Wood Quality

J Barbour, US Department of Agriculture Forest Service, Portland, OR, USA

Published by Elsevier Ltd., 2004

Wood Product Streams

The classical definition of wood quality is the suitability of a given piece of wood for a specific end use, and, accordingly, individual wood characteristics are not usually seen as universally good or bad. The exact set of characteristics that constitute high or low quality varies depending on the specific use. Some characteristics are, however, almost always desirable and others are almost always undesirable. Some examples of desirable characteristics are soundness (lack of decay), straight grain, small scattered knots or the complete absence of knots, and dimensional stability (a tendency to dry without warping and to remain straight in use). Some examples of undesirable characteristics are decay, large or unsound knots, lack of dimensional stability, and poor mechanical properties. Some wood products are very forgiving of variation in wood characteristics. Others require raw material with a narrow range of wood characteristics. Consequently, it makes sense to begin a discussion of wood quality by thinking about the broad categories of wood products and the characteristics that are important for each group. A convenient way to do this is to divide all possible wood utilization options into a small number of 'end product streams' with similar raw material requirements, for example (1) heat and chemicals, (2) fibers and particles, and (3) solid products.

Heat and Chemicals

The energy production stream is the least demanding in terms of wood characteristics. Raw materials with lower moisture contents and higher specific gravities are more desirable but fuelwood can include a variety of low-quality raw materials. These could come from small stems, crooked stems, stems with large numbers of knots, or stems with high proportions of defects such as cross grain, rot, reaction wood (wood associated with leaning or deformed stems), etc.

Many chemicals used every day are derived from wood, bark, extractives, or foliage. Raw materials used for their production must be cleaner than for energy and, although some species work better than others because of their chemical composition, fiber characteristics or other wood properties are relatively unimportant.

Fiber and Particles

Composite wood products such as oriented strandboard (OSB), parallel-strand lumber (PSL), waferboard, particleboard, medium-density fiberboard (MDF), hardboard, wood–plastic composites, wood–cement composites, and pulp for paper and paperboard are included in the fiber and particle product stream. Manufacture of these products requires cleaner raw material than energy production, although perhaps not more so than chemical production. In most cases, bark is seen as detrimental, so ease of bark removal from roundwood is an important feature. Manufacture of fiber- and particle-based products is also less tolerant of decay, reaction wood, pitch pockets, or other irregularities. It is, however, technically feasible to make these products from small stems or stems with substantial grain deviation as long as it is not associated with reaction wood and does not interfere with debarking or primary processing such as waferizing.

Solid Products

This stream is divided into structural products and appearance products. Solid products include roundwood, such as posts and poles, sawn lumber, and veneer. In some ways, the structural product stream is the most demanding. Products in this stream must meet engineering standards, such as specified mechanical requirements and they are intolerant of grain deviations or decay. On the other hand, they can contain some knots and discoloration without adversely affecting their performance.

The raw material requirements for structural products have changed greatly during the twentieth century. Technological improvements now allow sawing of logs as small as 9 cm in diameter on the small end, although economic constraints often preclude processing logs quite so small. Techniques were also developed to use weaker or less stiff lumber in parts of engineered products where mechanical properties were less important and abundant fast-growing species such as aspen (*Populus* spp.) replaced slower-growing softwood species for structural panel products. Not long ago, the only way to make a large beam was to saw it from a large log, but now it is possible to manufacture glulam beams, wood I-beams, or parallel strand lumber (PSL) from small logs. This means that as forest managers plan new plantations they have to take potential changes in technology very seriously. Raw material requirements for structural products still favor trees with fewer and smaller knots, straight grain, and less taper but tree size is not nearly as important as it was less than a rotation ago in many timber-growing regions.

Appearance products are similar to structural products except that they contain characteristics that people consider beautiful. Some examples are dark- or light-colored heartwood, various grain patterns, and lack of knots. In some cases, appearance products perform a structural function, such as in furniture, architectural beams, or posts, but in many applications such as fascia and molding they have no structural role. This means that for many applications the mechanical properties of appearance products are relatively unimportant. A high level of dimensional stability is, however, always important for these products.

Appearance products are typically the highest-priced wood products, although certain specialty structural products such as very long power transmission poles or large structural beams can rival them in price per unit volume. Even with high prices, it is not normally economically feasible to grow trees suitable for appearance products to replace traditional hardwood and 'old-growth' softwood supplies. Pruning trees to grow clear lumber and veneer is an exception, but profitable pruning requires shortening rotations by combing pruning with intensive thinning. The wood from these fast-growing trees looks quite different from clear wood sawn from trees grown more slowly. An alternative is to extend the supply products that look like old-growth by covering wood or non-wood substrates with thin veneers sliced from slow-growing hardwoods or softwoods.

Growth Conditions Influence Tree and Wood Characteristics

Foresters began to formalize theories about how growing conditions influence tree form, branch size, and other factors that control wood characteristics as long ago as the late nineteenth century. They observed that the size and vigor of the crown was important in determining both the morphological, or externally visible, characteristics and the basic wood properties (chemical, anatomical, and physical properties) of softwood trees. Since then, wood scientists have built on these early observations by using a combination of structured experiments and retrospective studies to develop an understanding of how silvicultural manipulation of stand conditions can influence tree characteristics and, consequently, wood products manufactured from them. Field foresters now routinely use this knowledge, but their understanding of all aspects of how to manipulate wood properties is far from complete. Some general inferences that apply to most softwoods are, however, possible.

Most silvicultural treatments that influence wood quality modify the size and vigor of the crown. Treatments that increase crown length or vigor create trees more like open-grown trees with deeper crowns, larger branches, and more conically shaped stems (taper) (**Figure 1**). Treatments that reduce crown length or vigor produce trees with characteristics more like those observed in trees from dense stands with short crowns, small branches, and more cylindrical stems. Understanding these simple relations between growing space, crown length, branch size, and stem shape is important in understanding how growing conditions influence the suitability of the wood from a tree for a specific end use.

A fairly well-developed theory involving the production of growth hormones and nutrients has arisen to explain why this happens. Simply stated, trees with larger crowns produce more growth hormones and more nutrients. Growth hormones encourage cell division and radial expansion of longitudinal wood cells (tracheids) as they mature. Nutrients contribute to the growth and thickening of cell walls. Growth hormones are mainly produced in actively growing branch tips, and nutrients are mainly produced by vigorous foliage. Trees with deeper, more vigorous crowns have both more foliage and a greater number of buds, so they produce higher hormone concentrations and larger quantities of nutrients than trees with short, suppressed crowns. The change in concentration of hormones and nutrients from the apical meristem (topmost bud) to the base of the tree has been suggested as an explanation for the changes in various wood properties from the center of the tree (pith) to the bark. This inner zone of changing wood properties is generally used to differentiate juvenile, or crown-formed, wood from mature, or stem-formed, wood.

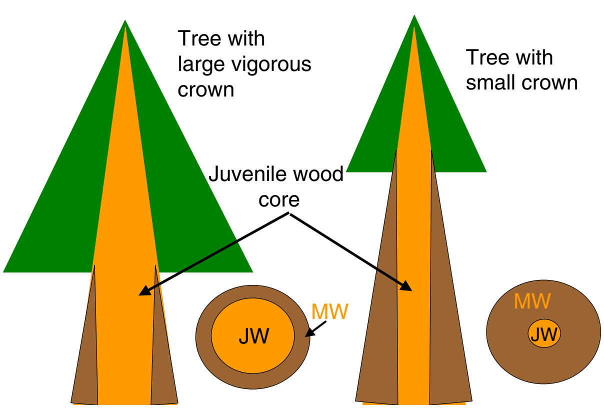

Figure 1 Relation of juvenile wood core size with crown size and vigor. With larger more vigorous crowns grow more quickly and therefore produce more juvenile wood (JW) and less mature wood (MW) than trees of the same diameter with smaller crowns.

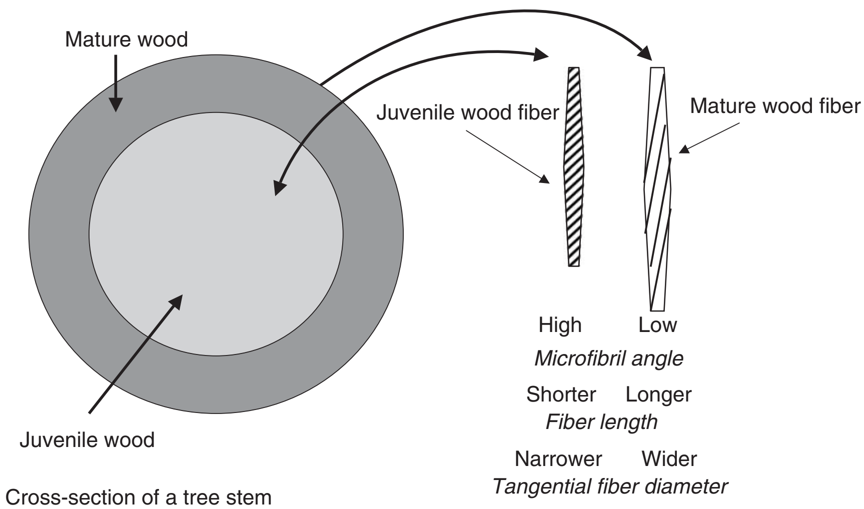

Figure 2 Variation in fiber characteristics in juvenile wood and mature wood. Juvenile wood tends to have shorter, narrower fibers with higher microfibril angles than mature wood.

For practical purposes, the transition from juvenile wood to mature wood is often thought to begin at the base of the live crown.

Another theory explains the changes in basic wood properties from the pith to the bark as the expression of aging by the cambial initials (actively dividing cells) in the vascular cambium. This theory holds that each time a cambial initial divides, it changes slightly (lengthens, grows wider, alters its cell wall structure, etc.) and as a result, wood properties change over time (**Figure 2**). This theory has been used to develop a plausible explanation of why some trees develop spiral grain as they age.

The Importance of Juvenile Wood

Juvenile wood often has different properties than mature wood. The duration of the period when juvenile wood is produced, the rate of transition from juvenile wood to mature wood, and the differences in properties between juvenile wood and mature wood are all important in determining the suitability of wood for specific end uses. There are always more knots in juvenile wood because it is formed when the crown is alive. Differences in chemical, physical, anatomical, and visual characteristics have all been reported for various species, and the importance of each depends on the wood product being manufactured (**Figures 3** and **4**). For example, differences in cell wall thickness and cell wall mechanical properties that are undesirable for lumber and veneer might actually result in fibers with excellent pulp and papermaking properties. Problems generally arise when solid products contain both juvenile wood and mature wood, but papermakers can use blends of juvenile and mature wood to obtain desired characteristics.

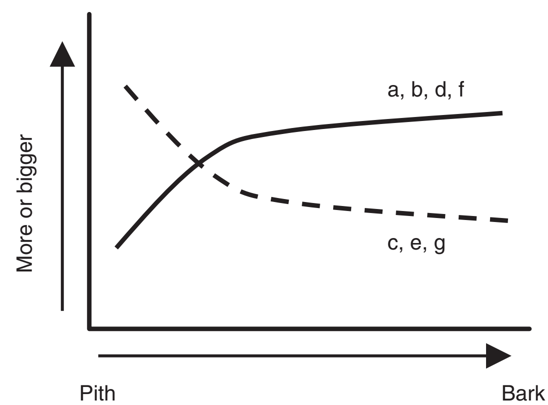

Figure 3 Pith to bark relation of various wood properties. The way some wood characteristics change from the pith to the bark is more or less universal among species. Example wood characteristics: (a) fiber length, (b) tangential cell diameter, (c) microfibril angle, (d) extractive content, (e) branch number, (f) branch size, (g) longitudinal shrinkage.

Variation within Growth Rings

Intraring variation of basic wood properties, or changes within individual annual rings, is another important factor in determining the suitability of wood for specific uses. The annual fluctuation in hormone and nutrient levels has been used to explain some of this variation. In the spring, when buds are most active, they produce high hormone concentrations. This promotes rapid radial expansion of new xylem cells, but the foliage has not yet fully matured so there are insufficient nutrients for substantial cell wall thickening. Large-diameter thin-walled

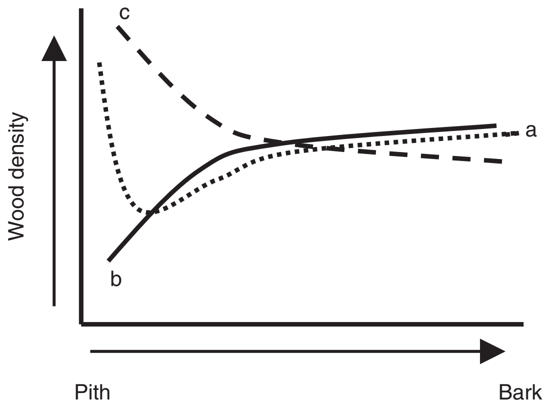

Figure 4 Different species tend to have different pith to bark wood density profiles. Pith to bark trends also tend to change with tree height so that the pattern is not always the same within a single tree. Typical patterns by species: (a) Douglas-fir and hemlock, (b) most pines, (c) most spruces.

earlywood tracheids are produced during this period. Later in the growing season, as expansion of growing tips is completed and the foliage is fully expanded, the situation is reversed; the concentration of hormones available for cell expansion is minimal, but there are plenty of nutrients to promote rapid thickening of the cell walls. As a result, thick-walled latewood cells are produced. A related theory suggests that the size of various cells is controlled by the need to move water through the stem to the foliage.

Factors such as soil nutrients, moisture availability, and temperature also are thought to influence the initiation of radial growth in the spring and cessation of radial growth in the fall. The time when growth begins or when it ends can influence the characteristics of individual growth rings. If growth starts late in the spring, perhaps owing to a late thaw, less earlywood is laid down before the transition occurs; if growth stops early in the autumn, perhaps because of a drought, less latewood is produced.

The Importance of Basic Wood Properties

Intraring characteristics are important because they play a role in determining the suitability of wood for specific uses. The proportion of earlywood and latewood and whether the transition between them is gradual or abrupt influences mechanical properties, machining, nailing and fastening, penetration of treating chemicals, and appearance of solid products. For some products, such as fine papers, an abundance of long, stiff, thick-walled fibers is seen as detrimental because they interfere with sheet formation in papermaking.

It is important to recognize that the influence of growth conditions on tree and wood characteristics is complicated by the interactions of many different factors. The interactions described here are complicated by other relations that control the orientation of cellulose microfibrils in the cell walls, cell length, and the proportions of cell wall components (cellulose, hemicelluloses, and lignin). Each of these basic wood properties varies within growth rings, from pith to bark, and from the base to the top of the stem according to a different relation with growth conditions, so it is often difficult to understand precisely why physical properties of larger pieces of wood change in the ways that they do.

The Importance of Morphological Characteristics

Morphological characteristics such as branching and grain orientation are equally or perhaps even more important in determining the suitability of a given piece of wood for a specific end use than are basic wood properties. More and larger knots are almost universally considered detrimental whether wood is used for lumber, veneer, composites, or fiber products. Notable exceptions are knotty-pine paneling and certain grades of lumber used in furniture manufacture, but these account for a tiny fraction of all wood products.

Knots are a primary factor used to determine lumber and veneer grade and value. In general, the more abundant and the larger knots are the lower the grade. Knots interfere with adhesives and reduce the mechanical properties of composite products like OSB, laminated-veneer lumber (LVL), and PSL, but they are generally not recognized in pricing raw materials for these products. This is probably because no reliable models exist to relate knot size, knot condition, and knot abundance to performance of these products or to waste during their manufacture. The effect of knots is better understood for fiber products like paper because they tend to interfere with the pulping, grinding, and refining processes used to turn raw wood into fibers. Knots are usually detrimental in composite products, but their high wood density produces more heat per unit volume when they are burnt for energy. They also contain high levels of extractives, which is desirable for manufacturing certain solvents.

Knot shape is also important. Shape comes partly from the morphology of branching and partly from manufacturing processes. Branches that join the stem at right angles to its long axis are known as low-angle branches. Low-angle branches produce the smallest knots for a given branch diameter. Branches that leave the stem at an angle result in larger oval knots and are, therefore, less desirable.

Trees with deeper, broader crowns produce larger, more persistent branches. They also tend to have more branches. One way this happens is when trees 'flush' or initiate height growth more than one time during a season (**Figure 5**). Trees with plenty of growing space located on good sites also tend to retain their branches longer and can produce more knots per whorl than those in denser stands or on poor sites. Depending on the species, more vigorous trees produce and retain more internodal branches (branches that grow between branch whorls). Taken together, these factors tend to cause the largest, fastest-growing trees to have more and larger knots.

The quality of knots also changes along the length of the stem. Live knots typically have the lowest impact on structural wood products and are even seen as desirable for some appearance products. Knots resulting from dead branches are generally more of a wood quality problem than those derived from live branches. When branches die, the vascular cambium loses its connection to the branch. This creates 'tight' or 'sound' knots which act like plugged holes in solidwood products. Dead branches begin to rot, and further below the live crown (down the stem) they become black or unsound knots. Unsound knots often fall out of products during the manufacturing process and leave holes. Unsound knots and holes are much less desirable than sound knots for most wood products. Finally, the branch is shed and eventually clear wood is produced but the process can take many decades in naturally grown stands.

A major challenge to forest managers is to design silvicultural prescriptions that maximize growth without producing trees with numerous large branches. One way to do this is to limit growing space early in the rotation then thin stands once there is sufficient height growth to allow crowns to recede above the top of the first log, typically about 10.5 to 12 m. The problem with this strategy is that it results in smaller trees but technological change is making this less important than it once was. Another option is to prune trees to shorten crown length, but this is an expensive process that is only appropriate in special cases where 'clear,' or knot-free, wood is desired. The high costs and uncertain markets for clear wood make foresters hesitant to prune unless they are confident that they can sell pruned logs for a much higher price than unpruned logs.

Branch initiation and branch growth are well enough understood that there are fairly reliable simulation models available for many of the important commercial conifer species. These models connect to individual tree growth and yield models used by forest managers to estimate the growth of stands under different conditions and evaluate whether branch size will exceed predetermined specifications related to wood product requirements. Financial analysis tools are available to help foresters evaluate the influence of branch size and pruning on the potential financial return from stands. These types of models help forest managers think about whether it makes sense to manage for small groups of end products or even specific products.

Designer Trees

If trees could be grown with particular sets of characteristics then they might be tailored for

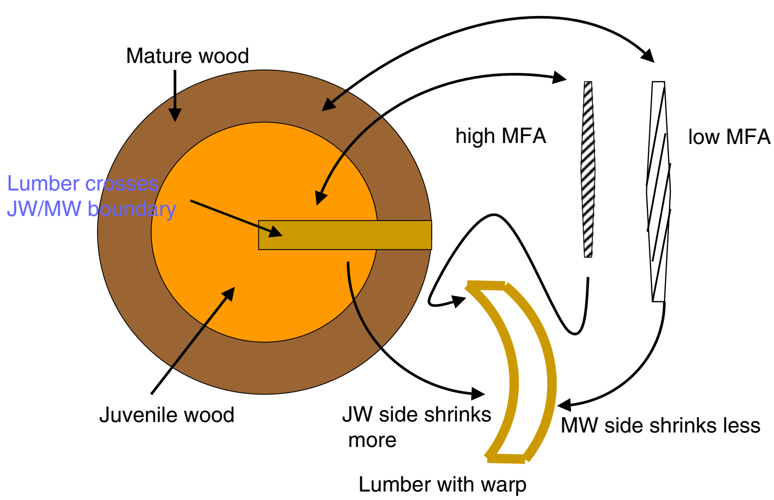

Figure 5 Effect of juvenile wood on warp. Higher longitudinal shrinkage of juvenile wood (JW) caused by high microfibril angles of cellulose fibrils can result in warp in lumber that contains both juvenile wood and mature wood (MW). MFA, Myofibril angle.

specific end products. Until recently, the length of time it took to grow a crop of trees always made this goal somewhat unrealistic and open to criticism. The uncertainty associated with predicting future demand for particular wood properties many decades in the future often seems too high. On the other hand, there have been a few situations where the economic value of large crops of trees was adversely affected by failure to consider the potential quality of the final crop. Two prominent examples are the extensive plantings of chir pine (*Pinus roxburghii*) established in South Africa early in the twentieth century for harvest in the 1930s and 1940s and the 'old-crop' radiata pine (*Pinus radiata*) that was planted during the 1930s and 1940s in New Zealand. The seed source of chir pine used in South Africa tended to produce severe spiral grain, which made the trees virtually unusable for anything other than pulp. This material was even unsuitable for roundwood applications such as posts and poles because they tended to twist as they dried and then to move with cyclic changes in moisture content. This movement loosened or broke power lines, fence wires, and fence boards attached to the posts and poles. The old-crop radiata pine was planted with 'wild' unimproved seed at relatively narrow spacings and left untended. Under such conditions radiata pine produces particularly poor stem form and variable branches. This made lumber sawn from these trees unsuitable for many uses. The size and frequency of the branches also made this wood less desirable for pulp chips. Given these experiences, foresters began to pay more attention to producing trees with good form and fewer, smaller, branches but it was still impractical to commit to specific plans for the use of trees scheduled for harvest three or four decades in the future. Today it is becoming more common for foresters in regions where trees can be grown in less than about 25 or 30 years to think seriously about the specific use or at least the product stream expected for a crop of trees.

There is also considerable interest in screening seed sources, genetic improvement, and clonal forestry to increase growth rates and improve wood quality. Combined with simulation models for planning silvicultural systems, these techniques reduce the likelihood of undesirable characteristics such as large or frequent branches or low wood density and increase the feasibility of growing trees quickly enough to fill specific market niches. For example, some of the hardwood species grown for pulp in tropical regions mature in as little as 5–10 years and rotations of conifers in temperate regions of 25 years or less are now common.

Economics and Wood Quality

Wood utilization is often more a question of what is economically feasible than what is technically possible so a discussion about wood quality is not particularly meaningful unless economics is considered. Every wood product requires some minimum set of wood characteristics in order to perform satisfactorily. There is also a maximum price above which consumers will look for a substitute material, will find another way to fill the need, or go without the product altogether. The interaction between performance and price is not particularly easy to quantify but it unquestionably influences whether individual trees or stands of trees are harvested for wood products. The idea of 'cull' trees and logs has been a part of forestry practices for many decades. Cull trees and logs do not have sufficient value to justify their harvest or processing. Often they contain too much defect (juvenile wood, rot, stain, spiral, grain, etc.) or they may be crooked or have too many or too large knots, or in some cases they are simply the wrong species. Size is often an important factor. In almost all wood-producing regions, precommercial thinning, or cutting small trees and leaving them in the forest, is a practice commonly used to accelerate growth of the trees remaining in the stand so they will reach merchantable size quickly enough to make forestry profitable. In remote areas, larger trees and logs are often treated as cull regardless of their quality. In some parts of the USA minimum merchantable log size is 23–25 cm on the small end, even though sawmilling and veneer peeling technology makes it feasible to use logs as small as 9 cm on the small end and most energy, chemical, fiber, and particle process can use even smaller logs. Even so, there are simply no markets for logs smaller than 23 cm in these places.

Topography and location frequently tip the balance between performance and price. Trees on flat ground are generally more easily harvested and therefore more profitable than those growing on steep slopes. In the past, when new areas were opened up for logging, the valley bottoms were almost always harvested first. Even today, there are vast tracts of old-growth timber with excellent wood characteristics that have not been harvested largely for economic reasons. The Russian Far East and much of Alaska are two examples where costs and accessibility kept these forests from being harvested over the past half-century. Social concerns about preservation of old-growth forests are now more important than costs in preventing harvest in Alaska, even though these forests contain some of the best-quality softwood timber remaining in the world today.

As the timber industry moves away from harvesting unmanaged stands to more intensive management systems of either naturally regenerated or planted stands, the interaction between price and performance will continue to determine whether individual trees or stands are harvested and the way they are grown. Managed stands that grow too slowly or are in places difficult to reach, far from transportation routes, or even in places where there are insufficient commercial forests, are less likely to be profitable. In some countries, agricultural land (which may originally have been forest) is being converted to plantations in preference to cheaper land located on steeper ground, because of the lower costs of land preparation, higher growth rates, and lower harvesting costs.

Most of the advances in manufacturing technology that eliminated the need for large trees were brought about by a desire to find ways to continue to use wood for structural products without having to grow trees for so long. The increased manufacturing costs required for these products is more than offset by the lower costs of holding investments in stands of trees for one-third to one-half as long as under unmanaged conditions. In fact, it is quite likely that without peeling (plywood and LVL), gluelam, engineered fasteners, and composites technology it would not be possible for wood to compete with alternative materials.

See also: **Solid Wood Products**: Lumber Production, Properties and Uses. **Tree Breeding, Practices**: Biological Improvement of Wood Properties; Genetics and Improvement of Wood Properties. **Wood Formation and Properties**: Formation and Structure of Wood; Mechanical Properties of Wood; Physical Properties of Wood.

Further Reading

Bowyer JL, Shmulsky R, and Haygreen JG (2002) *Forest Products and Wood Science: An Introduction*. Ames, IA: Iowa State University Press.

Brazier JD (1977) The effect of forest practices on quality of the harvested crop. *Forestry* 50(1): 49–66.

Cave ID and Walker JCF (1994) Stiffness of wood in fast-grown plantation softwoods: the influence of microfibril angle. *Forest Products Journal* 44(5): 43–48.

Clark A, Saucier JR, Baldwin VC, and Bower DR (1994) Effect of initial spacing and thinning on lumber grade, yield, and strength of loblolly pine. *Forest Products Journal* 44(11/12): 14–20.

Fight R, Snellgrove T, Curtis R, and Debell D (1986) Bringing timber quality considerations into forest management decisions: a conceptual approach. In: Oliver C, Hanley D, and Johnson J (eds) *Douglas-Fir: Stand Management for the Future*, pp. 20–25. Seattle, WA: University of Washington Press.

Hoadley RB (2000) *Understanding Wood: A Craftsman's Guide to Wood Technology.* Newtown, CT: Taunton Press.

Larson PR (1969) *Wood Formation and the Concept of Wood Quality.* Yale University School of Forestry Bulletin no. 74. New Haven, CT: Yale University.

Megraw RA (1985) *Wood Quality Factors in Loblolly Pine: The Influence of Tree Age, Position in Tree, and Cultural Practice on Wood Specific Gravity, Fiber Length, and Fibril Angle*. Atlanta, GA: TAPPI Press.

Nepveu G (ed.) (1996) *Connection between Silviculture and Wood Quality through Modelling Approaches and Simulation Software*, Proceedings of the 1st Workshop IUFRO WP S5.01.04, 13–17 June 1994, Hook, Sweden.

Nepveu G (ed.) (1997) *Connection between Silviculture and Wood Quality through Modelling Approaches and Simulation Software*, Proceedings of the 2nd Workshop IUFRO WP S5.01.04, 26–31 August 1996, Berg-en-Dal, Kruger National Park, South Africa.

Nepveu G (ed.) (1999) *Connection between Silviculture and Wood Quality through Modelling Approaches and Simulation Software*, Proceedings of the 3rd Workshop IUFRO WP S5.01.04, 5–12 September 1999, La Londe-Les-Maures, France.

Nepveu G (ed.) (2003) *Connection between Forest Resources and Wood Quality through Modelling Approaches and Simulation Software*, Proceedings of the 4th Workshop IUFRO WP S5.01.04, 8–15 September 2002, Harrison Hot Springs, BC, Canada.

Spurr SH and Hsiung WY (1954) Growth rate and specific gravity in conifers. *Journal of Forestry* 52(3): 191–200.

Thörnqvist T (1993) *Juvenile Wood in Coniferous Trees*. Stockholm, Sweden: Document D13: 1993. Swedish Council for Building Research.

Biological Deterioration of Wood

T L Highley, Henderson, NV, USA

Introduction

Wood does not degrade as a result of aging alone. Under proper conditions, wood will give centuries of service. The service life of forest products depends on their being protected from a variety of degrading agents. Given the appropriate conditions, degradation encountered will fall into one of three categories: (1) biological; (2) physical; or (3) chemical. This article concerns only biological degradation of wood, which is the most damaging of the causal agents.

Biological degradation of wood is caused primarily by fungi, bacteria, insects, and marine borers. Wood