A review of the effects of silviculture on wood quality

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Abstract

This paper reviews the effects of silviculture on wood quality. The term silviculture is employed to encompass a broad range of forest management practices which may alter a forest's composition, growth, and environment. Generally, the main components for assessing wood quality for structural purposes are strength, stiffness, and dimensional stability; while pulp and paper quality requirements include strength, tracheid dimensions, and chemical composition. The quality of wood is determined through various wood characteristics such as: density, microfibril angle, proportion of juvenile wood, fibre length, compression wood, and knots. The following sections will discuss how these wood properties affect end use quality of raw materials. The quality can be affected by various silvicultural techniques both at the microscopic and macroscopic levels. Silviculture treatments are most often implemented with the goal of manipulating tree growth to enhance vigor or crown size. Common treatments include spacing, respacing/thinning, pruning, and fertilization. Techniques following this approach are ultimately linked to the resulting wood characteristics. The review is separated into three major sections. The first section concerns properties and their effect on wood quality. Next, the effects of silvicultural on wood properties and characteristics will be discussed. The report concludes with considerations and recommendations in regards implementing each silvicultural technique are and how they can be applied to best meet the end-user requirements of wood quality. Finally, several recommendations are provided for where further research should be focused.

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Introduction

This paper reviews the effects of silviculture on wood quality. The term silviculture is employed to encompass a broad range of forest management practices which may alter a forest's composition, growth, and environment.

The review is separated into three major sections. The first section concerns properties and their effect on wood quality. Next, the effects of silvicultural on wood properties and characteristics will be discussed. The report concludes with considerations and recommendations in regards implementing each silvicultural technique are and how they can be applied to best meet the end-user requirements of wood quality. Finally, several recommendations are provided for where further research should be focused.

A Changing Resource

The raw material base for forest products is increasingly shifting from old-growth forests to both second-growth forests and plantation-stock (Kennedy, 1995). This shift is indicative to most of the wood species used commercially and is generally, characterized by shorter rotation periods in harvesting (Bendtsen, 1978). This changing raw material source is of concern to manufacturers of forest products, namely lumber, panel products, and pulp and paper because differences have been observed between the properties of old-growth and younger stock. While some of the changes in wood properties have been desirable for some end uses, many have been undesirable. This discrepancy brings up the question: what determines wood's quality?

Definition of Wood Quality

The term 'wood quality' is widely used, but cannot be defined in one specific way. Wood quality is defined as: the attributes that make logs and lumber valuable for a particular end use (Joza & Middleton, 1994). The wide scope encompassed by this definition creates ambiguity in the matter because desirable attributes in one product may not always coincide with the desirable attributes in another product.

In the production of pulp and paper, low density wood combined with long fibres results in collapsible, easy bonding fibres that exhibit low porosity and high strength (Joza & Middleton, 1994). These fibre characteristics result in higher quality paper products. Conversely, structural lumber manufacturing requires wood with high density, small knots, and straight grain characteristics to ensure a high quality product (Joza & Middleton, 1994). Also, the stiffness, or modulus of elasticity (MOE), is an important characteristic associated with the structural quality of lumber (Johnson & Gartner, 2006). The raw material requirements for plywood prioritize the same characteristics used in determining wood quality for lumber products. Generally, the main components for assessing wood quality for structural purposes are strength, stiffness, and dimensional stability; while pulp and paper quality requirements include strength, tracheid dimensions, and chemical composition. The quality of wood is determined through various wood characteristics such as: density, microfibril angle, proportion of juvenile wood, fibre length, compression wood, and knots. The following sections will discuss how these wood properties affect end use quality of raw materials.

Wood properties affecting quality

Density

Wood density, or specific gravity, is considered the main characteristic for determining the mechanical properties of lumber and the resulting yield of pulping processes (Hapla, Oliver-Villaneuva, & Gonzalez-Monila, 2000). Relative density of specific gravity is defined as the ratio of cell wall substance to lumen volume in wood (Kennedy, 1995). The importance of density is increased because it is a property which directly influences many wood attributes including strength, shrinkage, and pulp yields

(Joza & Middleton, 1994). These attributes, in combination with density, ultimately affect the suitability of the timber to be processed into lumber, panel products, or pulp and paper.

Density is directly related to clear wood strength (Bendtsen, 1978). Therefore, the structural performance of timber is often associated with its density. In a study of Eucalyptus trees, their density alone accounted for 81 percent of the variation in their MOE (Yang & Evans, 2003). Generally, wood with higher specific gravity is used for applications that have high strength demands. However, the sole use of density is not always the most accurate means of assessment to predict structural lumber's mechanical properties. Zhang (1997) found that density only partially influences the stiffness (MOE) and other mechanical properties of softwoods; furthermore, its degree of influence differs between individual mechanical properties. Finally, Zhang determined the relationship between MOE and density is best represented in a non-linear function. Therefore, the prediction of lumber's mechanical properties based solely on density may not always provide accurate valuation.

Wood density is also shown to affect the various shrinkages that occur during wood drying. Density has a positive relationship for both radial and tangential shrinkage but also has a negative correlation for longitudinal shrinkage (Pliura, Yu, Zhang, MacKay, Perinet, & Bousquet, 2005). Density, or specific gravity, is determined by the percentage of cell wall material. The proportion of tissue is a key anatomical factor in the volumetric shrinkage of wood (Zhang & Zhong, 1992). Supporting research states that density with chemical composition, contributes to shrinkage predictions, and bares a level of influence that varies for longitudinal and tangential directions (Leonardon, Altaner, Vihermaa, & Jarvis, 2010).

For wood panel products, density is an important characteristic for strength. The strength of panel products is usually limited by the strength of the wood used. Adhesive-wood bond strength increases with density, to a point, and then decreases with a further increase in wood density (Vick, 1999). The eventual decrease in strength that occurs in very high density wood is due to the adhesive's limited ability to penetrate the wood cells. Furthermore, the dimensional changes that occur during a change in moisture content are associated with high density wood (Pliura et al., 2005) significantly contribute to bonding difficulties (Vick, 1999). These issues concerning high density wood and adhesive bonds make lower density wood a favourable substitute. Lower density wood provides more contact surface area for glue bonds as well as more uniform and tighter finished products. The described behavior of lower density wood improves inter-wood stress transfer resulting in higher bending properties and more uniform mechanical properties (Hsu, 1997).

In pulp and paper, density is an important characteristic because it affects various end use properties. Relative density, in combination with other wood attributes, tracheid length, and cellulose/lignin ratio, influences both the yield and quality of pulp that can be produced from the wood of a single tree (Kennedy, 1995). An increase in density results in increased pulp yield, tear strength, and beating resistance; however, it causes decreased tensile strength, burst strength, and folding endurance (Gingras & Zhang, 1999). Low density wood produces pulp with more collapsible fibres, promotes bonding, and reduces porosity (Joza & Middleton, 1994). Similarly, a study of wood characteristics affects on pulp and handsheet properties showed high density woods produce bulkier, stiffer, and higher porosity sheets; while, lower density woods produced smoother, denser sheets with higher tensile strength (Wimmer, Downes, Evans, Rasmussen, & French, 2002).

Microfibril Angle

The Microfibril angle (MFA) is defined as the angle between the cell axis and the cellulose microfibrils (Neagu, Gamstedt, Bardage, & Lindstrom, 2006). It is commonly studied in reference to the S2 layer MFA of the cell wall. A decrease with age is a common trend for MFA. MFA is largest in the innermost rings and decreases in the rings further from the pith (Lindstrom, Evans, & Verrill, 1998). Also, MFA decreases for the same ring at higher positions within a tree observed by Bergander and Brandstrom (as cited in Neagu, et al., 2006) and is larger in the large growth rings of fast growing trees.

MFA has been shown to partially control the mechanical properties of wood cells and has a significant effect on wood and fibre product properties (Neagu et al., 2006). An increase in MFA results in greater longitudinal shrinkage (Barbour, Marshall, & Lowell, 2003). A review, written by Neagu et al. (2006), supports the statement that longitudinal shrinkage increases and transverse shrinkage decreases with increasing MFA. Furthermore, the differential shrinkage that occurs in wood is mainly attributed to MFA (Zhang & Zhong, 1992). MFA variability within a piece of lumber can result in decreased dimensional stability during drying due to the non-uniform shrinkage associated with MFA. The MFA of wood also affects its stiffness. In a study of Eucalyptus wood, MFA accounted for 87 percent of the variation in MOE (Yang & Evans, 2003). MOE is extremely sensitive when MFA is less than fifteen degrees (Neagu, et al., 2006). Therefore, the mechanical performance of lumber and panel products is affected by the MFA of the raw material. Pulp and paper is also affected by the MFA of the wood fibres used in production. The tensile strength of wood is closely related to MFA (Zhang & Zhong, 1992). Joza & Middleton (1994) also state that a large MFA causes increased warping and lower strength and stiffness in lumber products, and lower strength in paper fibres. An inverse relationship between tracheid length and MFA is apparent and makes wood fibres with large MFA values less desirable for use in paper products (Bonham & Barnett, 2001).

Juvenile Wood

Juvenile wood is defined as the annual rings closest to the pith produced under the influence of the apical meristem and the live crown; wood formed below the live crown is referred to as mature wood (Walker, 2006). Trees grown in faster rotations produce higher proportions of juvenile wood (Bendtsen, 1978). As the juvenile wood zone reaches maturity, wood characteristics are constantly changing (Kennedy, 1995). The change from juvenile wood to mature wood cannot be specifically defined to a particular annual ring because particular wood properties reach a mature stage at different times (Bendtsen, 1978) with differing degrees of abruptness (Kennedy, 1995). However, the transition from juvenile to mature wood usually occurs between five and twenty rings depending on the tree's species cross section at a given height within the stem (Bendtsen, 1978).

Juvenile wood, in comparison to mature wood, is characterized by having shorter tracheids, thinner cell walls, and lower density, lower transverse shrinkage, and lower strength. Also, it contains more compression wood, higher moisture content, and a larger: MFA, lumen diameter, and longitudinal shrinkage (Bendtsen, 1978). The characteristics of juvenile wood result in lumber with decreased strength and poor dimensional stability. The MOE of lumber completely comprised of juvenile wood can be 50-60% lower than mature wood lumber (Gingras & Zhang, 1999). The slender collapsible fibres of juvenile wood may be more suitable for pulp and paper products. However, suitability depends on the end-use specifications. Juvenile wood fibres bond well because of their collapsibility and improved inter-bonding. Both factors result in a high tensile strength (Kennedy, 1995). These characteristics make juvenile wood a suitable raw material for writing paper, but the low tear strength (Kennedy, 1995), and opacity of juvenile wood fibres make it unsuitable for newsprint (Gingras & Zhang, 1999).

Tracheid Length

Tracheid length is proportional to the age of an annual ring and is inversely proportional to ring width. Lindstrom (1997) found tracheid length is dependent on a logarithm of cambial age and growth ring width. These findings are supported by Bannan (1954) who observed shorter tracheid development during periods of accelerated growth and longer tracheid length development when growth rates were decreased. Tracheid length increases with tree height causing intra-tee variability that greatly differs between species (Neagu, et al., 2006). Tracheid length is also inversely proportional to MFA. A study of Silver Birtch trees reported that MFA decreases and fibre length values increase to minimum and maximum values, respectively, reaching maturity at the same annual ring (Bonham & Barnett, 2001). This suggests fibre length and MFA characteristics are closely related. A review of several studies on the relationship confirms a strong, negative correlation between tracheid length and microfibril angle (Fabris, 2000).

While tracheid length is regarded as less important to solid wood products, it is an important characteristic influencing the mechanical properties of wood pulp. For example, long fibres are desirable for paper requiring high strength characteristics for its end use (Gingras & Zhang, 1999). A study of fibre length determined that it has a strong, direct effect on tear index, bending stiffness, and pulp yield (Wimmer et al., 2002).

Compression Wood

Compression wood is formed on the underside of leaning stems. Ring formation is often characterized by the lower side of these leaning stems having abnormally wide growth rings that cause the pith to be off-center (Walker, 2006). It is thought to develop due to stress on the stem, namely gravity, but is also found to be produced in juvenile wood of trees experiencing rapid height growth (Barnett & Jeronimids, 2003).

Compression wood has different anatomical, chemical, and physical characteristics compared to normal wood. Compression wood tracheid dimensions are more rounded in their cross-sectional plane and have a thicker cell wall (Walker, 2006); also, their cell length is reduced (Plomion, Leprovost, & Stokes, 2001). Compression wood’s density can have increased values 50% higher relative to normal wood. High concentrations of compression wood resulted in a 22% increase in density relative to the opposing wood in the cross section (Donaldson, Grace, & Downes, 2004). Also, MFA is often much larger in compression wood with an upper range of 30-45^{o} (Plomion et al., 2001; Walker, 2006; Sahlberg, Salmen, & Oscarsson, 1997). Boone & Chudnoff (as cited in Bendtsen, 1978) performed a study that found an increase in the percentage of compression wood being associated with a decrease in bending stiffness. Furthermore, the lignin to cellulose content ratio is higher in compression wood (Walker, 2006).

The aforementioned characteristics of compression wood have adverse effects on its suitability for solid wood products. While compression wood has a higher density and is stronger in compression than normal wood, it is very brittle due to its tracheid dimensions (Ayrilmis, 2008); also, it fails without warning (Barnett & Jeronimids, 2003). The large MFA associated with compression wood causes increased longitudinal shrinkage; thus, it experiences reduced dimensional stability and a greater occurrence of warp when dried (Barnett & Jeronimids, 2003; Plomion et al., 2001). Compression wood experiences 10-20 times greater shrinkage compared to normal wood (Joza & Middleton, 1994). Therefore, it is undesirable for use as dimensional lumber or in other structural applications.

Compression wood also has negative effects on panel products. The effects of dimensional changes due to moisture content in medium density fiberboard (MDF) containing compression wood resulted in increased thickness swell and shrinkage values (Ayrilmis, 2008). Therefore, the occurrence of compression wood has a negative effect on the dimensional stability of MDF panels.

For pulp and paper processing, compression wood is an undesirable raw material. Compression wood decreased pulp yield (Plomion et al., 2001) partially because the fibres do not refine well (Joza & Middleton, 1994). The compression wood fibres are even less desirable because the increased lignin content results in higher operating costs during pulping; furthermore, the tracheid dimensions of compression wood fibre in conjunction with a high MFA impair its ability to flatten and fibrillate during papermaking (Barnett & Jeronimids, 2003).

Knots

Knot size and frequency are known to negatively impact the quality of wood in its end use. The negative effects of knots on wood properties depend on both knot size and frequency. A review by Aubry et al. (1998) determined a trend of MOE decreasing as knot size increased. The MOR of wood is shown to have a negative correlation with knot size (Grant, Anton, & Lind, 1984). The strength of wood, both in compression (Aubry et al., 1998) and tension (Kunesh & Johnson, 1972) is reduced due to the occurrence of knots. The surrounding decreased strength and stiffness of wood with to knots is attributed to the distorted grain surrounding knots. This distorted grain is an area where failure commonly occurs (Aubry et al., 1998; Riyanto & Gupta, 1996). The magnitude of knots' negative impact on the mechanical properties of wood is ranked in decreasing severity: tensile strength, MOR, parallel to grain compression strength, and MOE (Phillips, Bodig, & Goodman, 1981).

The adverse effect of knots on wood reduces its quality for several end uses. Structural applications of lumber are greatly affected by the occurrence of knots. Solid wood samples with over 50% knot area were tested in bending and had half the average MOE and MOR compared to samples with less than 20% knot area (Zhou & Smith, 1991). Lumber grading rules reflect the effect of knots by degrading lumber with large knots; lumber with a high occurrence of knots is also assigned a lower grade (Barnett & Jeronimids, 2003; Aubry et al., 1998). The use of wood with knots may also be less desirable for pulp and paper end uses. Wood developed on the stem directly underneath knots tends to be compression wood (Shepard, Shottafer, & Bragg, 1991; Walker, 2006). As previously discussed, compression wood is harder to process in terms of pulping and results in lower quality paper products. Knots themselves are difficult to penetrate with chemicals, causing them to be inadequately pulped. They are also resistant to defibration during mechanical pulping (Walker, 2006).

Effects of Silviculture on Wood Quality

Silviculture is the process by which forests are tended, removed, and replaced by new trees (Matthews, 1989). It is also defined as the manipulation of a forest stand to suit the needs for a particular end use (Kohm & Franklin, 1997). All of the properties discussed in the above sections are integral to the effective quality of wood when applied towards particular end uses. The quality can be affected by various silvicultural techniques both at the microscopic and macroscopic levels. Silviculture treatments are most often implemented with the goal of manipulating tree growth to enhance vigor or crown size. Common treatments include spacing, respacing/thinning, pruning, and fertilization. Techniques following this approach are ultimately linked to the resulting wood characteristics. Many of the techniques that change growth rates will compromise the resulting wood characteristics. Growth rate is important in silvicultural practices but it is not the focus of this paper. Therefore, one should remember that silvicultural induced growth rate changes may contribute towards, or be the cause of, observed variation in wood characteristics. The next section of this paper reviews the effects of several silvicultural techniques on the previously discussed wood properties.

Spacing

Stand spacing is one of the most common silvicultural techniques implemented (Matthews, 1989). Spacing is the distance between newly planted trees decided during the initial planting and will greatly affects the growing conditions of the trees. It determines how competitive trees will be with one another. Increased spacing results in less inter-tree competition which results in larger and longer living crowns leading to faster diameter growth (Hapla et al., 2000). However, wide spacing can also have negative effects on wood quality.

The larger crown size associated with wider spacing results in a larger juvenile wood core (Jiang, Wang, Fei, Ren, & Liu, 2007; Zobel, 1992; Barbour et al., 2003). The larger juvenile wood core is a result of prolonged juvenile wood growth before the base of the live crown dies and the transition from juvenile wood to mature wood occurs and is compounded by the faster growth rate of the trees (Kennedy, 1995). In this scenario, knot size and frequency are larger and more frequent (Barbour et al., 2003). The effect of wider spacing on knots is due to spacing’s effect on crown size (Hapla et al., 2000). The increased longevity of live crown at wider spacing causes increased knot size as branches have a longer growth period (Benjamin, Karshaw, Weiskittel, Chui, & Zhang, 2009). A study of varied stand densities suggests that the diameter of braches and the number of thick branches near the base of the tree increases with an increase in spacing (Deans & Milne, 1999). Similar results were found when comparing a 1,500 trees/ha spacing to three higher stand densities (Kasai, Yokota, Iizuka, & Yoshizawa, 2005). It is possible that the formation of compression wood is also increased with wider spacing (Barbour et al., 2003).The increased occurrence and size of knots likely attributes to the increase in compression wood formation observed.

Spacing has been observed to have either no significant effect on, or a positive correlation with microfibril angle (Barbour et al., 2003). A study of Western Hemlock revealed similar development patterns of MFA across the annual ring profiles for Western Hemlock regardless of the spacing (Fabris, 2000). The average MFA is not significantly affected by differing stand densities (Kasai, Yokota, Iizuka, & Yoshizawa, 2005). However, a study of *Pinus radiata* found that increased spacing from a stand density of 2500 stems/ha to 833 stems/ha resulted in a 15% increase in average MFA (Lassere, Mason, Watt, & Moore, 2009).

Wider spacing is attributed to a lower wood density in some reviews (Kennedy, 1995; Hapla F. , 1997). A study of Jack pine (*Pinus banksiana Lamb.)* stems spaced 2.7m, with comparable DBH to stems spaced 1.5m, observed density decreases of 4-18% (Kang, Zhang, & Mansfield, 2004). However, a large majority of papers reviewed suggest that initial spacing has either an insignificant or negligible effect on wood density (Fabris, 2000; Barbour et al., 2003; Jiang et al., 2007; Zobel, 1992). Of whom Deans & Milne (1999) support this conclusion by suggesting that most vigorous trees in closely spaced stands, which have large juvenile cores, will probably survive in closely spaced stands when self thinning occurs. Therefore they would likely have comparable proportions of juvenile core wood.

Similar to wood density, fibre length is generally unaffected by spacing (Barbour et al., 2003; Zobel, 1992). Supportive findings were observed in two separate studies of western hemlock and Sugi (Fabris, 2000; Kasai et al., 2005). While a qualitative trend of decreasing fibre length with increasing stand density was noticed in a study, by Jiang et al. (2007), of *Populus xiaohei*, spaced at 1000, 500, and 250 stems/ha, their statistical analysis revealed spacing had no significant effect on fibre length.

However, one study of *Pinus radiate*, spaced 2500 stem/ha, produced a 12% increase in fibre length compared to an 833 stem/ha spacing (Lassere et al., 2009). Decreases in fibre length for Jack Pine with increasing spacing, however slight, were deemed to be large enough to hinder the quality for use in paper products (Kang et al., 2004).

Spacing greatly affects the quality of wood. An increase in tree spacing adversely affects the mechanical properties of wood produced (Hapla F. , 1997). These decreases are, in a large part, due to the size and number of knots developed in wide spacing (Zobel, 1992). A 35% increase in MOE was observed in a 2500 stems/ha stand in comparison to an 830 stem/ha stand (Lassere et al., 2009). The spacing trial performed by Jiang et al. (2007) also resulted in the 1000 stem/ha stand with the highest MOE and compression strength, while MOR peaked at 500 stems/ha. The MOE followed a similar trend for Sugi stands ranging between 1,500-10,000 stems/ha (Kasa et al., 2005). The study also found the MOR to be positively correlated with a maximum value in the 10,000 stems/ha stand. However, there was no observed change in MOR between 10 year old red alder, or sycamore, spaced at 2500 stems/ha and 400 stems/ha respectively; however, greater compression strength and MOE resulted from closer spacing (Mmolotsi & Teklehaimanot, 2006).

These results show that increased spacing can have adverse effects on wood intended for structural purposes. In addition, increased spacing could potentially be a problematic issue for wood end use in high quality paper production because of resulting decreased fibre length and increased knot size and frequency. A dense initial spacing can be utilized and subsequently reduced in stand development. This is discussed in the next section.

Respacing and Thinning

Reducing stand density after initial planting is another silvicultural method used to decrease competition between trees. It bares several implications for the properties of wood produced. This modification is implemented at the pre-commercial or commercial stage of tree development. Precommercial thinning, or respacing, is the removal of trees, ranging from newly planted trees to developed trees with a wood value less than the cost of harvesting. Thus commercial thinning, or thinning, pertains to the removal of merchantable trees (Barbour et al., 2003). Respacing can be used as a 'weeding operation' to remove competing trees at a very early age, either within two years of planting or when, and if, low pruning is performed. Both respacing techniques promote rapid growth for un-felled trees (Evans & Turnbull, 2004). Early respacing, prior to canopy closure, has effects similar to the initial spacing on wood properties and quality (Barbour et al., 2003; Moore, Achim, Lyon, Mochan, & Gardiner, 2009; Hussein, Gee, & Watson, 2006). The similarities of effects are observed because respacing occurs before the live crown is forced to compete with adjacent trees (Cameron, 2002). However, respacing is beneficial as it enables the retention of the most vigorous and healthy trees for continued growth and, conversely, the removal of low quality wood producing trees - a benefit also potentially realized with thinning. Thinning has the same effects as spacing, namely, increased: knot size and frequency; occurrence of compression wood; and proportion of juvenile wood. It also has some effect on fibre length, and MFA. The effects of thinning on wood properties are discussed below.

Crown growth increases after thinning and promotes branch growth. Larger branch diameters, and, subsequently, larger knots are produced after thinning (Punches, 2004; Barbour et al., 2003). Again, the larger branch formation and increased crown vigour may cause increased compression wood production in the live crown (Barbour et al., 2003; Barnett & Jeronimids, 2003). Thinning affects crown size and is proportional to juvenile wood production (Barbour et al., 2003). However, juvenile wood growth in the stem depends on how much the crown recedes before the stand is thinned, as it is only produced near the live crown portion of the stem.

Thinning generally causes decreased fibre length and density, and increased MFA (Barbour et al., 2003). Tracheid length is slightly decreased with thinning (Zobel, 1992); however, no differences were found for tracheid length and MFA in a study of *Taiwania cryptomerioides* Hay under various thinning intensities which can likely be due to the young age of trees (Chiu, Lin, & Wang, 2005). A review of research on the thinning Douglas-fir stands concluded that density is only slightly reduced by thinning and that heavy thinning performed on 40-50 year old trees does not impair quality (Hapla F. , 1997). Supportive results from a study of two thinning regimes, of 20% and 22.6% stand basal area removal, resulted in 0.7% and 1.2% density decreases, respectively, relative to the control (Schneider, Zhang, Swift, Begin, & Lussier, 2008).

Thinning has a slightly negative effect on structural wood quality and adversely affects wood quality for pulp and paper end use. Mechanical properties, compressive strength and bending strength, were concluded to only be slightly reduced due to thinning without a loss of wood quality is not lost (Hapla F. , 1997; Wang, 2005). However, Schneider et al. (2008) estimated, using models, that MOE and MOR decrease after moderate thinning (5.8% and 0.7%) and heavy thinning (11.8% and 1.2%) respectively. 12.2% and 15% decreases were observed in MOE and MOR respectively, while a 33.7% loss of top grade lumber was observed by Zhang, Chauret, & Tong (2009) in regards to 35 year old balsam fir heavy respacing.

Pruning

Pruning is performed on branches on the lower portion of the stem with the goal of manipulating wood development. It is an essential silvicultural practice for clear wood production (Viquez & Perez, 2005). Accordingly, the most common goal of pruning is to achieve a higher percentage of clear, knot free wood in the stem (Zobel, 1992; Barbour et al., 2003). A study of hybrid aspens (*Populus tremula* L. & *P. tremuloides* Michx.) found that the time between pruning and clear wood formation was approximately three years, while unpruned trees continually produced lower quality wood due to dead branches (Wiseman, et al., 2006). Therefore, the benefit of clear wood has some delay, but the benefits are continuous thereafter. Pruning regimes for *Tectona grandis* are expected to produce approximately 40% of knot-free volume for a 20 year rotation (Viquez & Perez, 2005). Another benefit of pruning is crown size manipulation, forcing live crown recession, because it minimizes the amount of juvenile wood produced (Barbour et al., 2003). Pruning performed on young Douglas fir trees caused a reaction expected conditional to the maturation of juvenile wood (Gartner, 2005). The radial growth of the pruned area is less affected by the live crown and is likely to reach maturity earlier than that of unpruned trees. There are few existing studies of pruning's effect on compression wood formation and its effect is uncertain (Barbour et al., 2003). Compression wood tends to form on the underside of branches, as discussed in the knot section; therefore it is possible compression wood formation may decrease after pruning is performed.

Pruning's effect on density, microfibril angle and tracheid length is somewhat unclear. Density is generally observed to increase after pruning (Barbour et al., 2003). This relationship is mostly agreed upon, but some studies observe no significant change (Zobel, 1992; Alcorn, Bauhus, Smith, Thomas, James, & Nicotra, 2008). Gartner (2005) studied the effect of pruning, either 3.4 or 5.5 m, on trees age 13, 16, and 18. Ten years after the pruning, Gartner tested the trees and found that density had only increased in the live crown of the youngest trees. No decreases in density were observed in any other areas, likely because limbs removed were either dead or not vigourous; therefore, their contribution was lower. MFA is said to decrease, and fibre length is said to slightly increase after pruning (Barbour, Marshall, & Lowell, 2003). This may be attributed to the reduction of juvenile wood produced after pruning. However, one study of *Taiwania cryptomerioides* Hay found pruning had no effect on either MFA or fibre length (Chiu et al., 2005). Gartner (2005) observed 3-4 years of increased fibre length for the youngest Douglas Fir trees; however, he concluded that pruning has little or no effect on fibre length.

Pruning has favorable effects on wood quality. The elimination of knots is beneficial for all wood end uses. A study of pruning trees used for structural lumber found higher MOE and MOR and a reduced variability for both properties in managed trees and attributed the higher quality to relatively lower knot occurrence (Goto, Nakayama, Ikebuchi, & Furuno, 2009). Another study, on pruning's effect on veneer quality, showed an increased in the proportion of higher grade veneers compared to the control (Gibson, Clason, Hill, & Grozdits, 2001).

Fertilization

Fertilization can be applied as a silvicultural technique to promote growth at various stages of a tree's life. It can be applied to promote the establishment of the tree's root system or to alleviate nutrient deficiencies in sites with poor soil conditions and to support stem development during the high nutrient demand periods of rapid growth (Evans & Turnbull, 2004). Three macronutrients used in fertilization are nitrogen, phosphorus, and potassium; a focus has been placed on literature and studies with their use. The magnitude of fertilization's effect on wood quality depends on many variables such as the nutrients used, individually or in combination; the site condition; and the treated species.

Fertilizing promotes crown growth and depth from height increase and possible girth increase depending on the competitiveness of the stand (Evans & Turnbull, 2004; Wiseman, et al., 2006)**.** The crown enlargement and vigour increases the amount, and the length period, of juvenile wood production (Barbour et al., 2003; Zobel, 1992). Fertilizer applied to a Loblolly Pine (Pinus taeda L.) plantation caused a one year extension of the transition from juvenile to mature wood (Borders, et al., 2004). Increased crown production results in increased branch growth; therefore larger knots are formed in the stem (Wiseman, et al., 2006; Barbour et al., 2003)**.** The branches and crown expansion may also cause increased compression wood formation after fertilization (Barbour et al., 2003). Agreement on the effects of fertilization on wood properties is absent in the reviewed literature.

A decrease in density after the application of fertilizer has been well documented, particularly for conifers (Barbour et al., 2003; Bendtsen, 1978; Downes, et al., 2002; Antony, Jordan, Schimleck, Daniels, & Clark, 2009). The observed density decrease varies between studies; generally it decreases 5 to 15% for sites without nutrient deficiencies (Barbour et al., 2003; Lundgren, 2004). However, a review by Zobel (1992) reported studies of nitrogen fertilization causing no density reductions, as well as reductions between 3 to 20%. The variation in the studies was attributed to differences in fertilizer used. These results may also be attributed to the soil conditions, and nutrient levels of each site. The intensity of the fertilizer used also affects the change in density. A study of three different amounts of fertilizer applied (112, 224, 336 kg/ha) on Loblolly Pine (Pinus taeda L.) plantations only observed a decrease in density for the most intense fertilizer application (Antony et al., 2009). However, literature reviewed by Campion (2009) reported that density decreases are greatest in the live crown portion of the stem and if the base is mature, (i.e. the crown has receded) it is less affected and, if fertilization treatments are discontinued, density values generally recover to previous levels three years after fertilization (Love-Myers, Clark III, Shimleck, Jokela, & Daniels, 2009); A six year time period for density recovery has also been reported (Zobel, 1992).

The effect of fertilization on tracheid length and MFA is less prominent and varies between studies. Generally, MFA increases after fertilization (Barbour et al., 2003). A study found fertilization had significant effects on increased MFA (Downes, et al., 2002; Lundgren, 2004). However a different study of various nitrogen treatment levels and potassium, observed no change in MFA for all the concentrations of nitrogen applied (Antony et al., 2009). A small decrease in fibre length occurs in response to fertilization (Barbour, Marshall, & Lowell, 2003). However, studies reviewed by Bendtsen (1978) show varied results caused by the effects of fertilizers, reporting slight decreases or no change in length. These differences were partly due to low or negligible responses to fertilization by the trees. Decreased fibre length due to fertilization is also supported by other sources (Zobel, 1992; Campion, 2009).

Fertilization has adverse effects on the strength and stiffness of wood. The bending stiffness of wood is reported to decrease slightly (Bendtsen, 1978; Downes, et al., 2002). A decrease in stiffness is supported in a study which found the stiffness and strength were lower in fertilized trees than in the control (Antony, Jordan, Schimleck, Daniels, & Clark, 2009). Lundgren (2004) also reported lower stiffness and strength after fertilization. However, the stiffness values are often considered to still be relatively high (Bendtsen, 1978; Downes, et al., 2002). The negative reductions in mechanical properties can be reduced by the frequent and mild applications of fertilizer (Downes, et al., 2002).

Conclusions and Recommendations

The wood properties discussed in this review are: density, microfibril angle, fibre length, juvenile wood, compression wood, and knots. Each wood property can be manipulated by using silvicultural techniques; they are: spacing, respacing/thinning, pruning, and fertilization. The level of success in applying each silvicultural technique can vary due to factors such as location and species. However, given the right conditions, the success of silviculture applications would likely depend on factors such as the implementation timing, the application intensity, and application repetitions/duration. It is evident that a well defined goal needs to be established for any forest management plan to be successful. Well defined goals are required because there is a wide span of possible management applications and the variety of resulting outcomes researched makes accurately predicting outcomes difficult.

The quality of wood produced when utilizing silvicultural practices is highly dependent upon the intended end use of the raw material. The most common goal in silvicultural treatments reviewed was to rapidly increase stem dimensions. Adverse effects on wood properties, and their characteristics, were often treated as a concession to increased growth rate. Disregard for silvicultural effects on wood properties could be an unwise choice as quality is sacrificed for quality.

Wood grown for lumber production would ideally have a high density, low microfibril angle, and no: juvenile wood, compression wood, or knots. Trees managed with these targets should have close initial spacing and be respaced to ensure healthy and vigorous trees develop. During growth, pruning should be performed periodically in conjunction with fertilization. Combining pruning with fertilization could effectively offset potential growth decreases experienced after pruning. Subsequently, moderate thinning should be performed once canopy closure has been established. Crown size will be maintained more easily when a relatively high stand density is used. Also pruning will force crown recession and promote clear wood development. Both choices reduce the amount of juvenile wood production during stem formation. Reduction in Juvenile wood, and increase in mature wood, effectively decreases MFA and increases density. Growth of wood for pulp and paper could use the same strategies for lumber production but a few minor changes would likely improve the strategies' suitability for pulp and paper end use. The spacing could be increased because juvenile wood is less of an issue in pulp and paper production compared to lumber production. Likewise, thinning could probably be more intense. Pruning and fertilization should remain the same to eliminate knots and maintain normal growth levels.

There are a few areas of silviculture which warrant more attention. Fertilization seems to have a large potential for continued research to find combinations and intensities of fertilizer applications resulting in maximized in volume and maintaining quality. Also, the effect of multiple silvicultural techniques implemented simultaneously and/or in tandem is a possible area warranting more attention. However, the magnitude of a study involving three or more silvicultural techniques may not be feasible. Finally, there should be continued research for silvicultural techniques that minimize juvenile wood development because it is a major source of lower quality wood development.

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