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MANAGEMENT OF WOOD PROPERTIES IN PLANTED FORESTS

A PARADIGM FOR GLOBAL FOREST PRODUCTION

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Foreword

Planted forests provide not only wood and fibre, but also wood fuels and other non-wood forest products; moreover, they sequester carbon, rehabilitate degraded lands, help in restoring landscapes, protect watersheds and agricultural soils, and provide recreational areas and amenities.

In the year 2000, planted forests contributed about 35% of global industrial roundwood production, though they only represented around 9% of the world's forests. It can be safely assumed that, since then, their contribution has increased further.

With forest plantations becoming an increasingly important source of wood, policy, planning and management of forest plantations require increased attention. This refers also to harvesting, transport, wood and fibre processing technologies and to information on trade in forest products.

In planted forests, the range of species is narrower, the dimensions involved are generally smaller, the rotation lengths are substantially shorter, the wood properties are different and, consequently, the end use potential for trees from planted forests can vary substantially from those of trees from natural forests, to which wood industries, trade and consumers are presently accustomed.

This study takes an in-depth look at the impact that plantation management can have on the wood properties of timber species, thus affecting wood processing and end use options. Whilst recognizing that biotechnology can increase productivity of wood/fibre, resistance to insects and diseases and wood quality, the study also demonstrates that processing technology needs to further address the challenge of smaller log sizes, changes in wood properties and others, in order to produce forest products which can satisfy consumers.

Markets, consumer demand and technologies are constantly developing. They are the driving forces for investment and management options. The study looks at different models for production of wood and fibre in response to these changing signals. There is no right answer - forest managers must consider the unique context in which they are investing in planted forests and respond to the key driving forces as they see them, including those from the market place and from wood industries sectors, and also social demands and environmental covenants.

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I. Introduction

Within Species Variance

An observation that needs no elaboration is that trees of different species produce wood with different properties. Over time, this has led to consumer expectations based on common or trade names; and certain key species have attained high market value. Teak (*Tectona grandis*), rosewood (*Dalbergia spp.*), mahogany (*Swietenia* and *Khaya* species), walnut (*Juglans spp.*), black cherry (*Prunus serotina*) and redwood (*Sequoia sempervirens*) are examples of woods that, because of well-known intrinsic properties, command high market prices. In fact, the reputation of these woods is so widespread that other species, often with inferior properties, have been tagged with the same names – for example African teak (*Chlorophora excelsa*) and Philippine mahogany (various species in the genera *Shorea*, *Parashorea* and *Pentacme*). For this reason, throughout this document all common names are linked with standard botanical nomenclature, or in some cases we simply use the botanical nomenclature alone.

Prior to the last century most wood was harvested from indigenous forests growing from natural regeneration. As a consequence, soil type, moisture regime, climate, forest complexity and tree spacing were little changed over time. It was during this earlier time that commercial woods gained their particular quality reputations. But it should be noted that, even at this earlier period, some variation in wood quality was recognized based on origin of the timber.

In Europe, spruce (*Picea abies*) from high altitudes was valued differently from that growing at lower elevations. German oak (*Quercus petraea* and *Quercus robur*) was highly prized for veneer production because of grain pattern and ease of slicing; while English oak was valued for its greater strength, which lent it great value for shipbuilding - an enterprise that gave the British dominance of the seas for many decades. British colonists found that the pristine forest oaks of North America (*Quercus rubra*, and others) lacked the strength of British oaks and more closely resembled the weaker oaks of Germany. At the time these differences were ascribed to geographical or species variances, but we now know that the primary factor controlling strength in oaks is the rate at which they grow in diameter. Wider growth rings produce stronger wood in oak and similar woods (Panshin and deZeeuw, 1980; Summitt and Sliker, 1980). In the closed forests of Germany and pre-settlement New England oaks grew slowly, while the mostly hedgerow oaks defining agricultural lands in Great Britain received maximum light for rapid growth. Not incidentally these open-grown oaks also produced large branches that provided the compass timbers needed in shipbuilding.

As we move forward into an era where increasingly our wood supply will be coming from planted forests, the quality of the wood produced may be different from what consumers have come to expect for a particular species (Pandey and Brown, 2000). If this change is too great, market value will fall and market share will shift to other wood or non-wood substitutes. That this is not just a possible scenario for the future is revealed by examining the US construction lumber market during the past two decades. Rapid growth Southern pine (*Pinus spp.*) and Douglas-fir (*Pseudotsuga menziesii*) in planted forests are yielding wood that has quite different properties from that previously produced in natural forests (McAlister *et al.*, 2000; Megraw *et al.*, 1998). In this case – unlike the oaks previously cited – the wood produced is weaker and has quite different dimensional stability properties. As a consequence, framing lumber is weaker and studs and rafters twist and warp, leading to popped nails and distorted walls, and in the worst cases wall and ceiling separation. As this situation progressed, galvanized steel studs began to gain greater market share - despite the

fact that carpenters needed to learn new methods and buy new tools (Zhang and Gingras, 1998). In recent years the wood industry has regained much of the lost market by producing engineered wood web-beams and studs – but this has been achieved at higher costs to the consumer. Wood technological fixes, as in this case, can solve some planted forest problems, but they are generally not a solution where solid wood product is needed, or demanded for aesthetic reasons.

An examination of recent trends in global forest product export prices from 1990 to 2002 reveals that, since the mid-1990s, wood and paper products have declined in value (FAO, 2005a). During this time the one exception was sawn-wood, which remained high until 2000. Since then, however, sawn-wood has joined the downward trend. It would be premature to attribute a cause for this recent sawn-wood decline, but it coincides with a rapid increase in timber output from planted forests, and it mirrors an earlier more localized trend in Washington State (USA) where declining wood quality reduced sawlog demand (Mittelhammer *et al.*, 2005).

Consumer demand for wood products can often be linked to fickle societal taste changes. For example demand for wood as a flooring material in the US receded after World War-II, as cheaper, more 'modern' floor covering materials such as wall-to-wall synthetic carpeting or vinyl or other plastic tiles or sheet-goods came on the market. As those new markets matured, consumers began to see some of the faults of those materials and also yearned for the natural beauty of wood flooring. As a consequence, wood is now the most sought after flooring material in the USA, even for heavy use areas such as kitchens. Natural wood floors in Europe are also on the rise, often, as in Italy, replacing more traditional materials such as stone or terrazzo. Sometimes a new consumer demand leads to expansion of international markets, as in the case during the 1960s and 1970s when the Japanese decided that bowling was a cool new sport and New England suddenly found that it could barely keep up with Japanese demand for sugar maple (*Acer saccharum*) for bowling alleys, with prices inflated accordingly. For many applications natural solid wood or wood veneer has, and likely will continue to have, very strong appeal, even when other materials could be substituted.

Another factor weighing in favour of wood in the coming decades will be the increasing cost and potential scarcity of petroleum-based alternatives. Planted forests are renewable, capture carbon and help stabilize global climate and provide other environmental and recreational services. This bodes well for the future of wood as a raw material. Weighing against this optimistic view, however, will be loss of consumer confidence in wood, if important quality expectations are not met. Already, some market share has been lost to petrochemical substitutes, although promising compromises are seen in wood-plastic and wood-cement composites for building construction, decking and outdoor furniture (Anon, 2002). Not only are wood products competing with non-renewable products made from petro-chemicals, masonry or metals, but increasingly competition is coming from other renewable plant sources. Within the last few decades bamboo, wheat straw, rice hulls, sugar-cane bagasse, palm fiber and other plant materials have been tested (and in some cases profitably commercialized) as sources for board product that competes with wood (Durst *et al.*, 2004). The challenge, then, is to devise planted forest strategies that actively strive for maintaining or improving intrinsic wood properties, and matching wood quality to anticipated future market demands.

The Global Situation for Planted Forests¹

Based on FAO classification, planted forests consist of productive and protective plantations and planted components of semi-natural forests (Del Lungo and Carle, 2005). Between 1990 and 2002, timber plantation area increased an average of 14 million hectares per year, leading to a total of 187 million hectares (Gadow, 2005). According to one source (Leslie, 2003) planted forests will become the primary global source of wood products in the next 20-30 years. Yet preliminary FAO data suggests that this may have happened already. An estimated 7% of forest cover is in planted forests, 4% of which is in forest plantations, and these account for about 35% of global industrial roundwood harvest. When the other 3% of planted forests is added, the total area may approach 300 million hectares and account for about 50% of industrial roundwood supply - and this is projected to increase substantially in the future (FAO, 2005b).

The case for planted forests is controversial. Advocates assert that these reduce logging pressure on natural forests (Barber, 2004); but some case studies do not bear this out (Clapp, 2001). Regardless, the area of planted forests will continue to expand to meet world wood demand as more natural forests are excluded from logging activity - and under ideal conditions intensively managed planted forests can produce between 2 and 25 times more wood biomass per hectare than natural forests. For example, natural forests produce somewhere between 0.1 and 10.0 cubic meters of wood per hectare per year, depending on climate and soil conditions - an average is about 2-3 m³/ha/yr. Caribbean pine (*Pinus caribaea*) plantations in parts of Venezuela are producing 5-20 m³/ha/yr. Some Eucalypt tree species are growing at a rate of 30 m³/ha/yr, and Paulownia (*Paulownia tomentosa*) - a tree native to China - that can produce 60 m³/ha/yr in Brazil, while *Eucalyptus grandis*, a native of Australia can produce up to 90 m³/ha/yr in Brazil. These growth rates are being eclipsed annually as new planted forests with improved provenances are established in new areas.

What we do not know is how sustainable these very high yields will be, or what kind of environmental impact they may have (Tiarks *et al.*, 1998). Maintaining wood quality can be a major impediment in plantations with very rapid growth rates or where exotic species are used, but can also be a limiting factor in the success of planted forests with more modest growth rates where small differences in wood properties can spell the difference between success and failure in high-value niche markets.

Because the trend in market prices for wood products has been a declining one since the mid-1990s (FAO, 2005), finding higher-value small-market niches may be a useful solution for matching the quantity output of small-holder planted forests with the size of specialty markets. Examples of such markets include musical instrument companies, boatbuilding cooperatives, furniture designers and builders. These and other similar markets have small annual demand, but may require wood with particular properties and processed to specific requirements. If these requirements are met, market prices can be quite high. Furthermore, many of these specialty wood users in Europe and the USA have strong social and environmental ethics, both for themselves and their clients, and are, therefore, drawn to sustainably-managed wood sources, especially if they are certified. The area of certified forests in the world has increased from zero in the early 1990s to currently more than 176 million hectares; but 90% of these forests are in the temperate zone (FAO, 2005). In the past few years the Forest Stewardship Council (FSC) have modified their standards to include certification of plantations, but despite great potential the number certified in the tropics is very small. The cost of certifying small landholdings can be a significant hurdle, although non-governmental organizations (NGOs) and other sources of support are helping. Exporting indigenous species from planted forests, especially if lacking a certification stamp,

¹ Forests in which trees have been established through planting or seeding. Includes all stands established through planting or seeding, both of native and introduced species.

can be difficult in some countries that impose export bans on logs harvested from natural forests. Furthermore, as countries, inevitably, strengthen enforcement against illegal logging certification will become an even more valuable asset.

Interim Cost Recovery Strategies

Due to the large initial costs for establishing a planted forest and the annual costs of management for best wood quality, strategies need to be established to offset some or all of these expenses prior to final harvest. Traditionally, early thinnings for lower-value markets, such as firewood, have provided some interim income. But other opportunities also exist. Capturing carbon credits is one possible revenue source. The environmental benefits are particularly strong for short rotation (6-8 years) plantations that produce chips for board products that will be incorporated into houses or other structures. The carbon capture phase is rapid and very high, and the storage phase is quite long. Agroforestry is another option, particularly for growing high value, long-rotation hardwoods. Tea and coffee plantations established with valuable overstory trees can provide annual income as well as longer-term remuneration when the high value trees reach maturity (or provide too much shade). Ecotourism and recreation are other possible sources of revenue. Recent surveys in industrialized countries suggest that the production of wood or other forest products is not the 'major global value' that the general public attaches to forests, but rather, they view forested areas primarily as sources of environmental services (Leslie, 2003). Another option is the growing of trees with a "dual" purpose, e.g. wood and latex, as lately with *Hevea brasiliensis* in South East Asia.

Until recently ecotourism has been focused on natural, often protected, forests, particularly those with high biodiversity. However, more recently, perceptive tourists seeking a different experience are being drawn to other kinds of venues, even those that dramatically reveal environmental damage (for example, coal strip mines in Appalachia, USA). Well-managed community forests could become recreation and ecotourism destinations, especially if local culture and crafted wood and other forest products were part of the package. Sale of local products and guide fees could be a continuing supplementary source of revenue.

II. Scope and Limits of this Document

The purpose of this paper is to provide a conceptual framework for managers to use in planning forest plantings that will produce wood with particular properties to meet specific market demands. It can also serve as a useful resource for potential investors, giving them practical tools for asking critical questions before committing funds - and to be greater participants in the evolving management process. The major emphasis is on tropical to semi-tropical forest plantations, as this is where most current and projected planted forests are, and will be, located. Some of the tree species discussed are natural to warm temperate forests, but can adapt to more tropical conditions.

Space limits preclude precise prescriptions on planting, spacing, pruning, overstory management, harvesting, primary processing or other procedures for particular tree species or settings. Many of these are described in other publications, such as: Schmincke, 2000; Mayhew and Newton, 1998; Bootle, 2005; Larson, 1969; Krishnapillay, 2000; Sankar *et al.*, 2000; Hyytiäinen, 1992; Anon, 2000; Anon, 2003. Similarly, the realm of market niches for various woods is beyond the scope of this work, but are amply provided in other sources, such as: Anon, 2002; Keating and Bolza, 1982; Mullins and McNight, 1981; Summitt and Sliker, 1980; Record and Hess, 1943; Kribs, 1958.

We begin with a general discussion of wood properties and present four categories into one of which all woods can be placed. This is followed by a general characterization of these four wood categories in terms of basic properties. Using this as background specific wood properties are analyzed with respect to how they may be affected when grown under accelerated production in planted forests. In particular the following issues are discussed: (1) growth rate and strength properties, (2) growth rate and internal stresses, (3) growth rate and production of juvenile wood, (4) spacing and reaction wood, (5) drying defects in timber, (6) growth rate, soils and durability, (7) dimensional stability and chemical resistance, (8) growth rate and sapwood/heartwood ratio, (9) climate seasonality and wood properties, (10) genetics and wood quality, and (11) insect and disease management. Within each of these categories, practical examples are presented to put these concepts into real-world context.

Following this, we lay out two contrasting strategies for planted forest management: (1) the *intensive management model*, and (2) the *diversified market model*, describing how each is different in approach and goals. It is suggested that managers chose the model that best fits their long term plans.

Finally we provide a condensed discussion of key initial planning steps: legal analysis, site analysis, market assessment, and tree species choice and documentation. Planted forest management issues that need to be considered for five major situations are presented, followed by some concluding remarks.

III. Wood Properties

General Discussion

Wood is used for so many different products we need to be conversant with a range of properties that can vary. However once a manager establishes his market niches, a much smaller array of properties may be important to control. Here, we will survey the full array of variable wood properties over which one might want to have some influence.

A. Four Categories of Wood Structure Based on Cross-Sectional View²

During millions of years of evolution, trees have adapted to environmental change by adjusting physiological and biomechanical responses and these are reflected in the structure of the xylem, or wood (Baas *et al.*, 2004; Niklas, 1992; Carlquist, 1975). In parts of the wet tropics where growing conditions are similar year round, distinct annual growth rings may be absent (Record and Hess, 1943). We will consider these after first examining the cross-sectional structure of trees with defined growth rings – an exercise that provides revealing insights in relation to growth rate management.

Coniferous trees (generally called softwoods) produce a single cell type, the *tracheid*, that carries out the functions of both support and water conduction (Alden, 1997; Panshin and deZeeuw, 1980; Jane *et al.*, 1970). The simplest version of this is found in conifers characterized by a relatively uniform cross-sectional structure composed of tracheids with similar diameters and thickness of walls, but usually with some gradual increase in wall thickening near the end of the growth ring (latewood). This kind of conifer wood is termed

² The four basic wood types described here are illustrated in Figures 1 and 2, and can be seen directly on a smooth end surface of wood with or without slight magnification.

gradual transition (Figure 1). More specialized conifers develop a structure with large diameter, thin-walled tracheids in the earlywood and decidedly thicker-walled, smaller-diameter tracheids in the latewood (Wardrop and Preston, 1950). These conifers that partially separate the roles of conduction and support are called **abrupt transition** (Figure 2) softwoods. Sometimes it is difficult to easily place a conifer in one of these two categories because the dense latewood is a significant portion of the ring, but the transition is gradual (Figure 3). In these cases, we usually group the wood with abrupt transition species since, in terms of growth rate and mechanical properties, it behaves more like those woods (Anonymous, 2002).

Dicotyledonous woods, or hardwoods, have evolved to produce completely different cells for conduction and support. Water transport is carried out by relatively large diameter vessels (referred to as *pores* when viewed in cross-section), while mechanical support is achieved with thick walled *fibers*. Because of this division of labour, the size and distribution of vessels can be adjusted to meet a wide range of environmental habitats, and as a consequence hardwoods have become the dominant tree species throughout much of the world (Carlquist, 1988).

In regions of the world where climate is distinctly seasonal, with long cold periods that halt tree growth, a type of vessel arrangement called **ring-porous** often develops (Carlquist, 1988). A few **ring-porous** hardwoods are also found in the tropics, especially in response to monsoonal conditions that provide a relatively short growing season (Chudnoff, 1984). The characteristic features of **ring-porous** hardwoods are clustered large pores (vessels) at the beginning of the growing season followed by more scattered, smaller diameter pores embedded in fibers in the latewood (Figure 4). Some temperate region trees and most tropical species that are classified as **ring porous** may have only slightly larger and few larger pores at the beginning of the growth ring, or have a more gradual change in pore size transitioning into the latewood (Figure 5). These will be referred to as weakly ring porous.

Diffuse-porous hardwoods have similar size vessels arranged in various patterns throughout the growth ring, but typically in a relatively uniform distribution of pores (Figure 6). **Diffuse-porous** hardwoods dominate in the tropics, but are also common in many temperate zone habitats. They are readily distinguished from **ring-porous** hardwoods by lacking the distinct concentration of larger pores at the beginning of the growth ring. Tropical hardwoods that lack distinct annual growth rings are classified as **diffuse-porous**.

Figure 1. Gradual transition conifer with indistinct latewood (*Pinus lambertiana*)

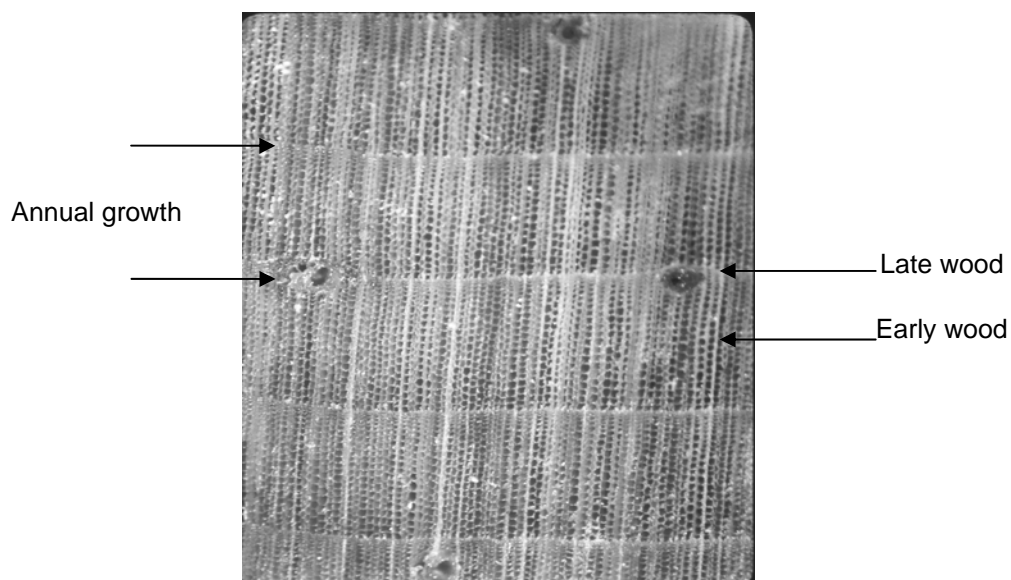


Figure 2. Abrupt transition conifer (*Pseudotsuga menziesii*)

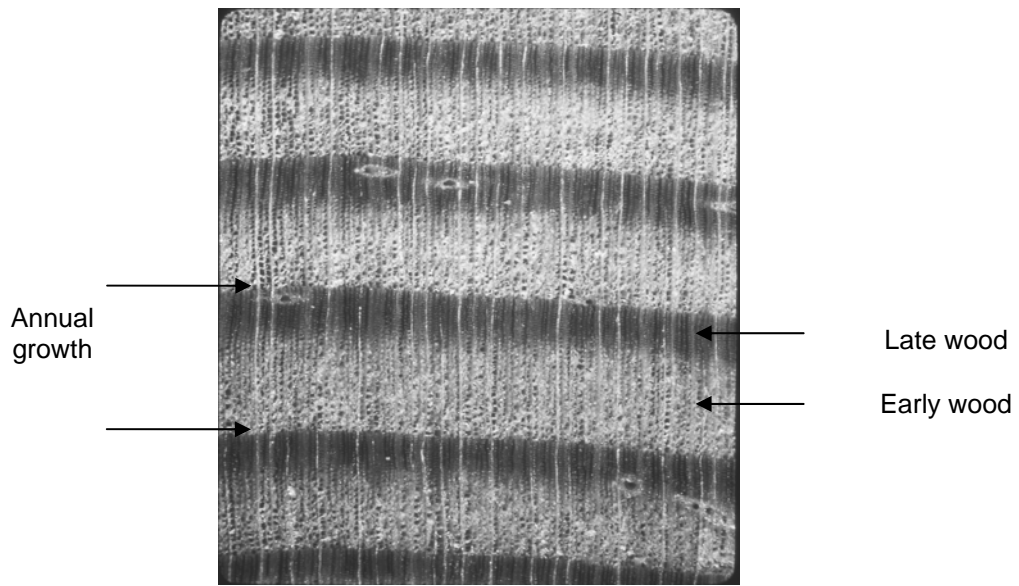


Figure 3. Gradual Transition Conifer with distinct latewood (*Tsuga canadensis*)

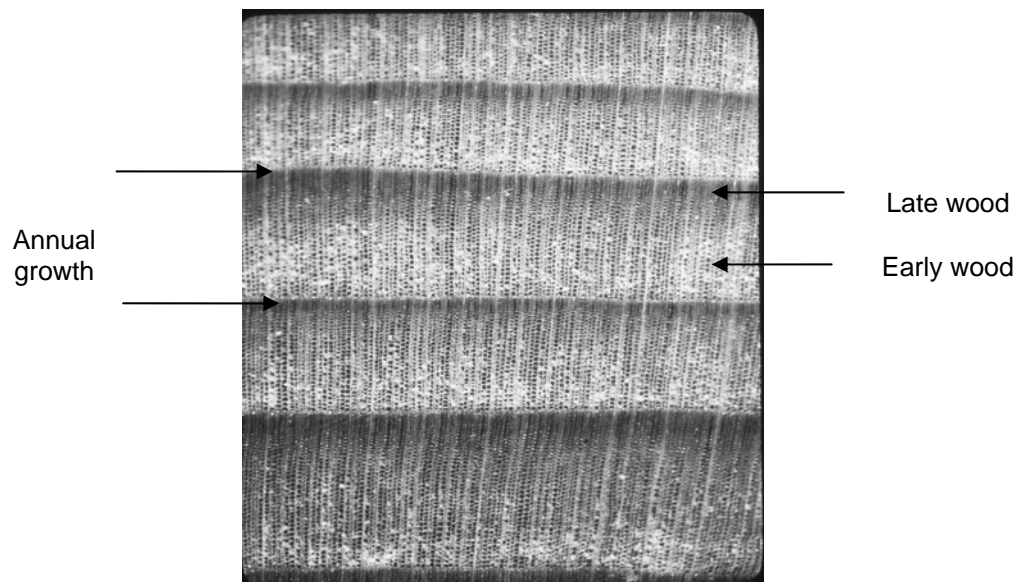


Figure 4. Ring porous hardwood (*Quercus rubra*)

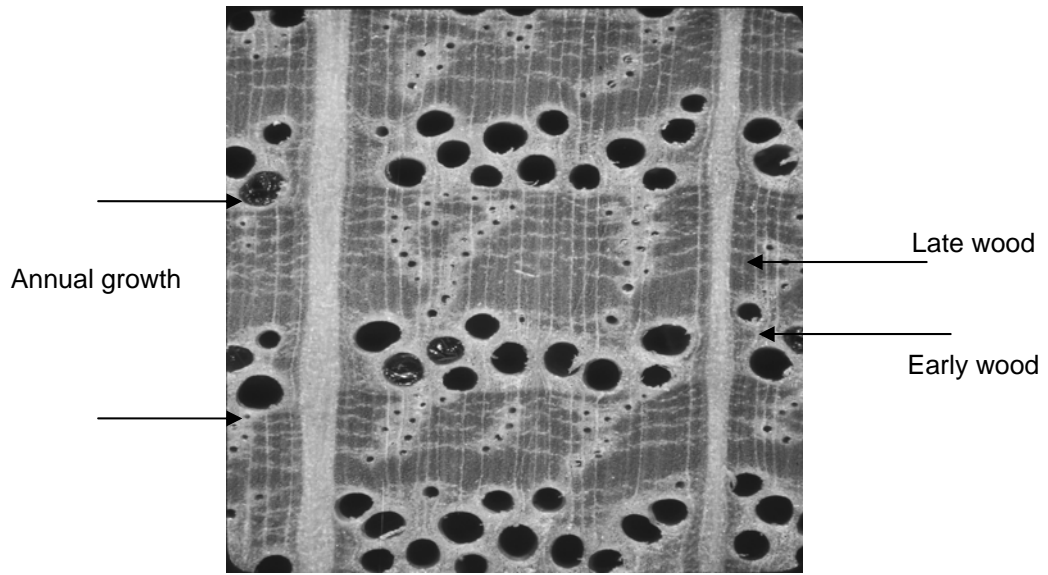


Figure 5. Weakly ring porous hardwood (*Juglans nigra*)

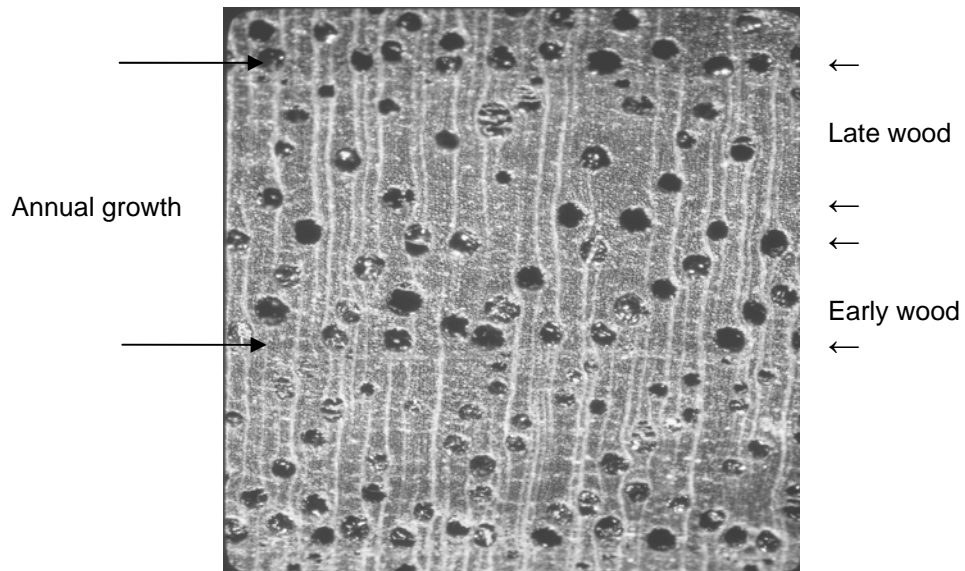
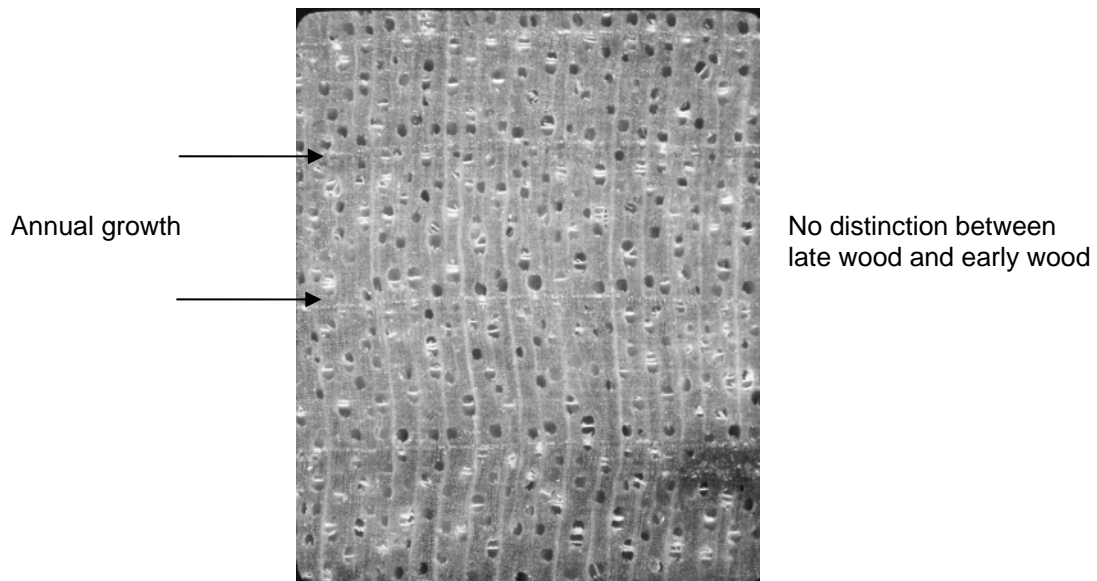


Figure 6. Diffuse porous hardwood (*Betula papyrifera*)



B. Characteristics and Examples

Abrupt Transition Softwoods

When growing in natural forests, these species generally have basic specific gravity (SG) values (green wood volume, oven-dry weight) that exceed 0.40, producing lumber that is strong and generally favoured for construction purposes (Anonymous, 2002; Summit and Sliker, 1980). When grown in short-rotation plantations these trees may have lower SGs and different wood properties, discussed subsequently. Examples of species in this grouping are (SG in parentheses):

- Warm Temperate - *Pinus caribea* (0.68), *Pinus oocarpa* (0.55), *Pinus patula* (0.45), *Pinus palustris* (0.55), *Pinus elliottii* (0.54), *Pinus taeda* (0.47), *Pinus echinata* (0.47), *Pinus radiata* (0.42);
- Cool Temperate - *Pseudotsuga menziesii* (0.46), *Pinus sylvestris* (0.42), *Pinus resinosa* (0.41), *Pinus banksiana* (0.40), *Tsuga heterophylla* (0.42), *Larix* species and hybrids (0.49⁺ or ⁻).

Gradual Transition Softwoods

The wood properties of these species are less affected by growth rate than the abrupt transition species, producing plantation grown wood that more closely resembles the properties of natural forest trees. Most of these species have SG values below 0.40. Many of these are also important construction timbers (Anonymous, 2002; Bootle, 1983; Mullins and McNight, 1981).

- Examples include: *Pinus strobus* (0.36), *Pinus monticola* (0.36), *Pinus lambertiana* (0.34), *Pinus cembra* (0.3-0.4), *Abies* species (0.33-0.34), *Picea* species (0.33-0.38), most members of the Cupressaceae, Araucariaceae, Podocarpaceae, Taxaceae.

Ring-Porous Hardwoods

Tree species that fall into this grouping respond to growth rate with distinct changes in strength properties. Those characterized as strongly ring-porous (Figure 4) are more affected by growth rate than ones categorized as weakly ring-porous (Figure 5). Listed here are tree genera that have at least some ring-porous members (Ilic, 1991; Martawijaya *et al.*, 1986; Bootle, 1983; Keating and Bolza, 1982; Panshin and deZeeuw, 1980).

Key: S = strongly ring porous; W = weakly or semi-ring porous; N = some members are not ring porous; Tr = tropical genera; Te = temperate genera

<i>Agonis</i> (W, Tr)	<i>Juglans</i> (W, N, Te)
<i>Acanthopanax</i> (S, W, Te)	<i>Maclura</i> (W, Te)
<i>Bombax</i> (W, Tr)	<i>Melia</i> (W, N, Tr)
<i>Carya</i> (S, W, Te)	<i>Morus</i> (S, W, Te)
<i>Castanea</i> (S, Te)	<i>Phellodendron</i> (S, W, Te)
<i>Castanopsis</i> (S, W, Te)	<i>Prunus</i> (W, N, Te)
<i>Catalpa</i> (S, W, Te)	<i>Quercus</i> (S, N, Te, Tr)
<i>Cedrella</i> (W, N, Tr)	<i>Robinia</i> (S, W, Te)
<i>Celtis</i> (S, W, N, Te)	<i>Sapindus</i> (W, N, Tr?)
<i>Diospyros</i> (W, Tr, Te)	<i>Sassafras</i> (S, W, Te)
<i>Eucalyptus</i> (W, N, Tr, Te)	<i>Tectona</i> (S, W, Tr)
<i>Fraxinus</i> (S, Te)	<i>Toona</i> (W, Tr)
<i>Gleditsia</i> (S, W, Te)	<i>Ulmus</i> (S, Te)
<i>Guaiacum</i> (W, Tr)	<i>Zelkova</i> (S, Te)

Diffuse Porous Hardwoods

Based on number of species, this is the largest of the four groups. Strength properties in these tree species are less influenced by growth rate than in ring-porous species (Lauridsen and Kjaer, 2002). However, development of internal stresses can be magnified by rapid growth, particularly in the denser species (Bootle, 2004; Cassens and Serrano, 2004; Archer, 1986). Most tropical hardwoods and several temperate genera fall into this category (Martawijaya *et al.*, 1986; Summitt and Sliker, 1980; Record and Hess, 1943). A complete listing of the most commonly used tree species in planted forests (enumerated by country) can be found in James and Del Lungo (2005).

Planted Forests

“Especially in the tropics, many forestry organizations are planting exotic species on a massive scale and are producing a large volume of “different” wood. Such wood is not desirable for some products and may be distinctly different from the wood that the same species produces in its indigenous environment. Huge amounts of it are now becoming available, requiring a reassessment of both manufacturing techniques and product type and quality” (Zobel, 1984).

In the 22 years since Bruce Zobel made the above pronouncement, many new planted forests have been established, often without recognizing the difficulties that could be faced at timber harvest time. This section examines how various properties may be different in wood grown in planted forests, especially if trees are growing more rapidly due to genetic manipulation, wide spacing, fertilization or irrigation, or are growing on different soils or in different climate zones (Mayhew and Newton, 1998; Zobel and Sprague, 1998; Bendtson, 1958). The emphasis is on describing wood property changes related to specific conditions and for different species groups. The issue of ‘wood quality’ is left to the discretion of the reader since, as Gartner (2005) has noted *“wood quality is the weighted value that society gives to wood characteristics that affect properties”* (see Appendix I for a cogent example).

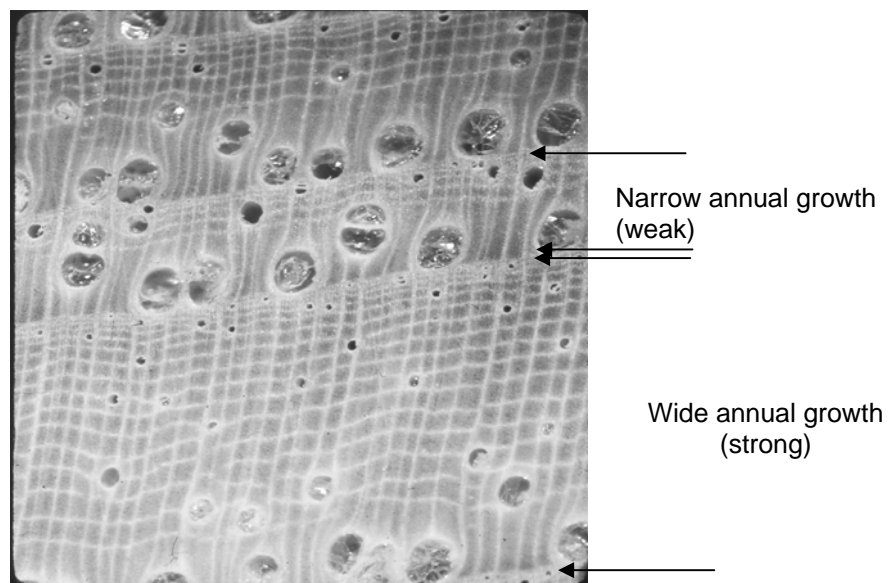
Growth Rate, Density and Strength Properties

Strength is an important criterion for wood that will be used for structural purposes, whether for building construction, boats, furniture, tool handles, sporting equipment, etc. (Anonymous, 2001; Chudnoff, 1984; Record and Hess, 1943). A surrogate measure often used to assess strength is wood density. Except in the case of compression wood (see below), density is generally a reliable indicator of modulus of rupture in bending, but less so for modulus of elasticity (Jagels *et al.*, 2003; Anonymous, 2001).

Strength is generally reduced in **abrupt-transition** conifers that produce very wide rings in planted forests. The percentage of weaker earlywood increases and the width and density of latewood generally declines (McAlister *et al.*, 2000; Haygreen and Bowyer, 1989). *Pinus radiata* is normally an abrupt transition species (Figure 2), but in plantation grown trees the wood may become gradual transition (Figure 1). The degree of strength loss is correlated with the loss in wood density. Abrupt-transition north temperate species such as *Larix* spp., *Pinus sylvestris* and *Pseudotsuga menzessii* will generally reveal some strength loss in plantations, but it will not be as severe as in species like the southern hard pines of the US that can adapt to plantations in tropical regions. **Gradual transition** conifers, with normally lower wood density will be affected to a lesser degree when grown under conditions favouring rapid growth, and since many of these species are north temperate trees, they do not adapt to tropical conditions.

The strength properties of **ring-porous** hardwoods (Figure 4) are generally enhanced when grown to produce wider rings. This is because the weaker large-pore earlywood zone is fixed in width in these species, so all added growth is in stronger latewood (Panshin and deZeeuw, 1980; Haygreen and Bowyer, 1989). Figure 7 shows a wide ring in *Carya*, as well as two narrow rings occupying about the same area and consisting of mostly weak earlywood. Species that are classified as **semi- or weakly ring porous** (Figure 5) have the same relationship between ring width and strength, but the magnitude of the change is less. Baseball bat and tool handle manufacturers in the US often set upper limits on rings per inch that they will accept in ring porous woods like ash, and hickory destined for these high strength requiring applications.

Figure 7. Ring porous hardwood with one wide and two narrow rings (*Carya ovata*)



Strength properties of **diffuse porous** hardwoods are often less prone to changes in density and strength related to growth rate, but those species that have large geographical ranges and rainfall and soil tolerances can display a considerable range in wood density and strength properties. *Swietenia macrophylla*, for example, has a natural range from the wet lowlands of Mexico and Guatemala through Panama, to the high and dryer altitudes of Bolivia. Within this natural geographic range basic specific gravity can range from 0.40 to 0.85. In planted forests where moisture and spacing encourage rapid growth, the density range is smaller and closer to the low end of the range (Mayhew and Newton, 1998).

A caveat needs to be noted here. Standard testing procedures for strength properties of wood are performed on small, clear specimens. Lumber grading rules downgrade this strength value as the number and size of knots increases. In the case of some planted forest trees, where no pruning was performed and trees are growing at wide spacing, the great number and size of knots may considerably reduce the use of the respective timber for construction purposes as is the case, for example, with *Acacia mangium* in South East Asia (Killmann, personal communication).

Growth Rate and Internal Stresses

In young saplings the weight of the crown, which is large in relation to stem diameter, induces compressive stress on the cambium in the tree trunk. As the tree increases in height and girth, axial compressive stress established near the centre of the tree is gradually replaced by axial tensile stress in the more recently formed outer wood. These opposing stresses may increase in magnitude with time or be partially relieved by elastic or inelastic strain (Bootle, 2004; Cassens and Serrano, 2004; Boyd, 1980; Boyd, 1972). Factors that can affect the magnitude of unrelieved opposing stresses are: (1) whether a tree is a conifer or hardwood, (2) whether the wood density is high or low, (3) if a hardwood, whether the wood is **ring-porous** or **diffuse porous**, and (4) how rapidly the tree grows.

Conifers, possibly due to the structure of tracheids or the different chemistry of the lignin, are less prone to develop large opposing internal stresses than are hardwoods, although star shake and ring shake can develop in some species like hemlock (*Tsuga* spp.). Hardwoods with low wood density generally relieve internal stresses in the living tree through inelastic strain (Boyd, 1980). **Ring porous** hardwoods, because of the very weak earlywood zone can also provide some stress relief in the living tree, although these species are not immune to stress-related defects (Cassens and Serrano, 2004). The species most prone to developing large unrelieved internal stresses are high density **diffuse porous** hardwoods – and this is greatly magnified when these trees grow rapidly, reducing the time during which some stress relief could occur.

Many moderate to high density *Eucalyptus* species that normally grow slowly in moisture restricted native habitats in Australia, produce very large internal stresses when grown in wetter indigenous planted forests, or as exotics in Africa, Asia and Latin America (Bootle, 2004). Felling or milling of these trees is quite dangerous as internal stresses are relieved by sudden and forceful splitting. Even when trunks are banded during felling, and protective cages are built around milling saws, the wood yield is quite poor. A relevant example can be found in *Eucalyptus camaldensis* grown rapidly in Pakistan (Killmann, personal communication). By contrast, the low density *Gmelina arborea* when grown rapidly in plantations does not usually develop large internal stresses. *Gmelina* wood only has a density of about 410 kg/m³ (compared to 470 to 500 for *Acacia mangium* and hybrids; and over 600 for most Eucalypts). The low density of *Gmelina* is often a source of complaint among planted forest managers, and as a consequence researchers are attempting to breed higher density varieties or hybrids (Dvorak, 2004). However, this may run the risk of introducing unwanted internal stresses, greatly reducing yield.

Growth Rate and Production of Juvenile Wood

Wood production by the layer of cambial cells between the bark and xylem is controlled by a combination of biomechanical and physiological influences – most critically by the weight of the crown and the concentration of plant hormones (auxins) and sugars transported from the leaves in the crown to the cambial zone in the trunk. When a tree is young the weight of the crown relative to the diameter of the stem is large, and the transport distance for auxins and sugars is short. During this period the cambium produces a kind of wood that has been descriptively labelled “juvenile wood”, “crown wood” or “core wood” (Zobel and Sprague, 1998; Cave and Walker, 1994; McMillan, 1973; Dadswell, 1958). As trees age the relative weight of the crown lessens and the transport distance for auxins and sugars increases. The cambium near the base of the tree responds by beginning to produce mature wood, with properties that are more acceptable for most wood products (Bendtsen, 1978). The differences between juvenile wood and mature wood are most pronounced in conifers and are of less importance in hardwoods (Zobel and Sprague, 1998; Bendtsen, 1978).

The volume of juvenile wood produced in a stem is related to how rapidly it grows and whether the lower crown is pruned, dies due to shading, or remains alive (Zobel and Sprague, 1998; Larson, 1969). Trees that are planted with wide spacing to maximize growth and are not pruned of lower branches will produce the largest core of juvenile wood. In some species of **abrupt transition** hard pines planted in warmer climates, juvenile wood can occupy 80 to 100% of the stem volume if trees are widely spaced, un-pruned and harvested at less than 20 years of age. Some managers have suggested that it would be wise to consider these as different tree species due to pronounced differences in wood properties (Zobel, 1984).

Juvenile wood is significantly weaker, and unlike mature wood shrinks or swells in the axial direction, due to a high microfibril angle in the secondary wall of the tracheids (Meylan and Probine, 1969; Boyd, 1985). If both juvenile and mature wood are present in the same board, the differential transverse and longitudinal shrinkage of these two zones will lead to significant warping and twisting (Meylan, 1972). Juvenile wood processed for pulp will require more chemicals and produce paper that is not as strong - and the percentage of fines in the waste stream will increase substantially (Zobel and Sprague, 1998; Dinwoodie, 1965). Ideally, conifers should be established with moderately close and even spacing followed by a program of judicious pruning and thinning as the stand ages. This produces a greater quantity of knot free, higher value wood at harvest. Many managers have opted for wider spacing and no thinning or pruning in order to minimize costs per unit volume of wood produced. Unfortunately this precludes the possibility of marketing the logs for quality lumber or veneer, and the quality for pulpwood is significantly reduced. Often not calculated in this strategy are the further economic losses at the paper mill due to increased fines (due to shorter and weaker tracheids) that reduce the volume converted to paper and increase the cost of waste stream management (Groom *et al.*, 2002; Anderson, 1951). One market for which juvenile conifer wood is acceptable is chips for board construction (with the possible exception of oriented strand board). However small diameter un-pruned trees can be difficult to debark and the high knot content may quickly dull knives and yield a low volume of acceptable chips.

Spacing and Reaction Wood

Trees exposed to windy conditions or when planted on steep slopes will produce an abnormal wood in an attempt to maintain vertical stem axes. In hardwoods this is called **tension wood**, and forms on the upper side of leaning stems. In conifers reaction wood forms on the underside of leaning stems, and is called **compression wood** (Panshin and deZeeuw, 1980; Jane *et al.*, 1970). As spacing between trees is widened the wind loading on saplings increases and the proportion of reaction wood increases. Also, uneven spacing can lead to unbalanced crowns and result in leaning stems and greater proportions of reaction wood (Bootle, 2004). **Tension wood** can affect machining properties, producing a wholly surface, and in some species, notably Eucalypts, can result in non-recoverable

collapse during drying (Bootle, 2004). **Compression wood** greatly reduces many mechanical properties, and increases lignin content and density (Panshin and deZeeuw, 1980; Wardrop and Dadswell, 1950). Since it forms mostly in the first several years of growth, when trees are most susceptible to bending, it further degrades the juvenile wood portion of the tree. The higher lignin content makes the conifer wood more difficult and costly to pulp for paper production.

Drying Defects in Timber

Several drying defects can be enhanced in rapidly grown plantation wood. As noted in the discussion of juvenile wood, warping, cupping, and twisting during drying will be greater in boards that contain both juvenile and mature wood. As an example, much rapid growth southern pine plantation wood in the US readily accepts pressure-treatment with water-borne chemicals for use in exterior decay or termite exposure situations. Often the wood is immediately bundled and wrapped with steel straps after treatment and shipped to retailers. Partial drying occurs during shipment and when the steel straps are cut much of the surface lumber is released, like a wound spring, as warped and twisted waste. In order to limit their losses, retailers generally store pressure treated wood outside exposed to rain and cooler temperatures, so that further drying is limited. The consumer is then burdened with the warping and twisting that occurs as the wood continues to dry after purchase. Because the juvenile wood of Southern pine is so easily pressure treated with biocides, many marine structures have been installed with pilings of this wood throughout the world. A number of these have failed, not because of decay or marine borer attack, but because the weak juvenile wood cannot withstand the normal impact stresses imposed by docking ships. These problems have led to finding alternatives in either non-wood pilings or stronger, naturally durable wood from natural forests, such as Borneo ironwood (*Eusideroxylon zwagerii*), or, when available, Demerara greenheart (*Ocotea rodiaei*).

The presence of juvenile wood on only one surface ply of plywood can also lead to future warping, especially if during manufacture the plywood was produced to a moisture content standard that was higher than the equilibrium moisture content of the end user. The author has observed this problem with floor underlayment buckling and warping after installation during dry winter conditions in heated buildings in cold climates, particularly if the plywood had been manufactured in a warmer, more humid tropical country.

Dense hardwoods, especially those with low permeabilities, are often difficult to dry even when harvested from closed canopy natural forests (Siau, 1995; Henderson, 1951) but if this wood comes from rapid growth plantations, where internal stress differentials are enhanced, drying defects such as collapse (enhanced by the presence of tension wood), splitting and honeycombing are likely to be much greater (Bariska, 1992; Kauman, 1958).

Growth Rate, Soils and Durability

The natural resistance of processed wood to biodeterioration from insects, bacteria, fungi or marine borers depends primarily on chemicals produced during sapwood to heartwood conversion in certain tree species. Sapwood of any species is generally prone to attack by biodeteriorating agents. A few examples of species for which the heartwood has gained a high market valuation for resistance to biodeteriorating agents are: mahogany (*Swietenia* spp., *Khaya* spp.), teak (*Tectona grandis*), kauri (*Agathis australis*), redwood (*Sequoia sempervirens*) and cedars (*Cedrus* spp., *Thuja* spp., *Chamaecyparis* spp., *Juniperus* spp., etc) for decay resistance; longleaf pine (*Pinus palustris*) and bald cypress (*Taxodium distichum*) for termite resistance; and turpentine (*Syncarpia glomulifera*), greenheart (*Ocotea rodiaei*), and Borneo ironwood (*Eusideroxylon zwagerii*) for resistance against marine borers (*Teredo navalis*).

The ability of a tree to produce resins, terpenes, flavenoids and other chemicals that render heartwood toxic or unpalatable to biodeteriorating organisms depends on genetically

controlled metabolic pathways and the availability of biosynthesis precursors. These precursor chemicals, as well as chemicals such as silica that are not further modified in the tree, are absorbed from the soil by tree roots. The chemistry of the soil is, therefore, critical for providing these chemicals. Soil pH and cation exchange capacity is also important because if the required chemicals are not in solution they cannot be absorbed by the roots. For example, soils under *Pinus radiata* trees in New Zealand often have lower pH, higher extractable aluminium and lower exchangeable calcium than the native soils prior to planting (Giddens *et al.*, 1997).

Soils exposed to excessive rainfall, as is common in many parts of the wet tropics, may be rapidly leached of soluble chemicals, reducing the amount that can be absorbed by roots (Tiarks *et al.*, 1998). Even under non-leaching conditions, but where moisture and tree spacing combine to accelerate wood production, the quantity of chemical precursors available at the sapwood/heartwood boundary may be reduced leading to the production of heartwood with reduced biodeterioration resistance. This 'dilution affect' can occur even with indigenous species planted on native soils where growth rate is greatly accelerated.

A further problem in intensively managed planted forests may be long-term depletion of soluble soil minerals after one or more harvests (Fox, 2000; Tiarks *et al.*, 1998). Soil fertilization to ameliorate this problem and to maintain biomass production usually does not take into account loss of chemicals in the soil that are needed for producing optimum heartwood properties. Indicative of this problem is the greater variation seen in the heartwood of *Swietenia macrophylla* now that it is being harvested from a wider natural range as well as from planted forests all over the globe. Decay resistance of heartwood varies, with colour ranging from yellow to deep red, and black or grey spots, or chalky or black inclusions can also be found; and Fijian grown mahogany often has pocket rot or more serious heartrot (Mayhew and Newton, 1998; Lamb, 1966; Record and Hess, 1943).

Finally, it should be noted that trees have developed decay resistance in the heartwood not for our benefit as we use the wood for various products, but rather to fend off potential heart-rot pathogens. The greater propensity for certain species, such as some Eucalypts, *Tectona grandis*, *Swietenia macrophylla*, and, especially, *Acacia mangium*, to develop heart-rot in planted forest settings could be linked to the above cited factors that reduce heartwood extractives (Barber, 2004; Barry *et al.*, 2004; Gales, 2002; Mayhew and Newton, 1998; See and Arentz, 1997).

Dimensional Stability and Chemical Resistance

For certain wood products a high level of dimensional stability is required. Examples include ship decking, musical instruments, scientific apparatus and tools (such as levels) for engineers, carpenters and masons. Teak and mahogany are woods with good dimensional stability. Resistance to caustic solution deterioration permits the use of some woods for vats or other chemical exposure situations. Redwood and some cedars are known for their chemical resistance.

The chemistry and quantity of extractives deposited in heartwood determine to a large degree the dimensional stability or chemical resistance of woods, and, as such, are subject to the same soil chemistry controls cited for bio-deterioration resistance. Growth rate can also be a factor as it contributes to the 'dilution affect' and, in denser woods, enhances internal stresses. In general, then, wood with wider rings may be less dimensionally stable, and may have lower chemical resistance.

The traditional uses of forest grown mahogany and teak in applications requiring good dimensional stability are being threatened by the recent substitution of rapidly grown plantation stock. Much teak planted outside its natural range is unsuitable for boat decking or garden furniture. Similarly, carpenters levels made from rapidly grown *Swietenia*

macrophylla (or sometimes even Philippine 'mahogany') have led to warped or cracked tools. Plastics and metals are taking over much of this market, despite the fact that carpenters and masons prefer the better shock-absorbing properties of wood when a level is accidentally dropped.

Growth Rate and Sapwood/Heartwood Ratio

Sapwood in living trees provides the pathway for water transport from roots to photosynthesizing leaves. Many species, especially those that respond positively to increased moisture and wider spacing, may adjust the width of the sapwood to meet greater transpirational demand in an expanding crown (Waring *et al.*, 1982). For some wood products wide sapwood is preferred; an example being the sapwood of ash for baseball bats. But if a species is being grown for the properties of its heartwood, such as teak (*Tectona grandis*), mahogany (*Swietenia macrophylla*) or kauri (*Agathis australis*), a wider sapwood will reduce heartwood volume at harvest (Steward and Kimberly, 2002). As previously noted, rapid growth that leads to wide sapwood may also induce the extractive 'dilution affect' in the heartwood. Teak (*Tectona grandis*) is an example of a species that responds positively to increased moisture by producing wider sapwood (Cordero & Kanninen, 2003). Similarly, sapwood of mahogany (*Swietenia macrophylla*) in rapid growth trees is wide (greater than 4-5 cm) compared to slower growing specimens (2.5 cm or less); and thinnings can have little value due to high sapwood proportion (Bulai, 1993; Streets, 1962). On the other hand, in black cherry (*Prunus serotina*), sapwood width is generally unresponsive to growth rate. In general, sapwood width in ring-porous hardwoods is somewhat more sensitive to growth rate (Panshin and deZeeuw, 1980).

Sapwood in a few species may have special attributes that enhance its product value. Mountain ash (*Eucalyptus regnans*) and several other Eucalypts growing in natural forests produce sapwood with very low starch content. Because of this the sapwood is highly resistant to *Lyctus* borer attack. Other Eucalypts that have higher sapwood starch contents are susceptible to Lyctid attack of wood products. Since this insect can attack soon after felling, it can prevent the export of logs or lumber to countries that have rigid sanitary import restrictions.

Climate Seasonality and Wood Properties

In the wet tropics, trees are often evergreen and photosynthesize year round producing wood on a continuous basis. In cooler, temperate climates or in monsoonal regions of the tropics, trees cease growth for a period each year, and this is often associated with the deciduous habit (periodic and simultaneous shedding of all leaves). Prior to the dormant period some tree species produce a different kind of wood – in conifers this is the denser latewood, triggered by shorter days and drier conditions (Hiller and Brown, 1967). Other trees produce a special wood when growth commences at the end of dormancy. **Ring-porous** hardwoods, such as oaks, produce large earlywood vessels at this time.

If seasonally adapted trees are planted in warmer regions where moisture and warm temperatures are available year round, they may lose some of the wood properties that are triggered by seasonality. **Ring-porous** woods, like oaks, that can adapt to tropical conditions can become diffuse-porous. For example oaks in Mexico and southern Japan are diffuse-porous. Monsoonal tropical species such as teak may also change when shifted to a non-seasonal environment. Conifers moved from seasonally warm temperate climates to the tropics (where daylength varies very little) may lose the capacity to produce a dense latewood. *Pinus radiata* exhibits this trait (Hiller and Brown, 1967). Each of these kinds of changes, as noted in earlier sections, can change wood properties.

Recent research suggests that, if seasonally adapted *Acacia mangium* are moved to conditions of continuous moisture, the incidence of heartrot increases (See and Arentz, 1997; Barry *et al.*, 2004). This has become a major threat in a number of areas in Indonesia and

Malaysia, where the majority of planted forests consist of this single species (Lee, 2002; Rimbwanto, 2002; Nair, 2000). This issue and its possible cause are discussed further under the insect and disease section below.

Genetics and Wood Quality

Just as different tree species growing in the same environment produce different kinds of wood, genetic strains or provenances of a single species can also respond differently to the same environment. This is the theoretical basis for provenance selection as a way of improving wood properties in trees. As a caveat it should be noted here that the majority of selection programs have focused on easily observable external tree features, notably height and volume growth, stem form and size and distribution of branches, with only small attention, if any, to wood quality issues (Evans, 2005).

Although some of the negative wood quality problems facing plantation species may be partially ameliorated by judicious provenance selection, this should not be viewed as a magic-wand panacea. Selection of different provenances for wood quality improvement may be coupled with a growth rate reduction, however, similar results may be more cheaply achieved through judicious silvicultural management.

In a study of five provenances of teak (Kjaer *et al.*, 1999), the authors found considerable variation in silica content (0.27% to 66%) and heartwood percent, but concluded that they could not separate this variation into genetic or environmental effects. Like other studies that fail to use the 'common garden' approach, true genetic differences can be easily masked or falsely revealed, leading to unrealistic expectations for genetic tree improvement in planted forests. Model trial systems such as Danida (Denmark) and CAMCORE (USA) are necessary before investment in expensive provenances can be justified (Lauridsen, 2003; Dvorak, 2004).

Conservation of genetic resources should be another goal in planted forests. Past high-grading of natural forests through multiple harvesting rotations has led to the loss of some genetic potential, often leading to smaller, lower-quality trees. Salvaging what is left in seed banks or by other methods will help to stem further erosion of the gene pool and provide the greatest potential for developing valuable new provenances.

Insect and Disease Management

Planted forests, especially those that are monocultures, provide potential conditions for rapid population increases in insect pests or the spread of disease pathogens (Barber, 2004; Wingfield and Robison, 2004; Nair, 2000). Yet reduced growth or mortality attributable to biotic and abiotic causes can be less in properly managed planted forests than in natural forests (Gadgil and Bain, 1999). A well thought out plan of integrated pest management (IPM) is a necessary part of planted forest planning. Using a mixture of tree species, age classes or different genotypes may provide some control for insect and disease problems; and employment of targeted strategies such as overstory protection against apical shoot borers during early height growth can be effective (Barber, 2004; Tilakaratna, 2001; Mayhew and Newton, 1998). For more than a half century shootborers in the genus *Hypsipyla* have been major deterrents to managing trees in the Meliaceae family for wood production (FAO, 1958). Many of these Meliaceae, in the genera *Swietenia*, *Khaya*, *Toona*, *Cedrela*, *Carapa*, *Entandrophragma* and *Lovoa*, produce some of the most valuable wood in the world (Griffiths, 2001).

Although DDT was once the control measure of choice (FAO, 1958), biological control through canopy light management, often with different overstory species, is now considered to be a reasonably effective means of minimizing damage from *Hypsipyla* and has been effectively practiced for several decades in Sri Lanka (Mayhew and Newton, 1998). In the few places in the world where *Hypsipyla* borers are absent, such as the remote eastern

Solomon Islands, Vanuatu, Fiji or Western Samoa, other insect and disease problems have arisen. In Fiji large numbers of trees develop pocket rot or severe heartrot, and pinholes caused by ambrosia beetles are very common (Mayhew and Newton, 1998). This problem has become so severe that market loss for Fijian mahogany has been predicted (Cown *et al.*, 1989).

Pre-screening of soils for presence of pathogens or insects may avoid future problems, and this could be part of a general soil analysis. These and other plant protection strategies, including firebreaks or other control measures, and the expectation for the use of some chemical or biological controls should all be part of a comprehensive IPM program. Post-harvest measures may also be required, especially to protect recently felled logs from sap-staining fungi or insects, which can lower value or even lead to refusal by export markets (Kim *et al.*, 2005).

The heartrot problem previously mentioned for *Acacia mangium* provides an interesting case study to examine in greater detail. This species is native to just three small islands in the Moluccas and parts of Irian Jaya in Eastern Indonesia (Pinyopusarek *et al.*, 1993), but has been planted widely in Indonesia (comprising more than 80% of planted forests) and Malaysia (Lee, 2002; Rimbwanto, 2002; Nair, 2000). Based on several studies, we know that the incidence of heartrot is greater in some areas than others. For example, it is greater in most of Malaysia than in Indonesia, but even within Indonesia the incidence can vary from 6.7% in East Kalimantan to 46.7% in West Java (Barry *et al.*, 2004; Nair, 2000). In general the heartrot is greatest in areas that are continually moist with higher total rainfall than in areas that have less total precipitation and have a definite dry period (Barry *et al.*, 2004; See and Arentz, 1997). See and Arentz (1997) have suggested that where rainfall is heavier and no seasonality exists, entry of decay fungi through dying branches might be enhanced. However, another explanation could be that heartwood extractives are reduced on the wetter sites due to greater soil leaching of precursors and the dilution effect, previously mentioned, for more rapidly growing trees. Evidence to support this theory can be found in the very recent research on heartwood extractives in affected and unaffected *A. mangium*, and comparisons with the more heartrot resistant *Acacia auriculiformis* (Barry *et al.*, 2005; Mihara *et al.*, 2005; Lange and Hashim, 2001). The take home lesson is to be very careful when establishing planted forests in areas that have different seasonality and precipitation regimes from the native habitat; the risks are often quite large.

IV. Summary Prescriptive Advice

The following discussion applies primarily to planted forests that will exceed a few hectares in size. Small-scale (1-2 hectare) woodlots can also be important components of the wood supply, but inputs such as seedlings, fertilizer, technical advice, as well as commitment to purchase the timber at harvest are often, in these cases, provided by private timber companies (Cellier, 1999). Even in these situations, however, some of the following discourse may empower the woodlot owner to establish more equitable agreement terms with the timber companies.

Two Approaches for Planted Forests

Two distinctly divergent approaches to planted forests are developing, and each has parallels in agriculture. Both are outlined here, and the choice of which path to follow will depend on the particular circumstances facing a manager.

Intensive Management Model. While hunter-gatherer societies once used more than 200 local species of plants and animals for food annually, the entire global population today relies for 70 percent of its food intake on only nine plant species, one bird and a few mammals. Sutton (1999) and others predict that planted forests will follow the same path and “we may

eventually get most of our wood from four or five species". This small handful of species will need to be highly responsive to genetic manipulation and stand management. A clear parallel in agriculture is the intensive domestication and genetic manipulation of cereal grain crops – and the accompanying global cultural adaptation to these grains. By the use of genetic engineering techniques, the usually long period required for introducing trait changes into trees may be shortened considerably (Tournier *et al.*, 2003; Walter *et al.*, 1998). Attempting to predict which tree species will become the final four or five candidates is futile, but, based on current interest and research, genera likely to be considered are *Pinus*, *Eucalyptus*, *Populus*, *Acacia* and some in the Verbenaceae (Raymond *et al.*, 2004; Seling *et al.*, 2001; Sutton, 1999; Turnbull, 1999; Wingfield & Robison, 2004; Pandey & Brown, 2000).

This intensive management scenario is most attractive to large industrial forestry enterprises (with parallels in agri-business). Although a disputed topic (Powers, 1999), some argue that intensively managed plantations can be healthier than indigenous forests, and have the potential for long-term sustainability (Gadgil and Bain, 1999; Evans, 2005). The establishment of predictable market conditions would, theoretically, provide long-term supply and demand parity, but may also introduce new challenges for pulp mill managers (Clarke, 2001). Intensive genetic engineering programs should increase productivity, and possibly properties (Lindstrom *et al.*, 2004), over time, as well as theoretically providing the mechanism for controlling insect and disease problems. On the negative side, market maturity, wood productivity increases and improved insect and disease resistance are only future possibilities and they, along with fertilizer and labour inputs, will require large capital investment. The ability to control insect and disease pathogens through genetic engineering is quite speculative at this juncture, especially considering the speed at which pathogens can mutate compared to the time required to introduce genetic resistance into trees (Wikler *et al.*, 2003). In the short term, at least, traditional pest and disease controls will be needed.

Diversified Market Model. Again referring to the agriculture model, although roughly 70% of our plant derived food may come from a very small number of species, the other 30% comes from quite a large number of species and varieties, particularly fruits (including nuts) and vegetables. Although we might survive on the nine plant species comprising the 70%, few would be willing to do so. Furthermore, as underdeveloped segments of society become more affluent, they will likely want a more diversified diet than they have traditionally relied on. This suggests that even if the intensive management model for planted forests becomes a reality, it will not serve all aspects of current market demand, and future market demand may become even more sophisticated. All of this points to a need for planted forests that will meet the needs of a diversified market, particularly as natural forests reach their limits for providing specialty woods.

For example, in New Zealand, as natural forest sources of totara (*Podocarpus totara*), a durable construction timber, and kauri (*Agathis australis*), a valuable boatbuilding wood, have dwindled, planted forests of *Cupressus macrocarpa* have been filling the market gap. Recently, other conifers (*Cupressus lusitanica*, *C. macrocarpa*, and the *Chamaecyparis nootkatensis* x *C. macrocarpa* hybrid) are being tested in demonstration plots as further alternative wood sources for these niche markets (Low *et al.*, 2005). Kauri, itself is now being tested as a planted forest species (Steward and McKinley, 2005). These plantings may be on a smaller scale, utilize a larger number of species, have uneven age structure and have longer rotation ages (Mayhew and Newton, 1998), but will also likely have smaller capital investment requirements and yield higher market prices. Integrated pest control measures and careful matching of soil and climate to tree species will be needed. Market stability over the rotation age could be unpredictable, although for well-known species (teak, rosewood and mahogany) the risk is smaller. Because of longer rotation ages, shorter-term product recovery strategies may need to be incorporated into planning.

A good example is found in India where East Indian rosewood (*Dalbergia latifolia*) is planted as an overstory tree in tea plantations. Tea harvest provides a steady annual income while harvesting of rosewood trees when the crowns provide too much shade, yields occasional very high profits that can be re-invested in new plantations of rosewood and other valuable tree species. Similar opportunities exist with coffee plantations, particularly now that shade-grown coffee brings such a premium price in the market.

In the near-term, some amalgamation of the two models may be a viable solution, but since forestry requires very long-term planning, a manager should decide which of the two models best fits his circumstances and plan accordingly.

Initial Planning

Regardless of the planted forest model of choice or the tree species chosen, five key pre-establishment assessments need to be made before beginning: (1) a social and environmental impact assessment, (2) a legal assessment, (3) a complete site analysis, (4) a market analysis and (5) a tree species adoption assessment. The following provides a brief summary of what is minimally needed in each of these processes, but should not be considered as inclusive. Particular situations will likely require additional research investigation. Additional sources of information on these subjects can be found in the Planted Forest Code (<http://www.fao.org/forestry/plantedforestcode>).

Social and Environmental Impact Assessment

An initial baseline assessment is needed, followed by long-term monitoring through planted forest rotation cycles. Potential environmental perturbations as well as considerations for the rights of indigenous peoples and cultures should be incorporated.³

Legal Assessment

What will be the land tenure situation: Is the land to be purchased or leased or be part of a concession? Do indigenous peoples have traditional land-use rights that need to be addressed? What are the government policies toward planted forests? Are carbon credits a possibility? Does the country have a forestry bureau or agency, and if so what are its laws or regulations? Does the forestry bureau operate more or less independently, or is it subject to political influence? Do export bans apply to certain wood species, and do they apply equally to planted and natural forests? Do government officials recognize forest certification, and if so, by which certifying agencies? How stable is the government and its infrastructure?

Site Analysis

Temperature range and extremes, annual and monthly rainfall (particularly as it relates to seasonality), access to water if needed for irrigation, soil depth, soil fertility, soil chemistry and pH, presence of soil insects or pathogens, topography, aspect, location and distance to primary processing facilities, transportation network and road conditions at various times of the year, available workforce and salary expectations of workers should all be part of an initial assessment prior to planted forest establishment (Wingfield and Robison, 2004; Raymond and Muneri, 2000; Pandey and Brown, 2000; Powers, 1999). Special considerations will be needed for certain species. For example, many planted Eucalypt species have the reputation of 'water pumps' because they have no stomatal control of leaf transpiration and, therefore, can quickly draw down local water tables (Calder *et al.*, 1992). Species for which special heartwood characteristics, such as bio-deterioration resistance, are important need to be carefully matched to soil chemistry and pH, as previously noted. Even minor chemical elements in the soil may be quite important. Boron deficiency can lead to thinner cell walls in *Pinus radiata* (35% thinner in earlywood and 25% thinner in latewood),

³ See the FAO Code of Conduct for Planted Forests for explicit details.

and may also affect lignification of walls (Skinner *et al.*, 2003). These differences can significantly affect strength properties.

Market Analysis

Short-term prospects, long-term expectations, finding specialty niche markets, local vs. export markets, primary processing (portable bandsaws, borate treating tanks) to increase value and to open export market potential, creating markets for crooks, limbs, roots, coppice and non-wood products, all need to be considered during initial planning. If the plantation will be a jointly owned by shareholders, then balancing their needs for short-term return against long-term economic sustainability will need to be part of the planning.

Tree Species Adoption Assessment

In choosing a tree species to plant, precise botanical identification is essential. Trade or common names are often meaningless, vary from place to place and may apply to several species. In some cases companies have established registered trademark names that obscure the true botanical identification. Only documented material with botanical (Latin) designation and source should be accepted. Where different genetic varieties or provenances are available, these need to be precisely identified and documented. Clearly, the choice of species needs to be well integrated with site and market assessments.

Wood Property Issues for Five Planted Forest Types

Tropical to semi-tropical planted forests can be established for a variety of reasons, but if the major goal is wood production most will fit into one of five general categories: (1) softwood plantations for paper or reconstituted wood products; (2) hardwood plantations for paper or reconstituted wood products; (3) softwood planted forest for solid wood or veneer market; (4) hardwood planted forest for solid wood or veneer market; (5) mixed species planted forest producing for various markets. Each of these is critiqued with a set of *wood property issues* and *planting issues* that are most critical to the type. Properties previously discussed at length are only highlighted here - for more details return to the appropriate preceding sections.

1. Softwood Plantations for Paper or Reconstituted Wood Products

Smaller-diameter, shorter rotation stems than are needed for solid wood markets are often acceptable for chip-based products. Desirable properties for paper and panel products are often similar but differ sufficiently that they are discussed separately here.

WOOD PROPERTY ISSUES

- **Paper and Paper Products**

Higher density wood is desirable for increasing pulp yield and improving tear strength, resistance to beating and improving bulk. Best for Kraft paper. Lower density, often juvenile wood produces lower tear resistance and lower yield, but provides paper with high tensile strength and good folding properties. Best for writing and tissue paper; poor for newsprint. Avoidance of compression wood is important because it increases difficulties in pulping, reduces yield and is wasteful of chemicals. Knots, decay and bark contaminants reduce yield, are wasteful of chemicals and if not removed can produce unacceptable paper - even low-value tissue.

- **Wood-Based Panel Stock**

For most chip and particle-board products a relatively low density is preferred – generally between 0.25 and 0.45 g/cm³ (Zhang and Gringas, 1998). Higher density woods are difficult to compress and produce panels of excessive weight. Gradual-transition softwoods provide more uniform chips, but abrupt-transition species that are growing rapidly in moist-tropical regions may produce similar, low-density, uniform chips – *Pinus radiata*, for example. The presence of compression wood dulls knives, lowers yield and can introduce weak pockets due to poor adhesion with resin. A low threshold of knots, decay and bark contaminants is often permitted, but excessive knots can quickly dull knives and produce unacceptable product.

PLANTATION MANAGEMENT ISSUES

- Since juvenile wood with low density is acceptable for many paper and reconstituted wood panel products, trees can be planted with wide spacing and fertilized and irrigated if necessary, but early pruning is necessary for capturing most markets and gaining highest return. Tree spacing needs to be uniform to avoid unbalanced crowns that will increase the percentage of compression wood. Because the trees will be widely spaced, very windy sites, especially those with a prevailing wind from one direction should not be chosen as this will lead to excessive amounts of compression wood. If species are planted as exotics or in climates different from indigenous sites, wood property changes need to be anticipated and assessed for acceptability. In general, abrupt transition conifers will have lower density and less prominent latewood when moved from warm-temperate to moist-tropical conditions. Choosing improved provenances, if available, may be cost effective in some cases. Insect and disease management will be critical in these monoculture plantations.

2. Hardwood Plantations for Paper or Reconstituted Wood Products

As is the case for softwoods, small diameter stems are generally acceptable. Paper is the primary market except for low density species like *Populus* or *Gmelina* that also can be used for panel stock.

WOOD PROPERTY ISSUES

- **Paper and Paper Products**

Fiber length is shorter in hardwoods than softwoods, and when combined with thicker walls can yield paper with lower tear strength. Higher density hardwood pulp is generally ideal for kraft paper especially if mixed with fiber from a higher density conifer, such as *Pinus caribaea* (McNabb and Wadouski, 1999). The low density, juvenile wood of very short rotation Eucalypts and *Gmelina spp.* yield fiber best suited for tissue, writing and printing paper (Campinhos, 1999). Harvesting Eucalypts, before the age of 6 or 8 years also avoids wood that has high polyphenolic extractive content which greatly increases the difficulty in chemical pulping (Zobel, 1984).

- **Wood-Based Panel Stock**

Low density species, such as *Populus spp.* and *Gmelina spp.*, can be chipped for board stock (Heilman, 1999). Higher density species can provide furnish for laminated veneer lumber (LVL) or finger-jointed lumber, but larger diameter stems are generally required than for paper.

PLANTATION MANAGEMENT ISSUES

- Basically the same issues exist for hardwoods as were noted for softwoods, except that juvenile wood is much less a concern and tension wood is the form of reaction wood in these trees. Internal stresses could become a problem if trees are grown to larger diameters.

3. Softwood Planted Forests for Solid Wood or Veneer Markets

Although some new, thin-kerf, bandsaw mills can handle small diameter logs, the yield is so low this is generally impractical. Both the lumber and veneer markets will require larger diameter logs. Most softwood lumber and ply markets are focused on construction materials; hence strength properties rather than aesthetics dominate. However, smaller niche markets, such as furniture, boatbuilding and musical instruments may require some combination of mechanical properties, resistance to bio-deterioration and aesthetics.

WOOD PROPERTY ISSUES

- Increasing stem straightness and decreasing taper are key ingredients to improving lumber or veneer yield; and for many products knots need to be limited. Wood density will be a primary concern as a direct monitor of bending strength and stiffness. The proportion of juvenile wood and compression wood need to be limited. In cases where significant proportions of juvenile wood are permitted timber design standards will need to be adjusted to avoid compromising current standards (Anonymous, 2006; Kretschmann, 1997).

PLANTED FOREST MANAGEMENT ISSUES

- Trees destined for lumber or veneer markets will require closer spacing at planting, with one or more pre-commercial or commercial thinnings. Pruning will ensure the highest value markets. Planting trees outside their natural climate ranges or seasonality limits may lead to timber production that fails to meet minimum acceptable wood density and strength standards (Turner *et al.*, 2001; Zobel, 1984). Abrupt-transition conifers will require the greatest scrutiny. The use of genetic varieties may overcome some of these problems, but provenance trials will be needed before committing to large-scale planting. For specialized markets where bio-deterioration resistance is important, soil analyses may be critical. Disease and insect pest control will be critical factors in the success or failure of these longer-rotation monocultures.

4. Hardwood Planted Forests for Solid Wood or Veneer Markets

Unlike the situation for softwoods, aesthetic considerations are often key factors in many hardwood markets (furniture, flooring, panelling). But mechanical and physical properties such as strength (furniture), hardness (flooring), dimensional stability (boat decking, garden furniture) or sound transmission (musical instruments) also may be very important to consider. The range of hardwood market niches is broader than for softwoods, generally requiring more specialized attention in species choice, matching to site and management practices.

WOOD PROPERTY ISSUES

- For solid wood and surface veneers of plywood, properties that closely match those found in wood from natural forests is generally the goal. Interior plies of furniture or panelling grade plywood are often produced from a low density hardwood that is easy to peel, with surface plies of a decorative wood. Exterior and marine grades have the highest quality requirements (knots and voids) and are generally made from a single species. Biodeterioration resistance may be a requirement for some markets. A minimum log diameter is generally required for veneer, and juvenile wood is to be avoided.

PLANTED FOREST MANAGEMENT ISSUES

- Many of the same issues listed for softwoods apply here, although the market niches are so diverse that management strategies need to be closely linked to market expectations. Soil pH and chemistry may be critical for producing expected heartwood colour and decay resistance. Since longer rotations will be needed for many markets, a mix of species with differing harvesting ages may be desirable. Agro-forestry, particularly using valuable hardwoods as shade for tea and coffee plantations, can provide steady income during a long rotation age. Uneven age management can also provide benefits for shade tolerant species or for controlling shoot borers or other insect pests.

5. Mixed Species Planted Forest Producing for Diverse Markets

This category comes closest to natural forest management, except the species mix is more controlled by not relying on natural regeneration. Species such as mahogany are particularly adapted to this sort of strategy, especially when combined with faster growing species to bring early financial returns. Shoot borer attack of mahogany in a mixed, multi-story canopy, planted forest is minimized as well. Wood property and forest management issues are basically the same as noted in the previous sections, but even more attention to specialty markets may be possible (crook timber for boatbuilders, musical instrument woods, etc.).

CONCLUDING REMARKS

- 1) Planted forests will become the dominant source of production timber within the next two or three decades.
- 2) Demand for wood as a raw material will increase or decline in direct proportion to the capacity of planted forests to provide material that meets consumer expectations.
- 3) Use of engineered wood products, derived mostly from intensively managed plantations, should continue to expand in housing and other construction areas. Markets for inexpensive laminate/particleboard composites for flooring, doors, furniture and other products may remain high in some sectors, but if historical trends are any indication solid wood (if quality can be maintained) is likely to erode some of those markets, especially among aging, more affluent populations.
- 4) Less well-known woods, particularly hardwoods, from natural forests are filling market niches where better-known species are in short supply. As some of these 'new' woods become better known, they may also become important planted species.
- 5) Before key genetic traits in trees in natural forests are further eroded by logging practices that favour the "best" trees, the remaining genetic resources need to be captured and used as the basis for tree improvement in planted forests.

- 6) Two types of commercial planted forests are proposed to meet consumer needs: one that relies on engineering technology to reconfigure wood biomass into useful consumer products; and a second type that provides for the diverse demands for wood in its natural form, with properties matched to specific products.
- 7) Planning for planted forests is needed now in order to anticipate consumer demand for wood two or more decades away.
- 8) If demand for wood should decline because we fail to anticipate consumer needs, other materials (particularly petrochemicals and metals) will fill the void, and this will limit possibilities for rural development, exacerbate the depletion of non-renewable resources and hinder the potential for carbon storage.
- 9) If planted forests are unable to meet consumer demand for the highest value woods for applications where non-wood substitutes are not a viable option, irresponsible or illegal logging of natural forests will likely be accelerated, leading to further loss of endangered tree species.

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Appendix I. Wood Quality Can Be a Subtle Attribute

How valuable is Wood?

We all know that certain woods, like Brazilian rosewood (*Dalbergia nigra*) for example, because they have beautiful grain pattern and come from trees that are in very short supply, often growing in locations that are difficult to access, have very high market value. Yet very common woods harvested from the right trees and handled in special ways can sometimes yield even higher prices. Some of the most valuable wood in the world today is found in the violins built by Stradivari and his contemporaries in Cremona, Italy from about 1664 to 1737. Today these violins sell for more than a million US dollars each. Until recently all the credit for the unique tone of those violins had been lavished on the violin builders. Certainly they were very skilled luthiers and knew how to carve the spruce tops to maximize sound transmission, but we now know that some of the credit for the special tonal properties of these musical instruments is attributable to how the spruce trees grew and how the logs were subsequently handled.

Recent research by Burkle and Grissimo-Mayer (2003) has revealed that spruce trees growing in the Italian Alps that provided the wood for the Cremona luthiers, grew during a particularly cold period in Europe known as the Maunder Minimum. Because the growing season was shorter and cooler the trees grew more slowly than normal, producing narrower rings and thereby increasing the volume of latewood, where sound is transmitted the fastest. High speed of sound transmission or 'response' allows a violin to capture and radiate all of the notes produced by the strings.

Of equal importance was how the spruce logs were handled before milling. During this period the spruce forests were under the absolute control of the Republic of Venetia. Spruce logs cut in the Italian Alps were transported by streams and rivers to Venice where they could be inventoried. Often these logs remained ponded in the Venetian lagoon for up to five years, during which time these green logs absorbed sea salts by diffusion. Based on laboratory tests (Erickson and Rees, 1940), we know that conifer wood impregnated with chloride salts, such as NaCl or MgCl, have compression strength improved by 25% or more. This added compression strength prevented the arched violin top from undergoing creep under the constant pressure of the strings, and, in addition, allowed the luthiers to experiment with thinner tops to improve sound transmission.

As managers, we cannot control future weather patterns or even wait for five years while logs steep in a brine solution, but we can manage planted forests to match the quality of the wood with anticipated market demands.