *(P. radiata)* found that site variations had little influence on their estimates. In Japan, MIYOSHI (1951) obtained differences in summerwood percent between Hinoki *(Chamaecyparis obtusa)* trees growing at different elevations.

The effect of site or environment on specific gravity has been extensively studied, the published results often being confusing and contradictory. Part of the confusion is caused by a difference in methods of sampling, resulting in a confounding of tree age (juvenile wood) with other factors. Although site alone was not a significant factor in specific gravity, when the site-DBH interaction was observed, site was important in determining specific gravity of slash pine (MILLER, 1959). LARSON (1957) found also for slash pine that much of his plot-to-plot variability could be accounted for by June and July rainfall and depth of the fine-textured soil. Scotch pine wood properties were found to vary most between extreme sites, according to SOLNCEV (1949); average differences between wood of pine in Europe and in Siberia are slight. EKLUND (1957) discusses the effects of temperature on summerwood formation. A study of the effect of rainfall showed that latewood growth was more related to the "weather" year than to the calendar year (MESSERI, 1953). PAUL (1950) states that Douglas Fir growing on low site quality has denser wood; similarly, WELLWOOD (1952) also reported that good sites produced lower specific gravity wood in Douglas fir. ANDERSON (1958) averred that denser, stronger softwoods are found on slower-growing sites. Speaking in more general terms of coniferous forest trees, CHANCEREL (1920) states that the heaviest, hardest wood is produced on good soil and in the warmer climates. From his study on red pine, JAYNE (1958) postulates that it is highly probable that environmental characteristics such as soil moisture and soil textures are closely associated with the specific gravity of wood. For white cedar *(Thuja occidentalis)*, HARLOW (1927) found greater specific gravity on limestone than on peat bog soils. From their extensive literature review, SPURR and HSIUNG (1954) deduce that site quality and wood specific gravity are not highly correlated.

Controlling the current soil moisture supply was important in the formation of summerwood of longleaf pine *(Pinus palustris)*, according to PAUL and MARTS (1954). MAMMEN (1952) reports clear correlations between specific gravity and seasonal precipitation, seasonal temperature, or both. SCOTT (1952) attributes the lighter wood of slash pine grown in the Dukuduku area (South Africa) to low rainfall. SCOTT and DU PLESSIS (1951) report that loblolly pine (and other species) planted in certain areas produced lighter wood than trees growing in other areas. For Sitka spruce *(Picea sitchensis)*, BRYAN and PEARSON (1955) found that the specific gravity and latitude were correlated, the heaviest wood being from trees in the southern part of England. For Douglas fir, KLAUDITZ and STOLLEY (1957) found no clear correlation between site conditions and wood properties, except that stems with highest densities were from regions with the lowest rainfall. HARRIS (1955) made a good study of the types of latewood and their relation to rainfall conditions. The influence of rainfall on specific gravity of Southern pines was indicated by PAUL and SMITH (1950), and ZAHNER (1955) states that plentiful soil moisture and dense wood seem to be related. In explaining some of the variations encountered in Mississippi, WHEELER and MITCHELL (1959) feel that rainfall has an effect on specific gravity, and that this effect is pronounced in loblolly pine. VOEGELI and REINHART (1956), reporting on Scotch pine, have tabulated the effects of drought years and seasonal distribution of rainfall to type of wood produced.

Most publications emphasize the magnitude of individual tree variation, no matter what the site or geographic area. In East Texas, ZOBEL and RHODES (1955) found some differences in plot averages, but these differences could not be correlated with any of the environmental factors studied, including site quality, moistness of site, and soil characteristics. Very large individual tree differences were observed. GÖHRE (1955, 1958) indicated that individual tree variability is so great among trees of Douglas fir and other species that it is difficult to obtain significant differences between races or geographic regions. As early as 1938, KOEHLER showed that the importance of locality of growth is generally overestimated, and that individual tree differences within a stand are large. SMITH (1958) reports individual Douglas fir tree variabilities to be much larger within sites than among sites which ranged from indices of 90 to 160. For Sitka spruce grown on three sites in Wales, MACGREGOR (1952) found little variation among plot averages but a large variation among trees on each plot.

Almost every paper cited above deals with growth relationships, as well as with the large individual variations in specific gravity present among trees growing under relatively uniform conditions. Almost without exception, it is recognized that individual tree variation is very large; many of the later papers indicate only a slight relationship between growth rate (as expressed by ring width) and specific gravity, if juvenile wood, or age of wood, is taken into account. There is a large body of literature, not cited here, dealing especially with growth and age effects on specific gravity.

Isolated reports of other environmental effects on specific gravity are available. Such things as pruning, thinning, insect attacks and day-length changes are reported to have some effect on specific gravity, but the effect of such factors will not be reviewed here. Some studies, such as HILDEBRANDT (1954), NYLINDER (1954), and others, indicate the importance of crown class or position of dominance in the stand. They both reported that the specific gravity of dominant spruce trees was slightly lower than for other trees in the stand. This relationship has not been found consistently in the Southern pines, if percentage of core wood is taken into account.

Tracheid Length and Cellulose Yields

Much less information is available on variations in tracheid lengths and cellulose yields. SCHÜTT (1958) and ZOBEL and McELWEE (1958 b) reported large tree-to-tree variations and small geographic variations in cellulose yield with different sources. ECHOLS (1958) found that the latitude of seed source was highly correlated with tracheid length in Scotch pine. HARLOW (1927) found no difference in tracheid length of white cedar from different sites, while LEE and SMITH (1916) reported that tracheid lengths of Douglas fir from the coast were somewhat longer than those from Douglas fir from the mountains. Differences were also reported for "strains" of *Pinus pinaster* by BISSETT *et al.* (1951). KRAMER (1957) reported large differences in tracheid lengths among individual loblolly pines of the same crown class and same age, growing under very similar environmental conditions. For Norway spruce *(Picea excelsa)*, NYLINDER and HÄGGLUND (1954) found positive relations between fiber length, on the one hand, and latitude, width of annual ring, late wood content and oven dry density on the other. They also found that geographical location of the site influenced cellulose yield, finding smaller yields as latitude rose and as height above sea-level increased. KENNEDY and JAWORSKY (1960), in a recent study, found that crown class, site, radial position, growth rate, and percent summerwood failed to account for the variation observed in cellulose content of Douglas fir. A considerable amount of individual tree variability was present.

Wood Property Interrelationships

Few data are available in the literature on relationships between wood properties of conifers. KRAMER (1957) showed that specific gravity and tracheid length were not related, as did SMITH (1959) for Hoop pine *(Araucaria cunninghamii)*. DADSWELL and WARDROP (1960) deal with possible interrelationships, while unpublished data by VAN BUIJTENEN[3]) and ZOBEL[1]) both indicate that many of the specific wood properties are not related to each other. ZOBEL and McELWEE (1958 b) found little relationship between specific gravity and cellulose yields when the latter was based on wood weight.

Research Methods

As a preliminary step to the present extensive study, a survey was made in 1956 to explore the variation patterns for the wood properties to be studied. This preliminary survey made it possible to estimate: (1) the number of wood samples needed per tree, (2) the number of trees needed per field plot, and (3) some idea of the total number of field plots to be sampled. Findings from the preliminary studies were published (ZOBEL and McELWEE, 1958 a, 1958 b). Results from analysis of the preliminary data indicated that maximum efficiency could be obtained by using one core per tree from a minimum of 22 trees per sample plot. In order to obtain a good estimate of within-tree variation, two samples were required from each fifth tree on all the plots. A study of the geographic and site variations, plus an estimation of the work load involved, indicated that probably 14 field plots would be sufficient to indicate any major trends. Wood samples were obtained from Georgia, Alabama, South Carolina, North Carolina, Virginia, Tennessee and Delaware. Only essentially even-aged stands were chosen, average ages of plots varying from 32 to 41 years. Average diameter varied from 11.7 to 15.7 inches at breast height *(Table 1)*. Trees sampled were dominants and codominants, excluding any diseased, injured or suppressed trees. Thus, the data represents the better trees in the stand. It would be ideal if one could stratify the sample plots simply by north and south, or Coastal Plain[4]) and Piedmont[5]). This simple stratification is not possible, since the influence is overlapping; thus, north Coastal Plain is different from north Piedmont. The effect of latitude alone cannot be easily separated out, at least not without increasing the number of sample plots involved. Locations of the sample plots are indicated in *Figure 1*, and *Table 1* includes some of the characteristics of the plots.

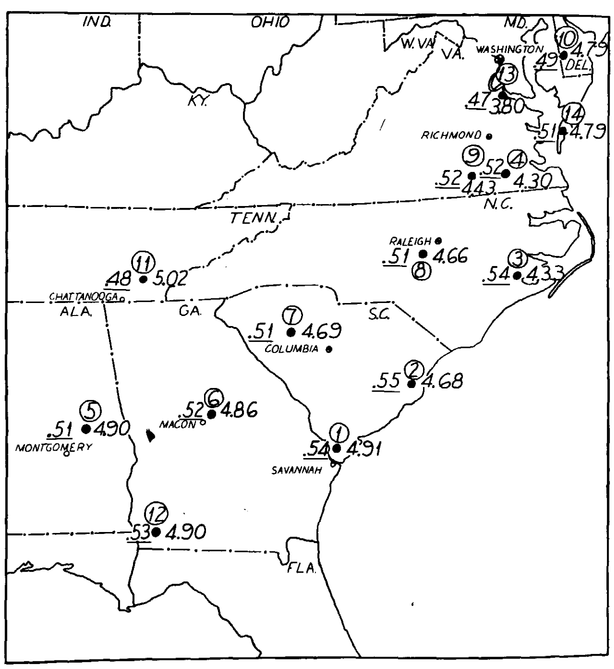

Figure 1. — Portion of the range of loblolly pine in the southeast from which samples were obtained. The encircled number is the plot number. The underlined number nearby is the average specific gravity of that plot; the other number is the average tracheid length of the plot. Each plot is represented by 22 trees, two samples from each of 5 trees, one sample from each of the remaining trees.

Wood samples were obtained at breast height (4.5 feet) with a large (11 mm.) increment borer. To reduce excess variation, core wood was removed from each wood sample in the manner described by ZOBEL *et al.* (1959); thus, all values cited in this paper are for outer, or mature wood. The breast-height values are strongly correlated with total tree values, at least for specific gravity and cellulose yield (ZOBEL *et al.*, 1960). For each tree the following wood characteristics were assessed:

1. Specific gravity of the outer (or mature wood), determined on the basis of green volume and dry weight.

2. Tracheid length of latewood tracheids, sampled from the 15th and 30th annual rings.

[3]) Personal communication.

[4]) Usually flat, soils often with sandy topsoil, usually underlain by clay soils. Drainage is often poor.

[5]) Usually rolling, soils usually heavy red clay. Drainage usually good.

Table 1. — Soil and stand characteristics of the field plots

Plot No.	Physiographic Location	County	Soil Characteristics			Side index (ft. at 50 yrs)	Age of stand (yrs)[1]	DBH stand
			Topsoil	Subsoil	Inches of topsoil			
12	Ga., C. Plain[2]	Decatur	sandy-loam	sandy-clay	14	85	37	13.3
1	S. C., C. Plain (S.)	Beaufort	clay-loam	clay	8	105	32	13.5
2	S. C., C. Plain (N.)	Georgetown	sandy-loam	sandy-clay	4	85	41	15.7
3	N. C., C. Plain	Craven	sandy-loam	sandy-clay	12	80	40	15.1
4	Va., C. Plain (S.)	Sussex	sandy-loam	sandy-clay	6	85	33	11.7
13	Va., C. Plain (N.)	Westmoreland	clay-loam	clay	7	80	40	13.1
14	Va., East. Shore[3]	Northampton	sand	sand	—	75	40	12.1
10	Del., East. Shore[3]	Sussex	sandy-loam	sandy-clay	6	80	35	14.8
5	Ala., Piedmont	Tallapoosa	clay-loam	clay	8	80	41	13.7
6	Ga., Piedmont	Jones	clay-loam	clay	2	90	43	12.5
7	S. C., Piedmont	Clinton	sandy-loam	clay-loam	20	90	37	14.1
8	N. C., Piedmont	Wake	clay-loam	sandy-clay	8	80	41	13.9
9	Va., Piedmont	Brunswick	clay-loam	clay	4	80	40	13.4
11	Tenn., Mt. Valley	McMinn	clay-loam	clay	10	75	40	11.9

[1]) All stands essentially even-aged.
[2]) Although this is in the general Coastal Plain region, the plot is located in rolling country somewhat similar to Piedmont in topography and soil.
[3]) These are essentially Coastal Plain. Note from Figure 1, they are on a peninsula.

3. Cellulose yields, consisting of a holocellulose-like portion, referred to as water-resistant carbohydrates (WRC) and alpha-cellulose (Zobel and McElwee, 1958 b). Both were obtained by a method enabling 30 simultaneous determinations. This method was "mild" and gave high yields, but good comparisons are possible among trees, since the method gives highly reproducible results.

4. Compression wood percentage, determined by the aid of a light box, according to the method used by the Forest Products Laboratory (1953).

Such determinations of specific gravities, tracheid lengths, WRC, alpha-cellulose, and compression wood were made for each of 308 trees. Averages by plots are shown in *Table 2.*

Table 2. — Average values for field plots

Plot No.	Physiographic Location	Sp. G.	Tracheid Length		%[1]) WRC	% Alpha-cellulose
			30-yr.	15-yr.		
12	Ga., C. Plain	.53	4.90	3.95	80.3	58.4
1	S. C., C. Plain (S.)	.54	4.91	4.18	80.1	58.0
2	S. C., C. Plain (N.)	.55	4.68	3.72	80.0	57.5
3	N. C., C. Plain	.54	4.33	3.85	80.5	58.2
4	Va., C. Plain (S.)	.52	4.30	3.57	79.3	56.1
13	Va , C. Plain (N.)	.47	3.80	2.95	79.3	55.3
14	Va., East. Shore	.51	4.79	4.27	80.4	58.4
10	Del., East. Shore	.49	4.79	3.83	80.2	56.4
5	Ala., Piedmont	.51	4.90	4.39	79.7	57.5
6	Ga., Piedmont	.52	4.86	4.17	80.1	57.2
7	S. C., Piedmont	.51	4.69	4.31	80.3	57.1
8	N. C., Piedmont	.51	4.66	3.69	79.7	56.1
9	Va., Piedmont	.52	4.43	3.70	80.3	58.0
11	Tenn., Mt. Valley	.48	5.02	4.13	80.0	56.2
	Coastal Plain Ave.	.53	4.49	3.70	79.9	57.3
	Eastern Shore Ave.	.50	4.79	4.05	80.3	57.4
	Piedmont Ave.	.51	4.71	4.05	80.0	57.2
	Mountain Ave.	.48	5.02	4.13	80.0	56.2

[1]) Water-resistant carbohydrates, obtained by a chloriting process.

In addition to information on wood properties, a considerable amount of other data was obtained for each tree, including crown characteristics, tree height, tree diameter, bole straightness and branching habits. Also, on each plot the soil type, soil depth, topography, type of stand and site index were determined *(Table 1).* Not all these characteristics will be considered in the present paper, since main emphasis here is on the wood characteristics. Only a few relationships, or lack of such, will be pointed out.

The data were recorded on punch cards and analyzed according to the nested sampling procedure described by Snedecor (1956). Data were analyzed on the IBM 650, where the analysis of variance for each character was computed. In addition to the straight analysis of variance, this program also yields the sums of products necessary for computing the sample correlation coefficients.

Variation Among Trees

This study was designed to indicate the extent of individual tree variability, as well as average differences among sites and geographic areas. Research workers engaged in sampling of natural populations have always been impressed with the large variation among individuals within any one population. Often this variation is so large that it creates difficulties in measuring differences between stands from different sites or different geographic areas. The variation among individuals confuses the picture of racial variation within a species, but for the plant breeder it is the basis on which progress in selection can be made. Generally, the larger the individual plant variation, the more rapid improvement can be made. Tree breeders who work with the properties of wood, therefore, are interested in knowing the amount of individual variation present for important characteristics like specific gravity and tracheid length.

The analysis of variance *(Table 3)* shows that between-tree variation is highly significant for both specific gravity and tracheid length. In cellulose yield and compression wood, variation among samples was large and differences between trees were not significant. Variation in within-tree samples for these latter wood characteristics will necessarily be high, because compression wood usually is found on one side of the stem only, but the duplicate samples are

Table 3. — Analysis of variance

Source of Variation	df	Mean Squares					
		Sp. Gr.	Trach. L. 30 yrs.	Trach. L. 15 yrs.	WRC %	Alpha-Cell. %	Comp. Wood %
Areas	13	.012786***	2.9622***	3.9089***	3.7937***	26.941***	509.4**
Trees in Areas	294	.001065***	.2027***	.1900***	.9913 N.S.	2.541 N.S.	207.1 N.S.
Determinations	70	.000391	.0746	.0838	1.0964	2.483	304.1

** Significant at 1% level
*** Significant at .1% level
N.S. Not statistically significant

extracted from opposite sides of the tree bole. The correlations between compression wood and specific gravity or tracheid length are low and the between-tree variation remains significant; cellulose yield, however, is closely correlated with compression wood *(Table 4)* and any between-tree variation present will be masked due to the large differences in compression wood present in two samples from the same tree.

There are several ways of expressing the individual variation present. DICE and LERAAS (1936) proposed a method which gives the total range of observations within each population, and also the means with the respective standard errors. This method may also be used to compare different populations statistically, but more sensitive methods have recently been developed for this purpose.

Figures 2 and 3 give the variation pattern for specific gravity and tracheid length by plots. Pooled variability within plots is used in the analyses and not reported for individual plots. Standard errors for means were computed

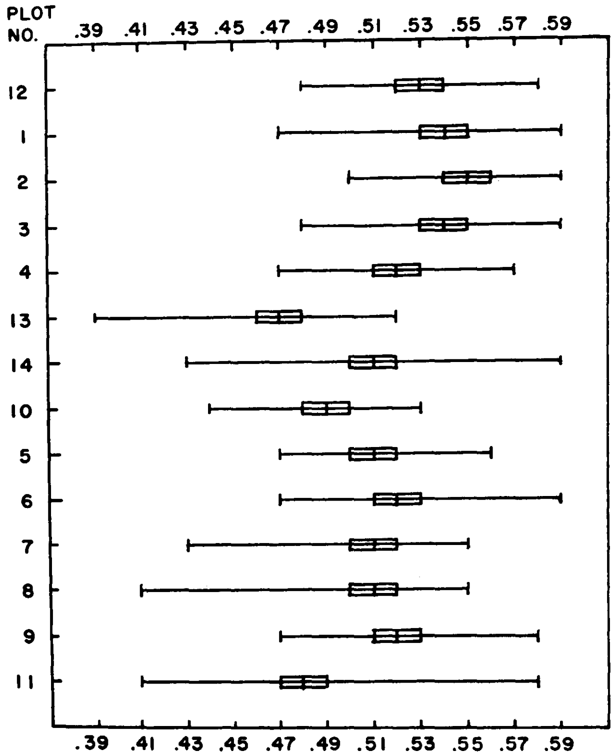

Figure 2. — Graphical representation of the specific gravity of the plots is shown by the method of DICE and LERAAS. The central vertical line is the average for the plot; the rectangle represents two standard errors on both sides of the mean. The horizontal line shows the total range of values found for each plot. Arrangement of plots is from north to south, roughly by physiographic areas. (See *Figure 1.*)

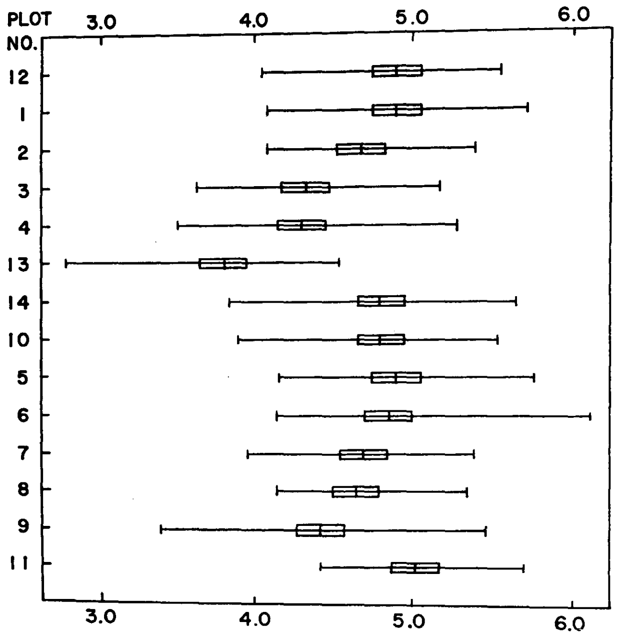

Figure 3. — Graphical representation of the tracheid length of the plots is shown by the method of DICE and LERAAS. See *Figure 2* for details.

from the pooled variability under the assumption that within-plot variances were not greatly different. This assumption is most likely correct; there was no indication from the data that the standard errors were different. The outstanding feature of both figures is the tremendous range of values present within each plot, even though only 22 trees were represented. If individual tree variation for specific gravity and tracheid length is highly heritable, appreciable progress can be expected from selection of these traits.

Variation Among Plots

The analysis of variance *(Table 3)* reveals that all the six wood properties vary among plots in a highly significant manner. The variation in compression wood is probably due primarily to environmental factors, such as exposure and stand quality, although the inherent spiral in loblolly pine may be important. WRC and tracheid length at 15 years are highly correlated with alpha-cellulose and tracheid length at 30 years, respectively, and are therefore, omitted from further analysis.

It is not sufficient to point out that differences exist among different plots. The pattern or trend in the distribution of the means must be studied and attempts made to explain the results. *Table 2* gives the averages for the different physiographic locations. The variation among means can be investigated using a test developed by DUNCAN (1955). In this test the averages are arranged from

p:	2	3	4	5	6	7	8	9	10	11	12	13	14	
R:	.023	.024	.024	.025	.025	.026	.026	.026	.026	.026	.027	.027	.027	
Plot No.	13	11	10	7	14	8	5	4	6	9	12	3	1	2
Mean	.472	.484	.486	.507	.509	.511	.514	.516	.517	.519	.534	.536	.538	.548

Figure 4. — "Duncan Test"; specific gravity related to physiographic location. For explanation, see text.

the lowest to the highest, and averages which are not significantly different are connected with a common line. *Figures 4, 5, and 6* illustrate how the method has been used for specific gravity, tracheid length, and alpha-cellulose to group the plots which are not different from each other. As shown in the figures, any two plot means not underscored by the same line are significantly different at the one percent level.

The results for specific gravity *(Figure 4)* shows that plots 13, 11, and 10 do not have any lines in common with plots 12, 3, 1, and 2. The other intermediate plots are underscored by common lines. Thus, there are three different groups or populations present for this wood property. When reference is made to the plot locations *(Figure 1)* a rather striking geographical distribution pattern becomes evident. The lowest specific gravities are found at the north and northwest extremes of the species range. The Piedmont has intermediate values, and the Coastal Plain of the Carolinas and Georgia belongs to the group with high specific gravity.

Tracheid length at 30 years shows a rather different grouping from what was found for specific gravity. *Figure 5* shows that a single plot, number 13, is significantly different from all the other plots. Plots 4, 3, and 9 are intermediate and the rest belong to a group which has the longest tracheids. By studying *Figure 1* it becomes apparent that there is a rather gradual increase in tracheid length going from north to south. The two samples from the eastern shore are the only exceptions to this rule, both plots having significantly longer tracheids than plot 13, which is located only 80 miles away and grown under somewhat similar climate and comparable soil conditions. Although it might appear that the "strain" from the eastern shore has longer tracheids than the pines on the mainland, further testing under controlled environmental conditions is necessary to establish this supposition.

Figure 6 shows how the yield of alpha-cellulose, on a weight basis, is related to the geographic location of the plots. Plots 13 and 4, the Coastal Plain of Virginia, belong to a group with low yield; plots 8 to 2 are intermediate, and the rest have a high alpha-cellulose yield. However, with the exception of the low-yielding Virginia group, there is no distinct geographic pattern present. Thus, plots 8 and 9 are significantly different although they are located only 100 miles apart in the Piedmont. Likewise, the two plots on the eastern shore are significantly different. In sharp contrast to the well-defined geographic pattern present for both specific gravity and tracheid length, the yield of alpha-cellulose does not seem to be adapted to any gross climatic or edaphic conditions.

Relationships of Different Wood Properties

Correlation coefficients for the six wood properties are given in *Table 4*. Some of the values for relationships such as those between tracheid lengths at 15 and 30 years, or WRC and alpha-cellulose are significant, as expected, and confirm previous work. However, several other relationships are not obvious, and it is necessary to take other factors into consideration in the interpretation of the findings. In the following few paragraphs each relationship which needs explanation will be discussed.

p:	2	3	4	5	6	7	8	9	10	11	12	13	14	
R:	.32	.33	.34	.34	.35	.35	.36	.36	.36	.37	.37	.37	.37	
Plot No.	13	4	3	9	8	2	7	14	10	6	5	12	1	11
Average	3.80	4.30	4.33	4.43	4.66	4.68	4.69	4.79	4.79	4.86	4.90	4.90	4.91	5.02

Figure 5. — "Duncan Test"; tracheid length at 30 years related to physiographic location. For explanation, see text.

p:	2	3	4	5	6	7	8	9	10	11	12	13	14	
R:	1.12	1.17	1.20	1.22	1.24	1.26	1.27	1.28	1.29	1.30	1.31	1.31	1.32	
Plot No.	13	4	8	11	10	7	6	5	2	1	9	3	12	14
Mean	55.3	56.1	56.1	56.2	56.4	57.1	57.2	57.5	57.5	58.0	58.0	58.2	58.4	58.4

Figure 6. — "Duncan Test"; % alpha-cellulose related to physiographic location. For explanation, see text.

Table 4. — Correlation coefficients for wood properties

Relationships	r-values		
	Between plots	Between trees	Within trees
Specific gravity × tracheid length at 30 years	.256 N.S.	−.162 **	−.125 N.S.
Specific gravity × tracheid length at 15 years	.288 N.S.	−.103 N.S.	−.099 N.S.
Specific gravity × % WRC	.370 N.S.	.085 N.S.	−.077 N.S.
Specific gravity × % alpha-cellulose	.744 **	.305 ***	.018 N.S.
Specific gravity × % compression wood	.140 N.S.	.051 N.S.	.238 *
Tracheid length at 30 years × tracheid length at 15 years	.850 ***	.425 ***	.330 **
Tracheid length at 30 years × % WRC	.488 N.S.	.065 N.S.	.268 *
Tracheid length at 30 years × % alpha-cellulose	.412 N.S.	.153 *	.280 *
Tracheid length at 30 years × % compression wood	−.110 N.S.	−.111 N.S.	−.217 N.S.
Tracheid length at 15 years × % WRC	.593 *	.040 N.S.	.297 *
Tracheid length at 15 years × % alpha-cellulose	.569 *	.160 **	.334 **
Tracheid length at 15 years × % compression wood	−.092 N.S.	−.127 *	−.266 *
% WRC × % alpha-cellulose	.767 **	.807 ***	.952 ***
% WRC × % compression wood	.254 N.S.	−.685 ***	−.858 ***
% Alpha-cellulose × % compression wood	.221 N.S.	−.623 ***	−.841 ***

* Significant at the 5% level.
** Significant at the 1% level.
*** Significant at the 0.1% level.
N.S. Not statistically significant.

The relationship between specific gravity and tracheid length is weak. It is, however, significantly negative between trees on any one site, although specific gravity differences account for only slightly more than 2.5% of the variation in tracheid length. This may be due to a positive relationship between specific gravity and compression wood, and compression wood has shorter tracheids. Thus, the slight relationship that may exist between specific gravity and tracheid length is probably "secondary" in nature.

It is rather surprising to observe that although there evidently is no relationship between specific gravity and the water-resistant carbohydrates, a relatively close relationship exists between specific gravity and alpha-cellulose Sites with average high specific gravity also have, on the average, higher alpha-cellulose yields, determined on a dry-weight basis. Also, trees within a stand have higher alpha-cellulose yields when their specific gravity is high. The reason for this may be that the cell walls in the summerwood contain a larger amount of alpha-cellulose than the cell walls in the springwood or it may be due to the mechanical effect of wall thickness on the method of cellulose extraction used in the present study. Further study is needed to clarify this apparent relationship. It is not surprising that the r-value for "within trees" is low; the sample with the higher specific gravity will often have a larger amount of compression wood. Due to the very high negative correlation between cellulose yield and compression wood, the "primary" effect may be nullified.

There is a slight positive relationship between cellulose yield and tracheid length. Plot averages for trees with long tracheids seem to be slightly higher in yields of both WRC and alpha-cellulose. This relationship also appears for individual trees in a plot; but the picture is not clear. Most likely, it is not due to variable amounts of compression wood present, because there are good cellulose-yield relationships within trees. There is no significant relationship, though a negative trend may exist between tracheid length at 30 years and compression wood percent; this same negative trend is stronger and statistically significant for 15-year tracheids. The cores showed unmistakably that the bulk of the compression wood was in those rings closest to the pith. While this paper reports compression wood percent for the whole core, actually compression wood will occur in the 15th ring much more frequently than in the 30th ring.

Effect of Growth Rate on Wood Properties

When expressed as rings per inch, there is some evidence supporting the belief that growth rate may affect the properties of wood. There are also numerous publications cited earlier which indicate that rings per inch have little effect and that differences in wood properties are due to other factors. The validity of using rings per inch as a measure of growth has been challenged by some writers, since basal area increase is a more realistic measure of volume growth rate. In fact, the use of rings per inch is looked upon by some workers as an "illegitimate reversal of variables". In the present instance, however, since the stands were all even-aged, and since the average ages of the stands were quite similar (*Table 1*), use of rings per inch should be appropriate.

Many studies dealing with growth rate effects are rather limited in scope in that they have explored the variation at a certain level, often within a tree or among very few trees. In order to understand the effect of growth rate on wood properties, it must be determined if it is related to site, individual tree growth, or both. The r values in *Table 5* should be of some value in indicating the effect of growth rate in loblolly pine, as discussed below.

Among trees in a plot, there is a slight positive relationship between rings per inch and specific gravity ($r = .133$). In other words, faster-growing trees have a tendency to have slightly less dense wood. However, the growth rate alone accounts for less than two percent of the variation in specific gravity of individual trees. Also, there is no indication that a fast-growing stand on a good site has a lower specific gravity; on the contrary, there is some indication that the better sites on the average have slightly higher specific gravities. Within an individual tree, it was found that there may be a trend towards higher specific gravity with increased growth rate, but this is probably due to an increased amount of compression wood, which is commonly more prevalent in wider rings.

Table 5. — Sample correlation coefficients for growth rate and wood properties

Relationships	r-values		
	Between plots	Between trees	Within trees
Rings per inch × specific gravity	−.111 N.S.	.133 *	−.185 N.S.
Rings per inch × % WRC	.155 N.S.	.100 N.S.	.263 *
Rings per inch × % alpha-cellulose	.086 N.S.	.184 **	.352 **
Rings per inch × % compression wood	−.111 N.S.	−.069 N.S.	−.294 *
Width 5 rings (24—29 years) × tracheid length at 30 years	−.632 *	−.259 ***	−.254 *
Width 5 rings (9—14 years) × tracheid length at 15 years	−.547 *	−.336 ***	−.270 *

* Significant at the 5% level.
** Significant at the 1% level.
*** Significant at the 0.1% level.
N.S. Not statistically significant.

Rate of growth seems to influence the yield of both WRC and alpha-cellulose in the same manner, even though the alpha-cellulose is somewhat better correlated with the number of rings per inch. With faster growth, there is a slight reduction in cellulose yield, this being accentuated within the trees, due to increased compression wood. The relationship between growth rate and alpha-cellulose yield accounts for only three percent of the between-tree variation in cellulose.

In order to obtain an estimate of the effect of growth rate on tracheid length, special measurements were made of the ring width for the five-year periods prior to the 15- and 30-year annual rings. Correlations were then computed between tracheid length and growth rate at the tree's particular age, and not between tracheid length and average growth rate for the life of the tree.

There is a highly significant negative correlation between growth rate and tracheid length, although this relationship at most accounts for only 10 percent of the variation between trees in a stand. This means that in breeding for both increased growth rate and increased tracheid length, relatively slow progress may be realized. However, much will have been gained if trees can be grown faster by improved silviculture, including fertilizers and genetics, without a simultaneous reduction in tracheid length. This may be possible, due to the large individual tree variation in tracheid length (*Figure 2*). It is emphasized that about 30 percent of the between-site (plot) variation in tracheid length is due to differences in rings per inch and that, in the future, thinning and other intensive forest management practices may result in harvesting a raw product with somewhat shorter tracheids. This trend will be increased by the utilization of more young trees with a higher proportion of core wood, but can probably be counteracted by intensive breeding for longer tracheids.

In the preceding discussion, considerable emphasis has been given to statistically significant differences. This alone may be misleading, since magnitude of the difference is the important issue in the genetic interpretation. It was indicated earlier that rings per inch-specific gravity was positively correlated at the five percent level; yet, rings per inch only accounted for less than two percent of the variation in specific gravity. All reported relationships must be viewed in this manner. When so viewed, it becomes evident that *Tables 4 and 5* show few relationships that are both highly correlated, and at the same time account for considerable amounts of the observed differences.

Summary and Conclusions

In 1956, a study was initiated on the wood of loblolly pine from a seven-state area (Georgia, Alabama, South Carolina, North Carolina, Virginia, Tennessee and Delaware), to determine site-to-site, geographic area, and individual tree variations. A comprehensive review of pertinent literature was also made and incorporated in this report.

The following wood characteristics were studied: specific gravity, tracheid length at 15 years and 30 years, percentage of water-insoluble carbohydrates (similar to holocellulose), percentage of alpha-cellulose and percentage of compression wood. These wood characteristics are phenotypic in nature and results must be interpreted in that light.

Highly significant differences were found between sites (plots) for all wood characteristics studied. Particularly specific gravitiy and, to a lesser extent, tracheid length followed a geographic pattern. Three distinct geographic groups are present for specific gravity; the low specific gravity group is made up of plots from the north and northwest extremes of the species range, the Piedmont has intermediate values, and the Coastal Plain of the Carolinas and Georgia belongs to the group with the highest specific gravity. Cellulose yields based on dry weight of wood did not appear to follow any geographic pattern.

Variation among trees within each plot was highly significant for specific gravity and tracheid length, but not for alpha-cellulose yield and compression wood. Ranges of individual values among trees within individual plots were extremely wide.

An attempt was made to determine if certain wood characteristics were highly related. As was to be expected, tracheid length at 30 years and tracheid length at 15 years were closely related, as were WRC and alpha-cellulose. Compression wood was found to have a high negative correlation with cellulose yields. Several of the other characteristics were significantly correlated, but the correlation coefficients were rather small. For example, there is a significant negative correlation between specific gravity and tracheid length; yet this relationship accounts for less than two percent of the variation. Another significant correlation, also with a small r value, was between tracheid length and alpha-cellulose yields. Both of these correlations are probably affected partly by compression wood, which showed a relationship to both tracheid length and cellulose yields.

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Zusammenfassung

Titel der Arbeit: *Geographische, standörtliche und individuelle Variation von Holzeigenschaften bei Pinus taeda.*

1956 wurden Untersuchungen über das *P. taeda*-Holz aus sieben Staaten (Georgia, Alabama, South Carolina, North Carolina, Virginia, Tennessee und Deleware) aufgenommen, um die standörtliche, die geographische und die individuelle Variabilität zu erfassen. Dazu wird ein umfassender Bericht über die einschlägige Literatur gegeben.

Folgende Holzeigenschaften wurden untersucht: spez. Gewicht, Tracheidenlänge im 15. und im 30. Jahr, Prozentsatz wasserunlöslicher Kohlehydrate (etwa der Holocellulose entsprechend), Prozentsatz Alpha-Cellulose und Anteil Druckholz. Diese Holzeigenschaften sind nur phänotypisch erkennbar, und die Ergebnisse müssen in diesem Sinne verstanden werden.

Zwischen den Standorten traten für alle untersuchten Holzeigenschaften hoch signifikante Differenzen auf. Einem geographischen Trend folgte besonders das spez. Gewicht und weniger deutlich die Faserlänge. Drei klare geographische Gruppen sind hinsichtlich des spezifischen Gewichtes zu erkennen: Die Gruppe mit geringem spez. Gewicht setzt sich aus den nördlichsten und nordwestlichsten Beständen des Verbreitungsgebietes zusammen, die Werte der Piedmont-Region liegen in der Mitte, und die der Küstenregionen von Carolina und Georgia gehören zu der Gruppe mit dem höchsten spez. Gewicht. Die auf das Holztrockengewicht bezogenen Cellulosewerte scheinen keiner geographischen Tendenz zu folgen.

Die Individualvariation innerhalb des gleichen Gebietes war für spez. Gewicht und Tracheidenlänge hoch signifikant, nicht jedoch für Alpha-Cellulose und Druckholz. Die Schwankungen der Individualwerte innerhalb des gleichen Probebestandes waren extrem stark.

Es fanden Untersuchungen statt, um festzustellen, ob bestimmte Holzeigenschaften eng untereinander gekoppelt sind. Wie erwartet, stimmten die Tracheidenlängen von 30 und 15 Jahren weitgehend überein, genau wie die Holo- und Alpha-Cellulosewerte. Der Druckholzanteil war mit dem Cellulosegehalt straff negativ korreliert. Auch zwischen einigen der anderen Holzeigenschaften wurden signifikante Korrelationen errechnet, jedoch waren die entspr. Koeffizienten rel. klein. So besteht z. B. eine gesicherte negative Übereinstimmung zwischen dem spez. Gewicht und der Tracheidenlänge, doch macht diese Verbindung weniger als 2% der Gesamtvariation aus. Eine andere, ebenfalls nur mit einem kleinen r-Wert versehene gesicherte Korrelation besteht zwischen Tracheidenlänge und Alpha-Cellulosegehalt. Beide Zusammenhänge werden wahrscheinlich vom Anteil des Druckholzes beeinflußt, der sowohl zur Tracheidenlänge wie zum Cellulose-Ertrag gewisse Verwandtschaft zeigt.

Résumé

Titre de l'article: *Variations géographiques stationnelles et individuelles des propriétés du bois du «Loblolly pine» (Pinus taeda L.).*

En 1956, une étude du bois du «Loblolly pine» fut entreprise dans une région couvrant 7 Etats: Georgie, Alabama, Caroline du Sud, Caroline du Nord, Virginie, Tennessee et Delaware; elle avait pour but de déterminer les variations pouvant exister suivant les régions, les stations et les individus. L'article comprend également une revue complète dans la littérature sur cette question.

Les caractéristiques du bois suivantes furent étudiées: densité, longueur des trachéïdes à 15 et 30 ans, pourcentage des hydrates de carbone insolubles à l'eau (analogues à l'holocellulose), pourcentage d'alpha-celluose et pourcentage de bois de compression. Ces caractères du bois sont de nature phénotypique et les résultats doivent être interprétés dans ce sens.

Des différences hautement significatives furent mises en évidence entre les stations (placettes) pour tous les caractères étudiés. La densité en particulier et à un degré moindre la longueur des trachéïdes présentent une variation géographique. Il y a trois groupes géographiques distincts en ce qui concerne la densité; le groupe à faible densité réunit les placettes situées dans l'extrême nord et nord-ouest de l'aire de l'espèce, la région du Piédmont présente des valeurs intermédiaires et les plus hautes densités sont trouvées dans la plaine côtière des Carolines et de Georgie. La production de cellulose basée sur le poids de bois sec ne semble pas suivre une variation géographique.

La variation individuelle à l'intérieur de chaque placette est fortement significative, en ce qui concerne la densité et la longueur des trachéïdes, mais ce n'est pas le cas pour la teneur en alpha-cellulose et la proportion de bois de compression.

Les valeurs individuelles présentent une variation très étendue à l'intérieur de chaque placette.

On a essayé de savoir s'il existait des corrélations étroites entre certains caractères du bois. Comme on pouvait s'y attendre, les longueurs de trachéïdes à 30 ans et à 15 ans sont étroitement liées, de même que la teneur en hydrates de carbone insolubles et en alpha-cellulose. La proportion de bois de compression présente une forte corrélation négative avec une teneur en cellulose. Plusieurs autres caractères sont liés de façon significative mais les coefficients de corrélation sont assez faibles. Par exemple. il existe une corrélation négative entre la densité et la longueur des trachéïdes; mais cette relation représente moins de 2% de la variation. On a tout de même une corrélation significative mais faible entre la longueur des trachéïdes et la teneur en alpha-cellulose. Ces deux corrélations sont probablement modifiées par la teneur en bois de compression qui présente une relation à la fois avec la longueur des trachéïdes et la teneur en cellulose.

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