Selecting and breeding for desirable wood

ABSTRACT
A major industrial need is to have greater wood uniformity. Wood differences that occur by species, geographic source, from tree to tree, and within a single tree itself make manufacturing more difficult. More uniform wood can be obtained by controlling tree form and growth rate through silvicultural manipulation and through direct genetic manipulation. This is illustrated for *Eucalyptus* on the lands of Aracruz Florestal in Brazil, where increased yields and uniformity are achieved through use of vegetative propagation.

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Wood is a remarkable and a most variable substance. Variation, however, can cause difficulties for manufacturers, resulting in less effective production and processing. In the manufacture of pulp and paper, when woods with variable properties, as in juvenile and mature wood, are used together, low-density juvenile wood is overcooked so that the mature wood is certain to be cooked sufficiently. This results in lower yields from the wood furnish and lower strength properties of the fibers and papers. A major advantage of uniform wood is that it gives better quality products with increased efficiency in manufacturing (*1*). Thus, developing more uniform wood or wood with characteristics more desired for the end product is of importance.

Of the several important wood properties, specific gravity is key. Because of its overriding importance, most emphasis in this paper will deal with specific gravity, although occasional reference will be made to cell length, a characteristic important for paper quality under certain conditions. Specific gravity as used here is a measure of the amount of dry wood substance per unit green volume, and most strength, quality, and yield characteristics of pulp products are closely related to it (*2*).

The first part of this paper will summarize the causes of variability in wood specific gravity, information one needs if more useful and uniform wood is to be developed. Both silvicultural and genetic controls of wood variability will be touched upon. The second part of the paper will briefly describe the large operational forestry program of Aracruz Florestal in Brazil, which represents one of the most intensive attempts in forestry to develop wood of the desired type and uniformity to enable a more economical production of high-quality products.

Why is wood variable?

There are many reasons for nonuniformity in woods. It is sufficient to mention briefly a few of the more important factors causing variation. These ideas will be substantiated by only a very few of the hundreds of references on the subject. Wood variability has been documented in several summary publications; the seven cited are some of the more important ones (*2-8*).

Species differences

The lack of uniformity in wood among species is well known. Although there is considerable variation among species of conifers, these variations are small when compared with the variability within the hardwoods. Differences in cell size, wall thickness, and length, kinds and proportion of cells such as fibers, rays, and vessels in hardwoods, proportion of earlywood and latewood cells, and numerous other cellular and chemical combinations make the wood of some species nonuniform and undesirable. The wood of the major southern pines varies only slightly among species, although within-species variability can be large. Even when average differences between coniferous species are of considerable magnitude, they usually are small relative to differences of wood qualities within a species.

Changes in wood when trees are grown in new environments cannot always be predicted; the only sure way to assess wood qualities is to test for them in the new environment. Some species like *Pinus taeda* and *P. oocarpa* seem to be stable and produce similar woods wherever grown; this is also true for such species as *Eucalyptus grandis*. Other species, e.g., *P. caribaea*, are highly variable and the wood properties cannot be predicted with confidence when the trees are grown in greatly varied habitats. No matter what the overall effect, the variability among individual trees of a species within a site is usually large.

Geographic differences

Wood is often quite different among different geographic sources within a given species. Although there are always exceptions, usually this kind of wood variation is more environmentally influenced than genetically controlled. Many errors have been made trying to grow desired wood by moving seed from one geographic source or habitat to another. Many acres of slash pine (*P. elliottii*) have been planted in the sandhills of the Carolinas—with the expectation that the wood produced would have high specific gravity similar to that achieved in its native range. In fact, the slash pine grown in this sandy area has a low specific gravity similar to and sometimes even lower than the local loblolly pine (*P. taeda*). The average specific gravity of wood of loblolly pine from different geographic sources varies from 0.58 to 0.47; similar trends are found for hardwoods. For example, geographic averages for yellow poplar (*Liriodendron tulipifera*) vary from 0.55 to 0.41 (*9*). The location where a species happens to be growing does not always have a major effect on wood quality. Some species such as red alder (*Alnus rubra*), for instance, appear to show no geographic variability in wood (*10*).

Tree-to-tree differences

The greatest lack of uniformity in wood is associated with tree-to-tree differences within sources within species. No matter where the trees grow, the same large individual tree variation occurs. About 70% of the total variability in wood among trees of *P. taeda* is associated with tree-to-tree variation (*4*). One can predict that if 50 *P. taeda* trees had an average specific gravity of 0.5, the range among the 50 would be from as low as 0.4 to as high as 0.6, a difference that will greatly affect yield and quality of pulp and paper. Tree-to-tree differences are equally large for most hardwoods. For example, large tree-to-tree variability exists in tropical mahogany, even though geographic source differences vary from 0.7 to 0.9 (*10*). The large tree-to-tree differences are most useful and encouraging to the geneticist, since they contain a large genetic component; this makes it possible to develop trees whose average wood qualities can be moved toward the desired qualities.

Tree form

The straightness of a tree and the presence of limbs of differing angles and sizes have a dramatic effect on wood quality and uniformity. Reaction wood (called "compression" wood in conifers and "tension" wood in hardwoods) is formed in conjunction with crooks or around knots in the tree bole (*8*). Reaction wood varies greatly from "normal wood," with differing specific gravities, cell dimensions, and chemical constituents (*11*). Crooked pine trees can have over half their merchantable volume as compression wood (*12*). The effect of straightness and limb size on pulp yields and quality has been determined in detail (*13*). It was found that crooked trees produced reduced yields of pulp per ton of wood although yields were not greatly affected by limb size. However, the critical paper tear strength, so hard to maintain at a satisfactory level when using wood of young pine, was significantly reduced in pulp from wood of both crooked and large-limbed trees when compared with straight, small-limbed trees.

The quickest and often easiest way to develop better wood is to manage the forests and to genetically develop trees that are straight and have small, horizontal limbs.

Within-tree differences

Most trees have a pattern in wood qualities from the center of the tree outward, from the base to the top of the tree, within an annual ring, and sometimes even on different sides of the tree related to the sun and temperature (*9, 14*). The within-tree patterns of variation have been intensively studied for many species. The group of conifers, including most pines, shows a drastic increase in both specific gravity and tracheid length from the pith to the outside of the tree (*4*). It is common for a loblolly pine tree to have a specific gravity near its center as low as 0.32, which increases to 0.55 or greater near the bark. There have been discussions about patterns in tropical pines. Increased specific gravity and tracheid length in *P. caribaea* were reported from the center of the tree to about the 7th ring, at which time the increase became less (*15*). Tracheid length varies from under 2 mm at the center of a pine tree to 5 or even 6 mm at the outside. Another group of conifers, represented by some spruces, hemlocks, and cypress, shows little variation in specific gravity from the center of the tree outward or may even have higher specific gravity at the tree center (*16–18*).

Individual hardwood trees also show varied patterns of specific gravity, some low at the pith as for *Liriodendron* (*9, 19*), others high near the pith like oaks (*Quercus*), and some uniform from the tree center to its outside like *Alnus rubra* (*10*), or nearly uniform like many of the eucalypts (*20*). Both conifers and hardwoods show an increase of tracheid and/or fiber length from pith to bark.

Because of the presence of the low-density juvenile wood near the tree center, most conifers have an overall higher specific gravity at the base of the tree and a lower specific gravity nearer the top of the tree, where the proportion of juvenile wood is higher. This even occurs for the relatively uniform red pine (*21*). Most hardwoods show only small changes in specific gravity with tree height, although several species have slightly higher specific gravity at mid-height.

Within-ring differences

The presence of bands of both thin- and thick-walled cells (referred to as springwood, or earlywood, and summerwood, or latewood, respectively) in the same annual ring results in great wood nonuniformity. Differences in cell wall thickness and other characteristics are large between the two types of wood (*22*). For example, specific gravity of latewood is from 30% to 100% greater than that of the earlywood in the same growth ring (*15*). Similar major differences in tropical pines have been reported (*23*). The first 2 to 4 growth rings from the pith had relatively uniform wood within the ring because no true summerwood was produced in this early-formed juvenile wood. Most paper qualities can be related to the characteristics of the summerwood; the springwood essentially serves as a matrix. Therefore, the summerwood percentage is most important for the physical and chemical properties of wood and its products (*24*).

Just as for the pattern of juvenile-mature wood from the pith outward, the springwood–summerwood pattern within a ring is a biological fact of tree growth which causes great variability. Although the pattern cannot be eliminated, it can be changed to become more predictable and constant. Auxin in the shoot regulates wood formation, and anything that will change apical growth patterns has an effect on the springwood–summerwood ratio (*25*).

Miscellaneous causes

Many other reasons have been given as to why wood varies. In the broadest sense, even though the pattern of variability in wood characteristics within a tree is fairly well genetically set, any action that changes the growth pattern of a tree can have an effect on its wood properties. Wood qualities often vary with the general soil and environment in which the tree is growing, but the internal patterns remain about the same, although they may be modified by differing environments.

The effects of growth rate on wood qualities have been one of the most debated of all characteristics. For hardwoods, the effect is usually minimal although the ring-porous species often show a positive correlation between growth rate and wood density, with the faster-growing trees having higher specific gravities. For the pines, most studies show little relationship, if wood age and juvenile wood are taken into account. Some conifers, such as the spruces, seem to have a closer but negative relationship to growth, with faster-growing trees having lower specific gravities.

Annual fluctuations in weather patterns cause large variability within the wood of some trees. Annual or cyclical fluctuations always occur and are not controllable; their magnitude is evident from the tree-ring analyses of wooden beams commonly used to date historical events.

Considerable changes in wood qualities are induced through silvicultural manipulation. Since growth-pattern changes affect wood, silvicultural treatments that change growth will also affect wood specific gravity. Silvicultural treatments, such as fertilization, cultivation, thinning, and site preparation, can affect wood density, but nitrogen fertilization seems to have the most dramatic result.

Developing more suitable wood

The magnitude and complexity of attempts to develop better and more uniform wood are great. Gross environmental differences, such as rainfall, temperature, and day length in different parts of a species range, are not controllable. Some growth factors can be controlled to aid in developing more uniform wood. When heavy nitrogen fertilization was used, it made wood more uniform, reducing specific gravity of the high-density trees much more than the specific gravity of the low-density trees, thus reducing tree-to-tree variability (*26*). Wood variability within a tree could be significantly reduced by controlling environments within a stand through silvicultural manipulation (*27*) and within a forest by tighter control of rotation age of the trees harvested (*28*).

It is most difficult to define wood quality. A number of people have attempted this (*5, 6, 29, 30*), but the fact is that wood quality can only be accurately defined when the final product is known. In this article the trap of defining wood quality will be avoided. However, for all products and all kinds of woods, greater uniformity is generally highly desired.

Greater uniformity through genetic manipulation

Trees within some species are more uniform than in others, so one simple method of reducing wood variability is to use the more uniform species if its wood is suitable. Some hardwoods possess very uniform wood (*10, 20*), but in most the variability is large; the best way to improve and make wood more uniform is through a breeding program (*31*).

The most important way to breed for wood quality improvement and greater uniformity is to select and breed individual trees. Wood specific gravity and fiber length are strongly inherited (*13, 31-34*). This makes possible development of such things as high-density loblolly pine (*35*) and, by so doing, to develop more desirable wood. In order to avoid the wood quality variances when normal juvenile and mature wood are mixed, it was possible to develop trees with higher specific gravity juvenile wood, which made the density of juvenile wood heavier by 2 lb/ft^3 and thus the overall wood from the tree more uniform (*36*).

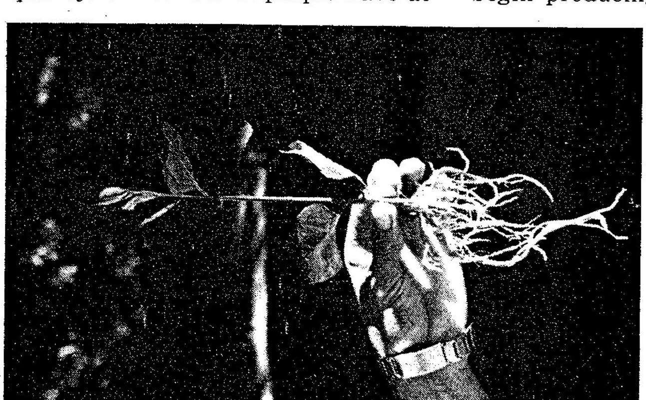
Breeding for desired wood, such as for higher density, does not directly develop uniform wood. There still is a large variation from tree to tree in the improved strain, but more trees will be in the desired area than in the unimproved one. It is also possible to actually breed for greater uniformity within a tree; families with low within-family variation were selected and developed (*37*). Results indicated that "genetic selection of families with denser juvenile wood or families that begin producing mature wood at an earlier age, or both, should also improve wood uniformity and strength."

Improvement of wood qualities by means of standard sexual breeding systems, such as through seed orchards, falls short of obtaining the improvement that can be obtained through vegetative propagation. Since all trees (ramets) from a given clone are genetically identical, and since inheritance of wood qualities is quite strong, the members of a clone have wood that is very similar. For example, Burdon and Harris (*38*), in reporting on clones of *P. radiata*, state, "The appreciable repeatabilities indicate that the objectionable pith-to-bark density gradient can be reduced by clonal selection." In Norway spruce, the range of variation within clones was found to be very small compared with differences among clones (*39*). Therefore, as vegetative propagation becomes more widely used, it will be possible to develop trees with less variable wood, both among and within trees.

A case example

In forestry, perhaps the most outstanding example of making an all-out effort to improve wood qualities of *Eucalyptus* is the program of Aracruz Florestal in the state of Espirito Santo, Brazil. The program has both short- and long-term objectives of maximizing yield and quality of wood from Aracruz's operations.

Immediate gain is being obtained through an intensive selection program to develop the desired growth, form, and wood qualities. Trees used as parents come from the company's extensive plantations, using the original "Brazil source" of *E. grandis*. Phenotypically superior trees are selected, many of which are hybrids. These trees are vegetatively propagated, which makes possible the greatest genetic gain in the shortest possible time (Fig. 1). Rotation ages are from 5 to 8 years, since the improved trees are merchantable at a young age (Fig. 2). The com-



1. This typical, eucalypt rooted cutting is well-developed and is only a few weeks old. Aracruz Florestal is using many millions of these annually.

2. Wood within clones is very uniform, and the growth rate is rapid for vegetatively propagated eucalypts. Slightly over 3 years old, these trees average 21 m high.

I. Frequency distribution and range of variability in wood specific gravity and bleached pulp yield (without bark) from eucalypts with excellent growth and form

Wood density		Bleached pulp yield	
kg/m³	*No. of trees*	*%*	*No. of trees*
301-350	1	40.1-41.0	1
351-400	11	41.1-42.0	3
401-450	172	42.1-43.0	...
451-500	863	43.1-44.0	6
501-550	1373	44.1-45.0	20
551-600	944	45.1-46.0	44
601-650	256	46.1-47.0	70
651-700	41	47.1-48.0	111
701-750	8	48.1-49.0	191
751-800	5	49.1-50.0	295
801-850	2	50.1-51.0	305
851-900	1	51.1-52.0	318
		52.1-53.0	178
		53.1-54.0	64
		54.1-55.0	18
		55.1-56.0	2
Total	3677		1626

II. Characteristics of the 25 clones currently being used and tested for Aracruz's plantations

Clone no.	*Specific gravity*	*Est. bleach pulp yield, %*	*Rooting[a] ability, %*
999	0.626	51.60	92
1486	0.603	52.63	88
2225	0.601	50.95	67
930	0.598	50.40	74
2215	0.597	52.45	66
1205	0.593	52.20	75
2029	0.584	52.18	87
1225	0.580	51.08	82
804	0.579	50.10	89
881	0.575	50.20	73
1235	0.573	51.80	66
1285	0.572	50.38	64
658	0.571	51.75	83
2130	0.566	50.15	79
534	0.566	51.10	83
1087	0.566	50.00	87
847	0.562	51.35	73
514	0.552	51.30	64
828	0.545	51.55	73
1439	0.544	52.45	77
1501	0.539	51.74	...
2086	0.537	52.15	82
1201	0.529	51.30	73
1320	0.519	51.35	64
1806	0.519	52.05	67
Avg.	0.568	51.37	76

[a]Clones with a rooting percentage below 60% are automatically rejected.

pany planted approximately 8 million rooted cuttings in 1981 and will plant 12.2 million in 1982. Regeneration using vegetative propagation is ideal for capturing and using genetic differences in growth, form, and wood properties. It, in effect, enables Aracruz to "tailor-make" wood most suitable for their products.

Benefit is being realized from the variation present in Aracruz's plantations. Company personnel have tested the wood for specific gravity and for bleached pulp yield (Table I). Variation in both specific gravity and pulp yield is huge; specific gravity varies from a low of about 0.35 to a high of around 0.85. Most of the trees are in the range of 0.5 to 0.6. Similarly, pulp yields vary from 41% to 55%, with most in the range of 48% to 52%. The company has an excellent opportunity to change specific gravity and cellulose yields in the desired direction using vegetative propagation, and it is obtaining improvement in both wood qualities. The decision has been made to use high-specific-gravity parents to improve yield per unit volume wood and paper strength. In addition, high cellulose yields within the high-specific-gravity parents are being sought. Improving cellulose yields can only be done using vegetative propagation, control-pollination, or two-clone orchards, since genetic gains in cellulose are very small when using the standard seed orchard approach (*40, 41*). Thus, Aracruz will obtain the double improvement of their Eucalyptus wood from higher-density wood plus greater yields per unit weight of dry wood substance from within the higher-density group of trees.

Selections were made from 7- to 12-year-old plantations. From the total 4,500 trees selected, 3,677 were tested for specific gravity and 1,626 for bleached pulp yields. Of these, 614 have been chosen for use that have pulp yields superior to 50%; those chosen had:

1. Specific gravity with bark of 0.50 (500 kg/m³)

2. Specific gravity without bark of 0.53 (530 kg/m³)

3. Estimated bleached pulp yield of 51.5%, without bark.

Within the 614 trees, a further selection of 192 with the wood specific gravity from 0.55 to 0.60 was made. These trees averaged:

1. Specific gravity with bark of 0.54 (540 kg/m³)

2. Specific gravity without bark of 0.57 (571 kg/m³)

3. Estimated bleached pulp yield of 51% (without bark).

3. Size is uniform in a four-year-old vegetative plantation.

Based on the above and on field tests, 25 clones have been chosen and are being tested in different environments (soil types) in Aracruz's forests. The clones now being tested are shown in Table II, in decreasing order of specific gravity.

As expected, there is no relationship between specific gravity and either bleached pulp yield or rooting ability. Specific gravity represents the amount of wood substance per unit *volume*, while cellulose yield is calculated per unit *weight* of dry wood; they are genetically unrelated.

By using the best trees, the company is developing wood of much greater uniformity, with higher specific gravity and higher cellulose yield per unit dry weight than wood from normal forests. In addition, Aracruz is starting to plant by 10- to 20-hectare clonal planting blocks (Fig. 3). Wood from each block will be essentially uniform. This gives great opportunities for controlling wood and paper uniformity. The wood uniformity has been developed on trees that had been first selected for form, disease and insect resistance, vigor, limb size, coppice ability, and rooting ability.

The plantations made from unimproved seeds are producing 36 m³/ha/yr at 7 years of age. The new plantations, made from selected trees propagated by rooted cuttings, are producing 70 m³/ha/yr at 5.5 years of age, based on detailed information on 10 clones. As the short-term program develops, the best 100 clones chosen in consideration of favorable growth potential and uniformity are being selected for operational planting.

Aracruz also has a long-term breeding program to produce better growth and quality along with still more desired and uniform wood. Very rapid and large gains have been made possible through selecting and breeding for wood qualities and by means of vegetative propagation.

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