L. decidua, *L. kaempferi*, *L. laricina*, and *L. sibirica* are planted commercially outside their natural distribution areas.

See also: **Silviculture**: Natural Stand Regeneration. **Temperate and Mediterranean Forests**: Northern Coniferous Forests.

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Thinning *see* **Plantation Silviculture**: Forest plantations; Rotations; Stand Density and Stocking in Plantations; Tending; Thinning. **Silviculture**: Silvicultural Systems.

TREE BREEDING, PRACTICES

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Biological Improvement of Wood Properties

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Introduction

The objective of this article is to discuss how wood can be changed either naturally or by manipulation and how these changes might affect the final product. All wood characteristics are the result of physiological effects (controls) on growth. When the physiological controls are determined by genetic or other within-plant influences, they are referred as internal. These are difficult to manipulate and require activities such as breeding to obtain the desired kind of wood. When the physiological controls are primarily influenced by forces outside the tree, such as weather, nutrient availability or other, one refers to them as external controls.

A good example of a wood property strongly controlled internally is wood density or wood specific gravity. This makes possible the development of high or low wood density races of trees within a species, when selective breeding is used. When the wood of the tree is primarily influenced by outside factors such as weather or wind, external control is indicated. If, for example, a southern yellow pine has been affected by ice or tip moth so that it is no longer straight, the reaction wood resulting will differ a great deal from wood that will result under normal growth conditions no matter what the genetic situation is.

The control of wood formation is certainly not simple or clear-cut as a definition might imply. For example, tree straightness is the result of genetic control but is also affected by environmental factors. Thus, no matter what genetic controls are acting, major environmental differences can result in wood of differing kinds. However, the simplistic way to assess what the wood in a tree will be, is to consider the result of the interaction of both internal and external influences.

General Concepts

Wood is a very pliable and variable substance and can be changed in numerous ways as described below. In the past, when a lot of old, or virgin, timber was available, there was not much need, or effort, to change the wood quality available for use. As the practice of forestry has become more widespread and important, especially since plantation forests have become a major supplier of wood, it has been necessary to grow wood most suitable for given final products; this means methods must be developed to change wood qualities to meet the needs of the intended product.

I will use the southern pine forests in the USA and eucalypt plantations in Brazil as examples of the changes and needs to modify wood properties. Initially, almost all harvesting of softwoods in the southern USA was from quite mature pine trees, from 30 to 70 years of age. There was little concern about wood variation and wood quality as the wood harvested was mature and there was little concern about variation affecting its utilization. After more intensive forestry was practiced, wood quality has become variable enough to have a major effect on its utilization. Different products were found to require different kinds of wood to make the desired product efficiently. A personal example will illustrate this:

> In 1951, I gave a talk to the pulp mill managers and executives from the southern USA about wood, how it varied, and what this variation could mean to the industry. The audience was polite enough to listen but it was evident during the talk that the attendees did not think wood variation was a very important problem since they had good wood to work with which varied only a little. After my talk, the manager of the largest group of mills in the South came to the podium, put his arm around my shoulders and said: ‘Son, your talk was interesting but we do not have to worry about wood variation. We are chemists; just grow us any kind of wood and we can make usable paper from it.’

Of course, in reality, this was true, but with the changes in wood from intensive forestry, it has become neither operationally nor economically correct. The differences in wood quality with shorter rotations (harvest age) and more intensive utilization of the trees available has resulted in a large proportion of juvenile wood being used. This, along with more intensive silviculture, has resulted in the costs, quality, and expected yields of the desired products changing. Because of this, the production of substandard products sometimes has been rather dramatic. Currently, wood quality has become recognized as of key importance for efficient production of the kind and quality of product to be produced. The properties of the wood used has become of major interest for pulp as well as for lumber, in both the conifers and hardwoods.

Although the emphasis here will be on wood quality and how it affects the final product, it is necessary not to underestimate the ability of the industry to alter methodologies to adapt to differing woods. Great progress has been made in this area; methods of sawing, methods of curing timber, particleboard construction, pulping technologies, and paper manufacture have all been altered to better use the younger, different-quality wood that is becoming available. Sometimes the changes have been reasonably efficient but too often they have resulted in increased costs and/or poorer-quality final products. The first need for an industry making a given product is to have the raw material it uses reasonably uniform. When this is so, it can develop the best methods of manufacture for a reliable and stable product.

It is necessary to note that the emphasis here is on solid wood and fiber production, used in construction and for paper products. However, there are other major uses for wood; reports are available that show that more than half the wood used on a world basis is for energy production. For example, until recently, a great proportion of the hardwood produced in Brazil was for charcoal, much being utilized for energy in the steel industry. (I worked for several steel companies in this area for a number of years, with the directive to develop wood most desirable for charcoal. This was done by changing species and selecting and breeding for fast-growing trees that had the genetic potential to produce the high-density wood best used for charcoal.) It has been well proven that the *Eucalyptus* wood ideal for tissue production differs greatly from that needed to make good charcoal. Because of the large basic variation in wood properties in the eucalypts, it has been possible to develop wood in the eucalypts most suitable for charcoal, or ideal for pulp, diverse as the needs for these products are. The details as to how such changes can be made will not be covered in this article (but see my books listed in the Further Reading section).

Important Wood Properties

Before one can consider changing wood, it is essential to know which properties are the most important. Although many wood properties can be altered, only a few are of key importance; five of these are listed below:

Wood Density

Wood density, or wood specific gravity, is by far the most important wood property, affecting nearly all products. Wood density and specific gravity measure the same thing – the solid wood substance in a given volume of wood – but they are expressed somewhat differently. (They are the ratio of the dry weight of wood in a given green volume of wood; this can be expressed as dry weight/green volume. The higher the ratio the denser the wood. In pine, a specific gravity of 0.41 is low density while one with a ratio of 0.62 is considered to be very high.) Wood density is normally the term used in the industrial area, while specific gravity is more commonly used by researchers. They can easily be determined from each other. They affect strength, stability, and appearance of solid wood products and grossly affect the kind and quality of paper produced. For example, low-density wood is best for quality paper products like writing papers and tissues, while high-density wood gives the best yields when pulped and is most suitable for fiberboard containers and paper that needs good tear strength.

Wood density is easily measured and can even be roughly estimated when looking at a piece of wood. It can be altered both through silvicultural and genetic manipulation.

Spiral Grain

Spiral grain is of primary importance for stability in solid wood products such as boards while it plays only a small role in its effect on pulp. Most spiral grain is found near the center of the tree; it varies from species to species and from individual to individual. Commonly, it is considered to be important if it exceeds 4 degrees, so is not important in some species with low spiral. Some species, especially in the tropics and sometimes in those like sweet gum (*Liquidambar styraciflua*) have an extreme spirality called interlocked grain. Such wood is extremely variable and not suited for solid wood products. However, there is a reasonable genetic component so a selection program will help.

Fibril Angle

Fibril angle (correctly called microfibrillar angle) is of increasing importance as its effects become better known and methods for its measurement are improved. The wall of a wood cell is not solid, it is made up of numerous microfibrills. The orientation of these in the wall is very important to the stability and quality of the products produced. Fibril angle is greatest near the tree center; it also varies greatly from tree to tree. It has a major effect on the stability of solid wood products and can have an influence on the quality of paper produced.

Wood Uniformity

Uniformity is of great concern to the manufacturer of wood products. The more uniform the wood, the better the product produced and the greater the efficiency in manufacture. As harvest periods for trees become shorter, a greater amount of juvenile wood is obtained, resulting in increased nonuniformity of the raw material available. Currently, there is much effort to change wood properties to obtain greater uniformity, and organizations that have been successful have benefited greatly economically.

Wood uniformity can be improved by controlling the time of harvest as well as growth conditions and silvicultural treatments such as fertilization and site preparation. We have found, in species such as loblolly pine (*Pinus taeda*), that a heavy nitrogen fertilization will usually result in low-density wood being formed for a few years but normally the use of phosphorus fertilizer has only a minor effect on wood density.

General Wood Properties

If space were available, one could list many other wood qualities that can be changed by external or internal means. Some of these can be of considerable importance under certain circumstances, such as the necessity for thin-walled cells and larger cell lumina in the manufacture of tissue papers or straight grain in quality boards. Other characteristics that may be of importance are cell length, resin content of the wood, amount of heartwood present, and numerous things depending on the product desired and the species of trees being used.

Methods of Making Changes in Wood

Wood can be altered in two major ways which will be described separately below: these are external and internal. The external one includes such things as altering tree form, differences in silviculture, and choosing the most desirable species and provenances within species. Internal changes can be obtained by controlling the amount and use of juvenile wood and through genetic manipulation and silvicultural control.

External Control of Wood Properties

Tree form is the most important tree characteristic that affects wood quality. Two major aspects of tree form are straightness of the bole and limb characteristics.

Straightness of bole Straightness of the tree bole is most important. Any time a tree is not straight, it forms a kind of wood called reaction wood. One can reduce the amount and severity of reaction wood by growing straighter trees, either through silvicultural manipulation or control of parentage using a breeding program.

Reaction wood in most conifers is called compression wood. It is formed on the inside of a 'bend' in the trunk of the tree or in the underside of limbs. Its main function appears to be to straighten the tree or push up the limb by pressure on the nonstraight area.

Compression wood has many unique anatomical and chemical characteristics, most of which are adverse to good wood quality. For example, it contains an excess of lignin, often as much as 9% more than the more normal wood; this results in low cellulose yields when pulped. The cells in compression wood have fissures that cause the cell to fragment into small segments not good for the manufacture of paper. The cell walls of compression wood are often unusually thick, resulting in a coarse fiber which is not suitable when making fine papers or absorbing tissues and which result in a nonuniform surface of the paper.

The cells of compression wood have flat fibril angles so it shrinks an exceptional amount longitudinally when dried (up to 9% or more). This makes for unstable boards. Quality is especially adversely affected when a board consists partially of regular wood and partially of compression wood; the result is that one part of the board shrinks longitudinally more than another portion which causes warping, cracking, and checking in the board.

In the hardwoods, reaction wood is called tension wood. It is formed on the outside of the curve in the tree bole. Its function is to pull the tree bole straighter. Opposite to compression wood, tension wood has an excess of cellulose, otherwise the short cells and other abnormalities in compression wood such as adverse fibril angles, are present. (Since paper is made from cellulose, years ago some industrialists suggested that we breed crooked hardwoods which would increase the amount of cellulose and reduce the lignin formed. However, the cellulose in tension wood is different than that in normal wood and, when pulped, gives low yields and inferior paper qualities.)

When tension wood is used for solid wood products, the boards often have a weak plane in them (high cellulose and low lignin) causing the boards to break easily. Also, because of the flat fibril angle, it is difficult to finish the boards by planing or use of sanding, because the angle of the fibrils prevents formation of a smooth surface.

One of the most interesting things relative to the biology of wood in trees is how such opposite methods (compression wood and tension wood) have developed in the conifers and in the hardwoods, both to straighten the tree. The wood properties resulting from the two methods differ greatly. The amount of reaction wood can be reduced by producing straighter trees. This can be partially done through the use of selection and breeding straight trees since the genetic control of straightness is usually moderate to high. Natural variability in straightness is large so the combination of that plus moderately high heritability results in dramatic improvement in the population resulting from a breeding program which emphasizes tree straightness. (Put roughly, gain is the product of variability in the characteristic times its genetic control.)

Straightness can also be improved through the use of good forest management. Uniform and well-spaced, well-established plantations will result in straighter trees. As one example, if a pine tree is planted poorly so the stem of the seedling is not above the root, the resulting tree will grow crookedly, with an excess of compression wood, for the rest of its life. Planting using machines often creates serious problems when the foot of the planting machine is too shallow, resulting in the planted tree's having trailing roots. Trees from such plantations have excessive crook in their stems causing a major degrade in their wood quality. Based on my experience, the fastest and best method to improve wood quality is to develop straight trees. Frequently, detailed studies as to the cause of crookedness have been made, blaming such things as seed source, when the act of good planting would have avoided the trouble.

Limb Characteristics

Altering limb characteristics can have a major effect on the type of wood product produced. Smaller and more horizontal limbs are most suitable for the quality of both solidwood and the strength and yields of pulp. These characteristics are influenced both by the knotwood itself and by the reaction wood which is associated with the knots. Limb size can best be controlled via tree spacing in the plantation; genetic control of limb size is relatively small. However, limb angle has a much stronger genetic control, and can be improved by a breeding program. When excessively limby trees are used, limb size and angle has an effect on product quality, especially on the stability of boards and the tear strength of the paper produced. Changes in limb characteristics are not as easy to obtain or as large as for wood density, but they can be very important for certain products.

Forest Management Approaches

Variation in methods of forest management can result in differences in wood. All management activities must be done carefully if wood quality is to be as desired.

Silviculture

Silvicultural treatments that change nutrients via fertilization can have a major effect on wood properties. Especially in the conifers, but also for some hardwoods, heavy fertilization, using a high nitrogen content, often causes a considerable lowering in wood density. In the hard pines, the wood produced when a heavy nitrogen fertilization is used is somewhat similar to juvenile wood with thin cell walls resulting in lower wood density and usually in shorter cells. The response to nitrogen rarely continues for more than 5 years. As a result, there will be excessive longitudinal shrinkage in the affected annual rings of boards made from this kind of wood which will be unstable when dried. Although detailed studies on the effect of fertilization on fibril angle have not been made, I predict that the wood from heavily nitrogen-fertilized trees will have flatter fibril angles than normal, making the wood similar to juvenile wood.

Phosphorus content of the soil usually has little effect on wood density, although a shortage of phosphorus sometimes results in higher wood density. Here, the addition of this substance will reduce the higher density to that of normal wood.

Fertilization Fertilization, especially in the tropics, is often mandatory if suitable growth is to be obtained; when this is so nitrogen fertilizer should be applied slowly in small quantities at each treatment, not in large amounts at one time during the midterm of the rotation. This is especially true in the pines; when a heavy application of nitrogen is made, the trees will form a band of wood in the tree trunk that is similar to juvenile wood, resulting in unsatisfactory lumber which is difficult to cure and stabilize.

Stand density A variation in normal stand density among trees will have little effect on wood other than the width of the annual rings; this can be very important for some products and species.

Species and provenance choice Matching species and provenance to site is of key importance. Normally, reasonably small site differences, or somewhat poor adaptability to the site, do not result in unusual wood but extreme site differences can result in wood so varied that it is not usable. For example, when *Pinus caribaea var. hondurensis* is grown in certain especially good environments the wood produced can be of very low density, making it undesirable for either solid wood products or pulp. The movement of slash pine (*Pinus elliottii*) to the same environment has resulted in very dense wood, with characteristics much like that of oak, making suitability for utilization very limited.

Pruning For most species, pruning is necessary if good solidwood products are desired, especially for conifers grown in the tropics. Under the environments there, limbs will hang on and not shed for many years and become almost like little steel rods; this results in degrade of the final product. Pruning is also usually necessary for quality tropical hardwoods but there are exceptions, like some of the best eucalypts, where the limbs die early and shed naturally. Caution is necessary when pruning; if done poorly leaving stubs, or if the bark is cut into the cambium when pruning, as almost always happens when machetes or axes are the tools used, pruning becomes adverse to quality. When the cambium is cut in the conifers, the result is pitch pockets and undesirable abnormal wood grain formation. In certain of the quality hardwoods, rot will occur which ruins the pruned log for quality products when harvested.

Pest Control

Both insects and diseases can cause major changes in wood properties. An example is fusiform rust on pine which results in a high resin content (double or more of the normal) and abnormally short, and sometimes forked, cell formation. Pulp yields from rust infected wood will be reduced as much as 50%; additionally, the wood will not be suitable for production of lumber. Eucalypt canker is similar to fusiform rust in that it affects both pulp yield and quality. Suitable boards cannot be sawn from the infected stem. Until brought under control genetically by the use of rooted cuttings from disease-free parents, the eucalypt canker had a major effect on the utility of wood from disease-sensitive species. There was considerable talk in the late 1970s of not growing eucalypts in parts of Brazil because of the high incidence of the canker and its effect on wood. It is important to control insect damage and disease in the tree trunks if normal wood quality is to be obtained. Additionally, supplemental nutrients, such as nitrogen, must be used carefully or there will be a degrade in wood quality.

Effectiveness of Forest Management

A good summary relative to the effect of forest management on wood is that anything that can cause growth differences in trees can also result in changes in wood properties. Such a reaction is especially obtained in the conifers, often less than for many hardwoods.

Internal Control of Wood Properties

There are two major causes affecting the internal wood properties of a tree. The first is the time of formation and location of the wood produced, generally subdivided as juvenile and mature wood. The second is the genetic and physiological control of the anatomy and morphology of the cells produced; these can be affected by breeding, as well as by some of the external controls outlined above.

Juvenile and Mature Wood

The quality and ratio of juvenile and mature wood are key to the determination of wood quality within the bole of the tree. All trees have a zone near the tree center (the pith) where there is a change, often rapid, in wood quality from the center of the tree outward. After a number of annual rings, the changes become smaller and more or less constant, sometimes with little change from ring to ring. This is mature wood; in juvenile wood, the variation is related to the number of rings from the pith, regardless of the height in the tree or the age of the tree. This results in a juvenile wood zone that has rapid changes followed by a mature wood zone with minor changes in wood properties, regardless of height in the tree. For example, a 30-year-old loblolly pine with 30 annual rings near the base of the tree will have about the first 10 rings from the pith as juvenile wood, the next 20 as mature wood. Therefore, a log from the base of the tree will consist largely of mature wood, while a log from the upper part of the tree is predominantly juvenile wood. Closer to the top of the same tree, where there might be only 12 annual rings; the first 10 will be juvenile wood with only the last 2 rings being mature wood. Although not strictly correct, the juvenile wood of a loblolly pine tree can be considered as being in a cylinder made up of the 10 rings from the pith. The wood qualities of this core will be essentially the same regardless of the height in the tree where they are measured. Differences in wood quality of each log is therefore dependent on the proportion of juvenile wood to mature wood. The age of the tree is not relevant to the presence of juvenile wood; it is determined at any height by the location of the cambium and by the number of rings from the pith, regardless of tree age.

Juvenile wood qualities vary from the pith outward. In the conifers the wood density becomes greater, the cell length increases, and spiral grain decreases and fibril angle decreases in wood produced from the older cambium as ring number becomes greater from the pith. Juvenile wood in most conifers has low density, short cells, a high spiral grain, and high fibril angle. Such wood gives low yields of pulp with weak tear strength. It is overall considered to be of poor quality related to strength and stability for boards when compared to the mature wood in the same tree. This pattern is usual for the hard pines and some diffuse porous (soft) hardwoods like sweetgum. Many of the hard hardwoods (like oak (*Quercus* spp.) and hickory (*Carya* spp.)) have a different pattern with high wood density near the tree center but with other wood properties that follow the same pattern as described for the pines. There are some diffuse porous hardwood species, like the eucalypts or poplars, whose juvenile wood is very similar to their mature wood.

There are many other wood properties that vary between juvenile and mature wood such as extractive content, or cell size. There are so many of these that they will not be dealt with in detail in this section.

Although often considered to be of low quality, juvenile wood is preferred for some products, like printing papers and tissues, where thin-walled cells are best. Such wood produces strong mullin (bursting strength) but the tearing strength is low. Juvenile wood of some conifers is somewhat similar to mature wood of the diffuse porous hardwoods and is sometimes used to supplement the need for hardwood fibers, such as when hardwoods are in short supply or are costly to obtain.

Wood from thinnings of pine in young plantations or tops from older trees is predominantly juvenile since mature wood has not yet has a chance to be formed. In some hardwoods like the eucalypts, the effect of juvenile wood is minor since the differences between juvenile and mature wood are quite small; this enables the use of short rotations without a major sacrifice in wood quality such as one finds in the conifers.

A major effect on wood and product quality differences within a tree relate to the ratio of juvenile wood present. One major control of the effect of juvenile wood is by varying the age of harvest or the part of the tree from which the wood is obtained.

Young plantations have a large proportion of juvenile wood; despite this, the economic importance of early harvest is often assessed without a proper consideration as to the kind of wood being obtained when there is a large amount of juvenile wood present.

There have been some studies on the genetic control of the amount and kind of juvenile wood. We have found considerable genetic control in loblolly pine but little has been done with this operationally since the effect of juvenile wood can be modified by changing rotation age or by use of the part of the tree bole with the desired percentage of juvenile wood.

Genetic Control of Wood Properties

The genetic control of wood properties is usually strong to moderate and the kind of wood can be influenced using selection and breeding. A strong additive genetic control is found for wood density but there is essentially none in cellulose yield. Strong additive genetic control along with a large suitable variation pattern makes possible the changing of important wood qualities in the desired direction when a selection and breeding program is followed. There are two major categories of genetic control, generally called additive and nonadditive. When the genetic variation is largely of the additive type, and where suitably large variation occurs, improvement by selection and breeding is relatively large and quick. The amount of additive genetic variation is usually represented by the term narrow-sense heritability (h^2) (common in the literature). This is a ratio indicating how much of the characteristic is controlled by additive genetic variation and how much results from other causes, including the environment and nonadditive variation. Thus, wood density has a high narrow-sense heritability (h^2) of 0.6–0.7, straightness of the tree of 0.3–0.5, and limb size shows a heritability of about 0.1–0.2.

Although a more exact formula is used by researchers, a working relation for estimating gain from selection is

$$\text{gain} = \text{SD} \times h^2$$

In this formula SD is the selection differential which is related to the variation in the wood property and the intensity of selection used to obtain the parents which give the desirable gain. Gain in a genetics program with a wood property is dependent on the variability present within the property, the intensity of selection used, and the heritability of that wood characteristic.

Only a few wood properties, like cellulose yield per unit weight of wood, have very little additive variation, but they have considerable non-additive variation. Gains from a selection program with them will be very small. When low additive variation is present, as for cellulose yield, the use of vegetative propagation (or a complex breeding system) is necessary to capture genetic variation in the new plantation trees. (A reduction or change in the amount of juvenile wood is difficult to achieve using a genetic breeding program, because the heritabilities are low).

Wood density Wood density is a characteristic that can be improved quickly and significantly through breeding because its genetic variation is large and consists mostly of the additive type. Other wood properties that are easy to change by selection are resin content of wood and cell length. Some of the more important wood characters like spiral grain and fibril angle (along with tree straightness) have intermediate inheritance and gains through selection will be less.

Operationally, then, when a high wood density tree with high heritability is crossed with another high density tree, its progeny will have relatively high density. If a high cellulose yielder tree (with very low heritability) is crossed with a similar tree, one cannot predict the cellulose yields of the progeny, because cellulose yield is inherited nonadditively. Many wood properties are intermediate, where about half the genetic variation is of the additive type, half nonadditive. When this occurs, a selection program is not fully efficient and is dependent on the amount of variation present.

Vegetative Propagation

Although genetic gain is more difficult to obtain when the genetic control is nonadditive, the use of vegetative propagation will enable good improvement. Vegetative propagation will result in the new plant having the characteristics of the donor parent, since the new plant (propagule), usually a rooted cutting, contains all the additive as well as the nonadditive genetic variation present in the donor tree. The use of vegetative propagation in producing trees for operational planting is becoming much more widely used as methodologies for successful vegetative propagation are being improved.

The simplest way of producing improved wood for characters with a large portion of nonadditive variation is to use vegetative propagation to produce plantable trees.

Wood Uniformity

Wood uniformity, both within a tree and among trees, is a most important characteristic. When wood used in a manufacturing operation is reasonably uniform, efficiency in manufacture and quality of the final product will be greatly improved. Conversely, however, if juvenile and mature woods are both included in the same mix or board, and are treated similarly in manufacture, the final product will be variable and the efficiency and the value of the manufactured product will drop considerably.

The best way to obtain uniformity among plantation trees is to use vegetative propagation since the wood of the propagules from a given tree will all have wood similar to its donor tree. This methodology is now being much used in operational programs; one of the best examples is for the eucalypts when their wood is intended to be used for tissues. The mills have determined the best wood for making tissues and then rooted cuttings from the donor trees with these characteristics are used in establishing plantations. Both the quality and yields of tissues made from such plantations are greatly improved. This method of producing planted trees is now being applied to many other species as techniques for developing the propagules improves; in the future a great proportion of the wood available from plantations will have the desired wood uniformity and properties suited for the final product.

For the long term, the major improvement in wood, both through external and internal sources, will be to develop wood that is uniform and ideal for a given product line. Both the internal and external methodologies of changing wood must be used it such a goal is to be achieved.

See also: **Tree Breeding, Practices**: Breeding for Disease and Insect Resistance; Genetics and Improvement of Wood Properties. **Wood Formation and Properties**: Formation and Structure of Wood; Mechanical Properties of Wood; Physical Properties of Wood; Wood Quality.

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Genetics and Improvement of Wood Properties

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Introduction

Wood quality must be defined in terms of the end product: what is good for linerboard is not necessarily good for newsprint. The most critical properties for breeding programs are usually wood specific gravity, tracheid length and microfibril angle, although many other properties are also important. In general, wood properties are strongly inherited, with heritabilities of 0.5 and up. This would make breeding for wood properties easy if they could be determined easily and cheaply. Unfortunately this is true only for wood specific gravity. Therefore, much effort has gone into developing assay methods suitable for small wood samples which can be taken from the tree with little damage.

Wood quality can be improved by silviculture and by breeding. Spacing, thinning, and fertilization all have major effects on the growth of the tree and the properties of its wood. Selective breeding also has a major impact. Traditionally, the selected trees are grafted into seed orchards, progeny tested, and rogued. The time between the start of the program and the harvest of the first trees is typically 50 years making it appropriate to breed for a general purpose tree. For species that can be vegetatively propagated another approach is feasible: clonal forestry. Using it with shorter rotations allows development of trees suitable for specific products.

What is Wood Quality?

This is a difficult question to answer. Many years ago some of the pioneers in forest tree improvement asked managers of the local paper mills what wood properties they considered desirable, and were unable to obtain helpful answers. It was not until the 1970s that breeders started to ask the right questions. The quality of any raw material is defined as its suitability for use and quality is affected by many properties. There is a wide range of products made out of wood and it is therefore necessary to define wood quality in terms of the end product. What is good for linerboard is not necessarily good for multiwall sack paper and might be disastrous for newsprint. This is the most important point to keep in mind when considering wood quality.

What Are the Important Products?

Wood products belong in two major groups: solid-wood products, and pulp and paper products. Solid-wood products include not only lumber, but also plywood, oriented strand board and particle board. They can be used for construction as well as furniture. Pulp and paper products can be produced by three major processes: the sulfite process, the kraft process, and mechanical pulping. The sulfite process is used extensively for spruces and firs. The kraft process is more flexible and can be used for most species, including almost any pine. Mechanical pulping is often used for lighter woods such as poplars, but can be used successfully for some pines. The sulfite process is very suitable for producing high quality writing papers. Unbleached kraft is used extensively for the production of linerboard and sack paper, while bleached kraft can be used for writing papers, computer paper and paper used in copy machines. Mechanical pulps are primarily used for newsprint.

What Are the Important Wood Properties?

First we must distinguish between the wood of two major groups of trees: hardwoods (essentially broad-leaved trees) and conifers. The two groups have distinctly different wood. That of hardwoods is more complex, and its most distinguishing feature is the presence of vessels the elements of which are connected to each other through large pores. Other elements include fibers, tracheids, and parenchyma. The hardwoods are further divided into ring-porous and diffuse-porous species (**Figure 1**). Conifers have tracheids, ray parenchyma, and resin ducts. The tracheids are much longer than those in hardwoods.

The wood in conifers usually has distinct springwood and summerwood, also called earlywood and latewood. Springwood has large-diameter tracheids