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Review

Wood and Fiber Quality of Plantation-Grown Conifers: A Summary of Research with an Emphasis on Loblolly and Radiata Pine

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Abstract: With conifer plantations having an increasingly important role in meeting the fiber needs of society, an understanding of the effect of silvicultural practices on wood quality is critical. The perception of wood quality varies, making it hard to define in a single statement; however, possibly the most succinct definition is "a measure of the aptness of wood for a given use". In general, properties that have a positive influence on a specific product assist in defining changes in wood quality. Since wood properties exhibit large variability within annual rings, within trees, and among trees in a stand, and have both genetic and environmental components (i.e., vary with different physiographical regions), it is imperative to have an understanding of wood properties at multiple levels. In this paper, we review the typical variation patterns in wood properties of conifers, with specific emphasis on loblolly pine (*Pinus taeda* L.), and radiata pine (*Pinus radiata* D.Don), two of the most common conifer plantation species globally. We also describe the impact of conventional silvicultural treatments on wood quality. Modeling efforts to predict variation in wood properties within trees, and in response to silvicultural treatments are also summarized.

Keywords: durability; microfibril angle; *Pinus radiata*; *Pinus taeda*; silviculture; specific gravity; wood density

1. Introduction

Globally, plantation forests have an increasingly important role in meeting the fiber needs of society. Since 1990, the area of planted forests increased from 167.5 million ha to 277.9 million ha in 2015 [1], with approximately 52% of this area comprising coniferous species, of which the majority (42% of the total area) were from the Pinaceae family [2]. Breeding programs, which are usually focused on specific species, exist and have the primary aim of increasing productivity [3]. Coupled with intensive silviculture, improvements in mean annual increment are dramatic. For example, the use of genetically improved loblolly pine (*Pinus taeda* L.) seedlings with suitable silvicultural management resulted in mean annual increments of up to 9–12 m^3/ha/year being achieved over a 25 year rotation, when compared with 2–6 m^3/ha/year for the same rotation in the past [4,5]. Further improvements are expected, and research on loblolly pine suggests that combining optimal silviculture operations with the best genetic material could increase its mean annual increment to 21 m^3/ha/year [3,4]. The situation is similar for radiata pine (*Pinus radiata* D. Don), which is already a very productive species achieving mean annual increments of 25 m^3/ha/year on 25–30 year rotations [6]. Likewise, deployment of improved genetic material, coupled with silvicultural practices that ensure full site utilization, and overcome site limitations, could see mean annual increments of more than 40 m^3/ha/year on many sites [7,8]. While improvements in productivity in these two species are impressive, they were often to the detriment of wood quality [9]. Hence, an understanding of the impacts of silvicultural practices on wood quality is critical.

Many definitions of wood quality exist, with possibly the most succinct being "a measure of the aptness of wood for a given use" [10]. Historically, the utilization of wood of a given species for one or more specific purposes owing to its unique properties and availability was common, and wood properties that had a positive influence on a specific product described or quantified wood quality. Of these, wood density (or specific gravity, SG) is possibly the most important wood-quality indicator, partly because of its influence on both the yield and quality of fibrous and solid wood products (including modulus of elasticity—MOE, and modulus of rupture—MOR) [11–13], and partly because of ease of measurement. Microfibril angle (MFA) is another important measure of wood quality as it determines shrinkage properties [14,15], and, coupled with wood density, explains much of the variation in MOE in clearwood [16,17], with knots also influencing MOE in lumber [18–20]. In addition to MFA and density, properties such as fiber (or tracheid) length, fiber diameter, and cell wall thickness and coarseness are important quality indicators, primarily for paper manufacture [21]. Wood chemistry, which includes the relative proportions of cellulose, extractives, hemicellulose, and lignin (including the ratio of lignin monomers, syringyl and guaiacyl), is important in determining the quality of chemical pulps [22]. Factors determining the quality of mechanical pulps include absence of color (pulps are only partially bleached), low resin content, and low density [21].

Tree improvement programs and the management of stands for specific products can make significant improvements in wood quality by targeting specific wood properties (particularly those that have a positive influence on a target wood product). However, the effect of these practices on wood quality is complex, and research is ongoing to understand responses in wood properties. The time and cost involved in measuring wood properties using traditional methods on a large scale has hindered research, and also limited the ability for tree improvement programs to incorporate wood quality into decisions on tree selection. In the last 20 years, rapid, nondestructive techniques for measuring wood properties were developed, and their emergence greatly reduced the cost of measuring wood properties in large numbers of trees, increased the potential for improving wood quality in the future, and improved our understanding of the effects of improved planting stock, and silvicultural practices on variation in wood properties. Instrumentation applicable to cores and discs collected from trees, and to standing trees include the following:

- X-ray densitometry (density);
- X-ray diffraction (MFA);
- SilviScan (density, MFA, stiffness, tracheid properties) [23–25];
- Near-infrared spectroscopy (properties related to the chemistry of the wood, pulp yield, and a range of physical-mechanical properties) [26,27];
- Acoustics (stiffness) [28–30]; and
- Resistance drilling, and pin penetration (density) [31–34].

In this paper, we review typical variation in wood properties of conifers, with specific emphasis on loblolly pine and radiata pine, two of the most common conifer plantation species globally. We also describe the impact of common silvicultural treatments on wood quality. Furthermore, we summarize modeling efforts to predict wood property variation within trees and in response to silvicultural treatments.

2. Wood Property Variation

Wood is a heterogeneous material, and its properties vary regionally, among stands within a given location, among trees within a stand, and with positions within a tree (with height, radially, and also within annual rings, i.e., earlywood (EW) and latewood (LW)) of a given species. An illustration showing the tree-to-tree variability in pith-to-bark ring SG, at breast height of loblolly and radiata pine, is presented in Figure 1.

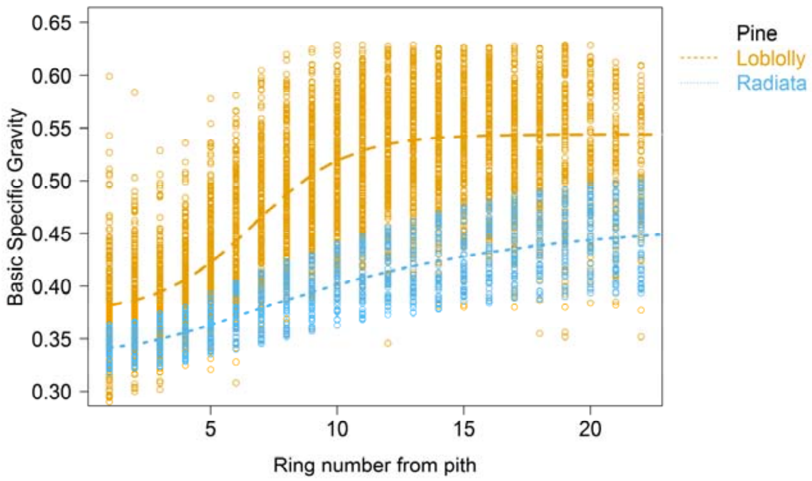

Figure 1. Plot showing the variation and mean trend in ring specific gravity (SG) from pith to bark (ring number from pith) at breast height for loblolly and radiata pine. The plot is based on a subset of the loblolly pine data reported by Jordan et al. [35], and data from Kimberley et al. [36].

An increasing trend in ring SG with physiological age (ring number from pith) is evident in Figure 1, and is typical of the hard pines; the large variability in SG among trees is also apparent. Figure 2 illustrates the variability of ring SG in loblolly pine by physiographic region within the southern United States (US). The figure is based on data collected by the Wood Quality Consortium from conventionally managed stands across the native range of loblolly pine in the southeastern US. Based on these data, an increasing trend was observed for ring-SG variance from pith to bark, with an overall observed variance of 0.0041 (minimum = 0.0016, maximum = 0.0065, note SG is unitless). Similar variability patterns were also observed in loblolly pine for other wood properties, such as MOE and MOR [37], MFA which decreases with cambial age [38], and wood anatomical characteristics. There is also a trend of increasing wood density with ring number from the pith in radiata pine. Considerable regional variation also exists, which is mostly associated with differences in mean annual temperature [36,39,40]. Other wood properties of radiata pine, such as spiral grain angle and MFA, have characteristic pith-to-bark trends [40–44]. Burdon et al. [45] summarized these general trends for loblolly and radiata pine.

The observed variation in wood properties among and within trees is mainly attributed to tree genetics, environmental conditions in which the tree grows, and their interactions [46–48]. Environmental variables, primarily water availability, and temperature, have significant influence on the temporal variation in wood properties [49]. Over and above the natural variation, silvicultural practices (such as early competition control, pruning, thinning, and fertilization) impart significant change on variation in wood properties within trees.

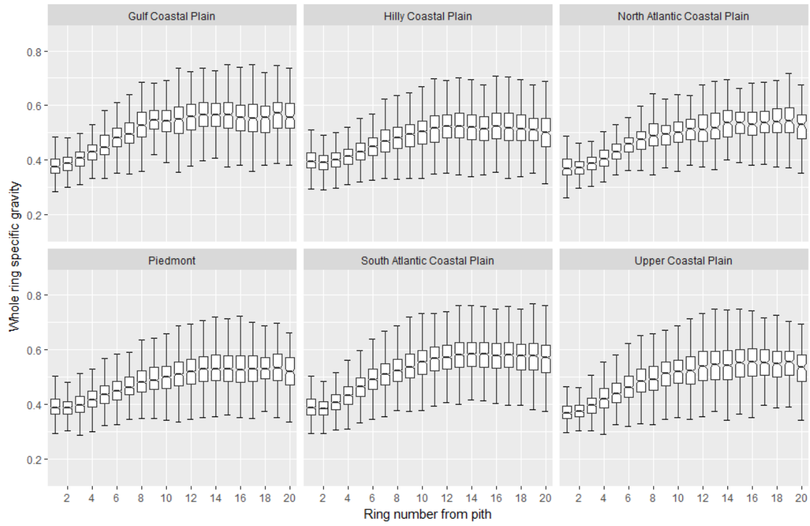

Figure 2. Plot showing the trend in whole-ring specific gravity (SG) from pith to bark (ring number from pith) at breast height for loblolly pine. Here, the notched point represents the median, the filled diamond represents mean ring SG, the range of the box represents interquartile range, and lines represent the range of ring SG (minimum, maximum) within each annual ring from pith to bark (data collected by the Wood Quality Consortium at the University of Georgia).

3. Silviculture and Wood Quality

In recent years, the focus of conifer plantation management was on maximizing profitability through improving the yields of more valuable log grades. Common practices applied include selection of genetically improved tree stocks, control over initial planting density, improved site preparation, including competition control and fertilization at planting; and thinning and fertilization at mid-rotation [50]. The effect of such practices on wood quality was the subject of considerable research, with findings on loblolly pine and radiata pine being the most frequently reported.

3.1. Planting Density

Recently, tree growers were inclined to establish plantations with wider initial spacing (coupled with chemical weed control, and fertilization at planting) as it reduces establishment costs, and accelerates growth. Genetic improvement in stem form, and advances in nursery practices mean that fewer trees need to be established to ensure an acceptable number of crop trees. The accelerated growth rate produces trees of merchantable size at a younger age (as young as 16–22 years, in both loblolly pine and radiata pine), thus shortening rotation length.

Planting with wide spacing stimulates early diameter growth, and produces crowns with large-diameter branches [51,52]. Hence, trees planted with wider initial spacing contain a greater proportion of corewood [53–55], and have larger-diameter knots [54,56–58]. The presence of the large corewood zone, and more knots in these short-rotation trees results in a large decline in lumber quality, and thus, in lumber recovery [9,59,60].

The effect of spacing on wood properties, such as SG, MOE, or MOR, was studied in the past, and the results (an increase in SG, MOE, and MOR at higher planting density) are generally consistent across a wide range of conifer species [61–63]. In loblolly pine, Clark et al. [57] observed an increase in whole-stem SG, MOE, and MOR with an increase in initial planting density, using samples collected from a 21-year-old unthinned spacing study (seven initial spacing levels ranging from 1.8 m $\times$ 2.4 m (2244 trees/ha) to 3.6 m $\times$ 3.6 m (746 trees/ha) were sampled). Similar improvements in MOE for trees planted at high initial densities were reported in radiata pine [64–68]. The magnitude of the improvement can be large, for example, a 39 percent increase (from 5.4 GPa to 7.5 GPa) was seen in outerwood dynamic MOE (nondestructive test for MOE, MOE_{dyn}) for 17-year-old radiata pine, as planting density increased from 209 stems/ha to 2551 stems/ha [64].

Lasserre et al. [66] reported an increase in wood stiffness for 11-year-old clonal stands of radiata pine with an increase in planting density from 833 stems/ha to 2500 stems/ha. More detailed assessment of internal wood properties of trees from these stands showed that there was a decrease in MFA, and ring width, and an increase in MOE_{dyn}, fiber length, LW percentage, and cell wall thickness, with no changes observed in density, and fiber width [65]. Similar results were reported in black spruce (*Picea mariana* (Mill.)) trees from stands established at four initial densities (3086 trees/ha, 2500 trees/ha, 2066 trees/ha, and 1372 trees/ha), with lumber yield, MOE, and MOR reduced in stands planted at low initial density [62].

In contrast, Clark et al. [53] reported that initial planting density had minimal influence on wood SG of loblolly pine, with higher-SG wood in annual rings produced in the corewood zone, and lower-SG wood produced in the outerwood zone of trees planted with wider spacing. This reversal in the SG trend might be due to the production of denser earlywood in the initial period of growth in trees planted with wider spacing, owing to reduced competition.

One hypothesis that was proposed to explain the increase in MOE (MOE_{dyn}) at high initial planting density is that MFA decreases, and fiber length increases in response to the reduced radial growth rate, owing to increased competition for light [65]. From a biomechanical perspective, one mechanism for a tree to increase in height without a corresponding increase in diameter is to increase its density-specific stiffness, which is, effectively, to reduce its MFA. Though evidence exists to support this hypothesis, particularly in radiata pine where Watt et al. [69] found that MOE_{dyn} is related to tree slenderness (ratio of height to diameter at breast height), further research is needed to confirm physiological and biomechanical responses. An important consideration with decreased planting density is the general increase in branch size, which decreases both MOE and MOR when the target product is lumber [63,70].

3.2. Fertilization and Competition Control upon Planting

A common silvicultural practice to increase the growth of young plantation softwoods is the control of competing vegetation by applying herbicides. Reducing competition from herbaceous and woody species increases the availability of moisture and nutrients, and, when coupled with fertilization, can produce significant improvements in growth. On colder sites, it is also important for reducing the risk of frost damage to young trees. However, until recently, knowledge regarding the effects of these practices on wood quality was limited.

In general, early-age competition control substantially increases corewood diameter in conifers. For example, the corewood diameter of loblolly pine trees that received herbaceous and woody weed control in the first 3–5 years of growth was 20 percent greater than that of trees not receiving any weed control [71–74]. Similarly, annual nitrogen fertilization, and vegetation control increased corewood diameter by 62 percent, when compared with no vegetation control in loblolly pine at 12 years of age [75].

Other than an increase in corewood diameter, changes to SG following competition control are negligible. No effects on the wood properties of loblolly pine at the annual ring level, such as ring SG, EW and LW SG, and LW percentage, were observed following competition control [71,72], and weed control plus fertilization [73,74] at an early age. However, some changes were observed in the basal area-weighted whole-core wood SG (sampled at 1.37 m) of loblolly pine trees at 15 years of age that received complete weed control, when compared with those that received no weed control, based on experimental trials established across sites in the southeastern United States [72]. Similarly, Clark et al. [75] reported a decrease in weighted stem SG (6–10%), when compared with the control (no treatment) for loblolly pine at 12 years of age, following annual nitrogen fertilization, and vegetation control. No information is available on the influence of early-age competition control on MFA and stiffness of loblolly pine wood. In radiata pine, a decrease in corewood MOE_{dyn}, following control of woody weeds, was reported by Watt et al. [76]; however, another study found no significant effects of early-age control of herbaceous weeds on MOE_{dyn} [77]. A more comprehensive study across a broader range of sites showed that weed control did have a negative impact on MOE_{dyn} of 6-year-old trees, decreasing it by 16% on average [78].

The above examples notwithstanding, wood properties are largely unaffected by early-age competition control; however, this practice does increase the diameter of the corewood zone. Like initial planting density, competition control might affect the quality and recovery of lumber if tree harvest depends on a merchantable diameter, rather than a target age. If, in practice, trees grow to similar final diameters, those growing in stands that received early competition control and fertilization would attain merchantable size sooner, and would, therefore, have a greater proportion of corewood at the time of harvest.

3.3. Mid-Rotation Thinning and Fertilization

Mid-rotation fertilization following thinning is another common silvicultural practice, more so in loblolly pine than in radiata pine. Thinning increases the amount of growing space available, ensuring that stands do not become overstocked, and also enhances the overall quality of the stand by concentrating growth on the best trees in terms of growth, form, and hence, potential to produce high quality wood products. Fertilization following thinning aids the growth response, and may ameliorate any existing nutrient deficiencies in the soil.

Mid-rotation fertilization following thinning, depending on the type and rate of fertilizer applied, does have an influence on wood properties. Based on some of the studies on loblolly and radiata pine, SG of wood produced following fertilization is decreased when compared with that of unfertilized trees [79–84], with the effect lasting for 3–4 years post-fertilization. In radiata pine, nitrogen supply was shown to be an important factor affecting wood density [84,85]. Studies in loblolly pine also showed a response to applied nitrogen. For example in a stand that was thinned and fertilized with 336 kg nitrogen/ha at 14 years of age, a decrease in MOE_{dyn}, air-dry density, and tracheid wall thickness, was reported when compared with the control [80]. In a later study based on the same trees, static bending tests were conducted on samples taken from different radial positions within the trees, and it was found that both MOE and MOR decreased in wood that was produced immediately after fertilization [86]. However, such responses in wood properties might depend upon whether the stand is thinned or not before fertilization, and upon climate interactions post-fertilization [81], as another study found no change in wood SG following fertilization (even for 336 kg nitrogen/ha) in an unthinned stand [87]. Although mid-rotation fertilization is less common in radiata pine, particularly in New Zealand, studies were undertaken to understand the impacts on growth and wood properties. In a study in New Zealand, nitrogen was applied in the form of biosolids at two rates (300 kg·N/ha and 600 kg·N/ha) to a radiata pine stand, at 6, 9, and 12 years of age [88]. At 14 years of age, the current annual volume increment was 40% higher in the 300 kg·N/ha treatment relative to the untreated control, and there was a small, but significant, reduction in wood SG and MOE_{dyn}.

In summary, fertilization post-thinning produces a growth response. Even though trees have started producing outerwood at mid-rotation, the application of nitrogen increases the number of tracheids for a given area, with a concomitant reduction in tracheid radial diameter, and wall thickness [89]. Wood properties are negatively affected, but the response depends on the rate of fertilizer applied, site conditions, and age of the stand. To better understand fertilization effects on wood properties, studies should be established on sites covering a wide range of environmental and edaphic characteristics; this is particularly important given that the area of plantations, particularly loblolly pine, being fertilized is increasing.

3.4. Irrigation

Relatively few studies examined the effect of irrigation on conifer growth, and wood quality because it is not commonly an operational treatment, with the notable exception being fertigation with treated sewage effluent. However, irrigation trials do allow a more fundamental understanding of how water availability impacts tree growth, and wood quality. In a loblolly pine irrigation-fertilization trial, an improvement in outerwood LW SG was observed following irrigation [90]. Conversely, in another experiment where trees were only irrigated, whole-core SG increased in the irrigated trees, but latewood SG did not change [91]. In both studies, it was found that irrigation enabled LW formation to continue later into the growing season. Where irrigation is combined with fertilization, this increased production may enable trees to achieve SG values similar to those of unfertilized trees. Studies in radiata pine also concluded that irrigating in summer and autumn was most beneficial to wood quality, as it resulted in an increase in average density, and maximum density [92].

4. Wood Quality and Durability

Natural durability of wood can be an important determinant of its end use, particularly in the selection of wood for external applications. The crystalline nature of cellulose, and the presence of lignin in wood provide partial resistance to insect attack or fungal decay, though the presence of extractives in wood is the principle source of decay resistance in almost all tree species [93]. Extractives, which include fatty acids, phenolics, resins, terpenes, and waxes, arise from sugars and starch following the death of sapwood parenchyma cells. Extractives accumulate in the inner part of the tree, and over time, this leads to the formation of heartwood [94]. The variability in natural durability among species, owing to differences in heartwood formation, and the type of extractives present, has always been of interest to wood users. In a comprehensive review, a measure of the natural durability (decay resistance on a scale of 1 to 4, with 1 being very resistant to decay, e.g., in old growth redwood (*Sequoia sempervirens* (D. Don) Endl.), and 4 being nonresistant, e.g., in radiata pine) was provided for the wood of 1500 species [93].

With plantations (and younger trees) providing an increasing proportion of our wood, an understanding of the influence of environment and silviculture on extractive production, and heartwood formation, and hence, wood durability is very important; however, our knowledge is extremely limited [94]. The volume of heartwood and the concentration of extractives, proportional to wood durability, largely depends on tree age in many species. For example, Sellin [95] showed that the proportion of heartwood in Norway spruce (*Picea abies* (L.) Karst.) trees increased with tree age, while in western redcedar (*Thuja plicata* Donn ex D. Don), DeBell et al. [96] found that the extractive content increased going from the pith through to the bark. An immediate consequence of the shift to wood from plantations is that species which produce durable wood may fail to do so if grown on short rotations, for example, in redwood [97] and Port Orford cedar (*Chamaecyparis lawsoniana* (A. Murr.) Parl.) [98]. Taylor et al. [99] observed a positive correlation between growth rate following thinning, and heartwood extractives in Douglas fir (*Pseudotsuga menziesii* (Mirbel) Franco), which might result in a moderate increase in durability. However, a consistent relationship between growth rate following silvicultural treatments (thinning and fertilization), and the accumulation of extractives in heartwood of western redcedar was not observed [100].

In pines of the southern US, heartwood formation may start at 15 to 20 years of age depending on site conditions, crown size, and initial spacing [101]. In radiata pine growing in New Zealand, heartwood formation typically starts at 12–14 years of age, and advances outward at approximately half a ring per year [102]. With rotations less than 30 years, and often less than 25 years, most of the wood from pine plantations (particularly loblolly pine and radiata pine) is primarily sapwood, of which the natural durability is very low. Many plantation conifers produce wood having low to moderate resistance to decay. If used in applications where durability is expected, then it is necessary to treat such wood with compounds toxic to the organisms, responsible for wood degradation [103]. For species such as loblolly pine and radiata pine that produce heartwood with low natural durability, it is often undesirable to produce trees with excessive heartwood, as this can often be more difficult to dry and/or treat with preservatives.

5. Mathematical Models for Explaining Variation in Wood Properties and Wood Quality

Models to predict wood properties were developed, and applied to various plantation-grown coniferous species. Models are important, as they allow users to predict trends in wood properties and, hence, to determine the quality of wood produced at a given age. Models to predict important wood properties (e.g., SG, MFA, and MOE) at resolutions spanning whole-tree to ring levels exist for a range of species. These models also enable the effects of silvicultural practice on wood properties to be quantified (see Section 6), by removing potentially confounding effects of factors such as tree age.

Several simple–linear-regression models relating core wood properties to whole stem properties in breast height increments were developed for conifers to assist in the nondestructive estimation of wood quality, for example, in loblolly and slash pine (*Pinus elliottii* Engelm.) [104–107], and in radiata pine [108,109]. Though these models provided reasonable estimates of whole-tree wood properties, they failed to account for within-tree variability, as these trends are not linear.

More recently, wood growers and buyers have realized the need for sophisticated models to explain within-tree variation in wood properties, i.e., from pith to bark, and with height. These models also recognize and account for the hierarchical structure of many datasets of wood properties, something that was often ignored in many early models. An example is the model developed by Tassissa and Burkhart [110] to explain within-tree variation of ring SG in loblolly pine, using data collected from a region-wide thinning study, established across the southeastern US. Daniels et al. [111] used a nonlinear model (three-parameter logistic function) to explain within-tree variation in loblolly pine SG, with ring number from pith as an explanatory variable, based on data collected from conventionally managed stands across the southeastern US. The model was later improved to predict variation in ring SG for loblolly pine over its growing range in the southern US, by taking into account site-to-site and tree-to-tree variability [35,112]. Models explaining height variation in SG were also developed, based on data from discs collected at various heights of trees, sampled from conventionally managed loblolly pine plantations [112–114]. Other than prediction of SG, models to predict radial and longitudinal variation in MFA [38,112,115,116], MOE, and MOR were developed for loblolly pine [37,55]. A schematic representation of predicted within-tree variation in SG and MFA, with ring number from pith, is presented in Figure 3.

One of the earlier modeling efforts in radiata pine developed a suite of models at various resolutions to explain within-tree variation in density. It involved a logistic function to explain the variation in pith-to-bark ring-by-ring density at breast height, and a modification of this model was also designed to predict within-stem variation in density [40]. In addition, a quadratic model to predict variation in density with height was proposed, as well as a modified exponential model, with tree age as an explanatory variable, to predict wood density of logs, and whole stems [40]. Subsequent analysis resulted in a system of models to predict outerwood density at breast height, ring-by-ring density at breast height, wood density of annual growth sheaths, and whole-log average density [36,39,85]. These models are also able to include the effect of genetic improvement on wood density [47].

Models to predict other wood properties of radiata pine also exist. Examples include models to predict within-tree variation of spiral grain [43,117], and to predict microfibril angle [42] as a function of ring number from pith and height, as well as another to predict variation in within-tree stiffness across a wide range of environmental and stand-density gradients in New Zealand [69]. Models with the capability of predicting a range of wood properties in species, such as loblolly and radiata pine, improve our ability to manage optimal wood-utilization, wood-quality, and end-product potential, particularly when they are coupled with models of growth and yield.

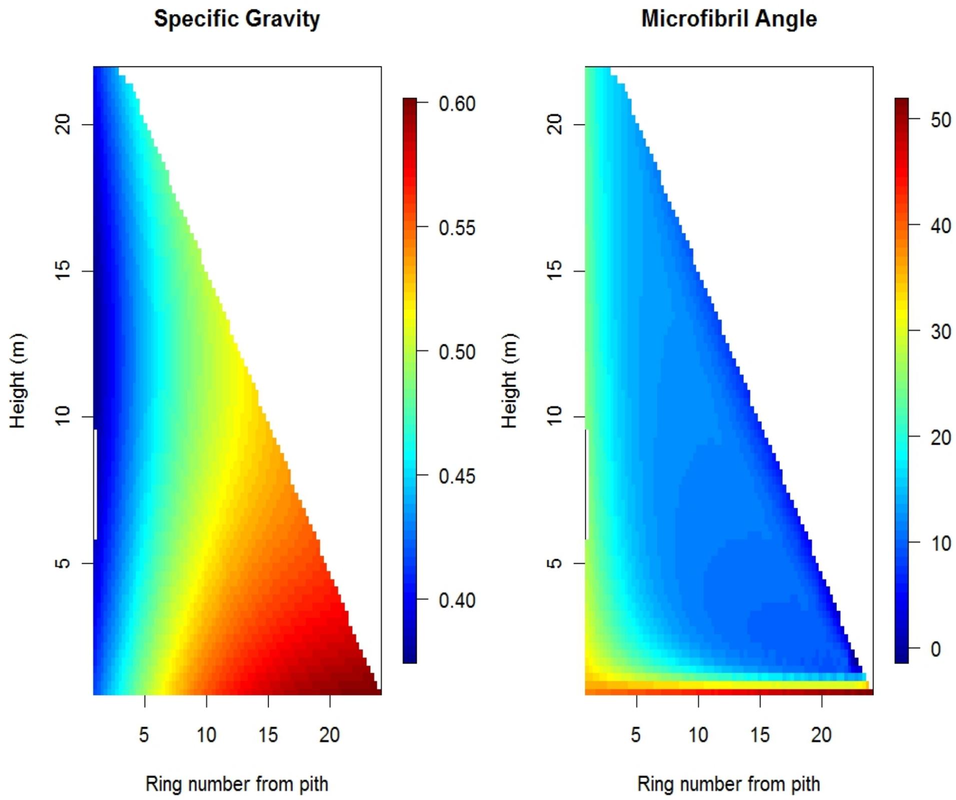

Figure 3. Maps showing within-tree variation in specific gravity (SG) and microfibril angle (MFA) for a loblolly pine tree from the Lower Coastal Plain in the United States. The SG and MFA maps were based on predictions from models proposed by He et al. [108] and Jordan et al. [112], respectively.

While our focus was on loblolly and radiata pine, there were also modeling efforts in Norway spruce, Sitka spruce (*Picea sitchensis* (Bong.) Carr.), and Scots pine (*Pinus sylvestris* L.). Examples include the work of Leban, Daquitaine [118], who developed a predictive model for variation in EW density from pith to bark for Norway spruce, which was a nonlinear function of ring number, and the widths of LW and EW. In a later study [119], linear and nonlinear models were used to explain height variation in cross-sectional basic density (disc properties), LW percentage, and diameters of corewood and heartwood in Swedish-grown Norway spruce, and Scots pine. In further research on the same species [120], ring-based models to predict pith-to-bark variation in wood density, as a linear function of EW percentage, and cambium age at any height, were developed. In addition to the wood-density model, models to predict EW percentage, and fiber length were proposed, using linear functions of ring width, or radial growth and cambial age [120]. In a more recent study based on plantation-grown Scots pine, nonlinear mixed-effects models were used to predict within-tree variations in MFA and density [121,122]. Nonlinear mixed-effects models were also used to predict within-tree variation in wood properties of Sitka spruce. For example, nonlinear functions of ring number from pith, and ring width were used to model spiral angle [123,124]. On the other hand, Gardiner et al. [125] proposed separate nonlinear models, one with ring number from pith, and another with ring width as explanatory variables, to model pith-to-bark variation in wood density.

6. Mathematical Models Predicting Silvicultural Responses in Wood Properties

Often, changes in wood properties following the application of any silvicultural practice are of secondary importance relative to growth responses. In many cases (for example, early-age competition control, and fertilization), profiles of pith-to-bark wood properties, with ring number from pith, are unchanged with respect to the applied treatments, while only the growth rate of the tree, and the corewood diameter are affected [72]. Models explaining variation in wood properties following silvicultural treatments are rare, and more research is required. In loblolly pine, Antony et al. [126] modeled responses in SG of LW following mid-rotation fertilization, as a function of the rate of fertilizer applied, and time since fertilization. In another study, Antony et al. [55] modeled the effect of initial stocking on variation in wood stiffness within trees (Figure 4).

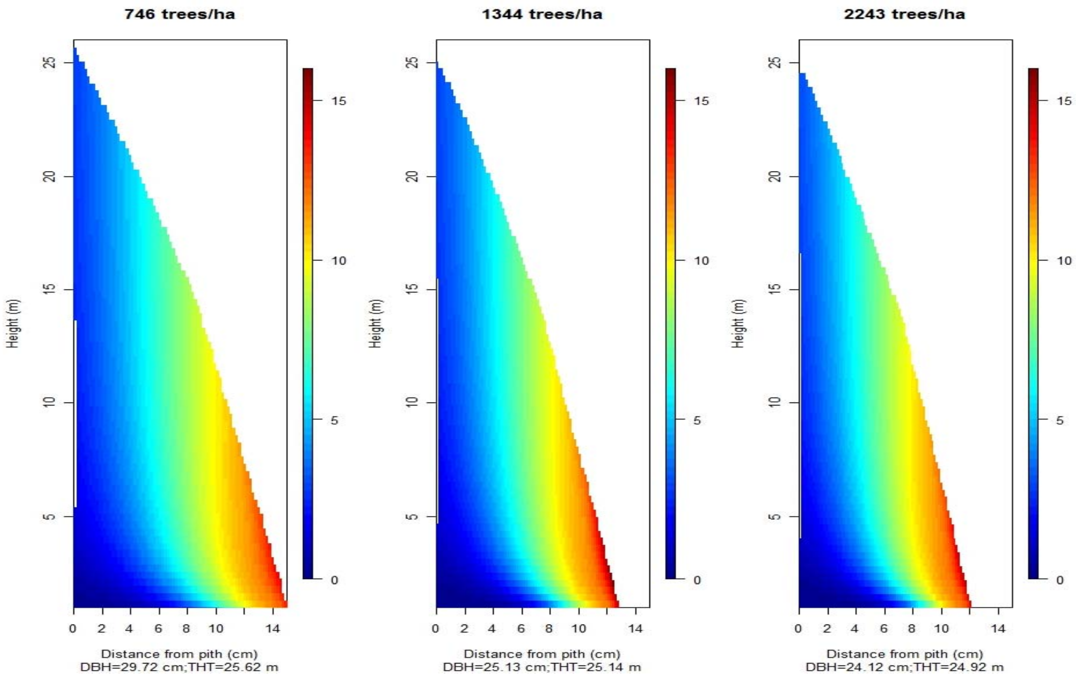

Figure 4. Maps showing within-tree variation in stiffness (GPa) of loblolly pine for a tree with average diameter at breast height, and total height, planted at three initial planting densities. The maps were produced based on predictions from a model by Antony et al. [51]. DBH: diameter at breast height; THT: tree height.

In radiata pine, many of the models developed to predict ring-level wood properties include a ring-width term in them, which enables the impact on wood properties of silvicultural treatments that affect growth to be determined [36,42,43]. Such models can then be coupled to growth- and yield-prediction systems. However, such models do not account for the change in wood properties that cannot simply be explained by changes in growth rate, such as in families that can have relatively high growth rates, while still maintaining high levels of stiffness and strength [127]. As with loblolly pine, models were also developed for radiata pine to predict the direct effect of silvicultural treatments on wood properties. For example, Watt et al. [68] developed models to predict within-tree variation in SG, MFA, and stiffness, with initial planting density, with each variable expressed as a function of stand density, age, and height.

7. Conclusions

Wood quality is a multifaceted term, and is usually defined by properties (physical, mechanical, anatomical, and chemical) that influence end-product quality. Substantial evidence exists for the positive influence of silvicultural treatments on growth. Based on the available literature, practices such as initial planting density, early-age competition control and fertilization, and mid-rotation thinning and fertilization do have an influence on the properties and/or type (corewood vs. outerwood) of wood produced. However, the relative magnitude of the effects of these various practices is unknown, and future research should focus on determining this across a range of sites. Despite this, there is sufficient evidence to show that, by selecting appropriate stocking regimes, managers could control wood stiffness, and the recovery of high-grade lumber, as increased planting density produces stiffer wood (by decreasing MFA, and reducing the proportion of corewood within a tree). Early-age competition control and fertilization increases the proportion of corewood within a tree, while mid-rotation fertilization following thinning results in a decline in SG, wall thickness, and MOE, with little change observed in MFA. Plantation managers should be cautious regarding management strategies they adopt, and should carefully consider wood-quality implications. For many plantation conifers, mathematical models, and decision support systems are available to select appropriate management strategies. Since many silvicultural operations negatively influence dimensional properties of lumber and its recovery, wood quality has the potential to diminish some of the economic gains achieved, due to increases in growth rate, and overall gains in productivity.

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