REVIEW

Enhancing Forest Value Productivity through Fiber Quality

David Briggs

ABSTRACT

Developing markets for carbon storage and bioenergy, shifting of the pulp and paper industry to biorefineries, and the potential of new technologies present the forest sector with exciting transformative opportunities and challenges. One of these challenges will be to understand the implications for fiber (wood) quality. This article provides a definitional context for fiber quality; examines traditional visual qualitative assessment methods and changes that are producing a shift toward methods to quantitatively measure properties; and briefly reviews the effects of age, silviculture, genetics, soil, climate, and location. With this background, the following four fiber quality research gap areas are identified: (1) poor understanding of the relationships between the properties of wood across various scales and their effect on product performance; (2) lack of understanding of how physiological processes, genetics, silviculture treatments, and growing environment conditions affect properties of wood at different scales; (3) the weak scientific infrastructure to address gaps 1 and 2; and (4) the lack of models that integrate fiber quality into decision support systems that can be used to improve planning of investment, silviculture, harvest, and marketing activities. To address these gaps, it is suggested that a lead organization be formed to define and set priorities, establish funding, and organize and oversee the research program.

Keywords: fiber quality, productivity, silviculture, wood quality

Sustainable forest management has many definitions such as "the capacity of forests, ranging from stands to eco-regions, to maintain their health, productivity, diversity, and overall integrity, in the long run, in the context of human activity and use" (Helms 1998). However stated, all seem to agree that management will be conducted in such a way as to produce a combination of ecological, social, and economic benefits indefinitely (Barbour 2007). Sustainable forest management may be relatively easy to accomplish on public lands where statutes can ensure that forested areas are "zoned" for a specific dominant use such as parks, wildlife refuges, municipal watersheds, to name a few, or require integrated or bundled services, such as generation of income for public trust funds for schools and infrastructure, providing recreation amenities, water, habitat, and protection services (Partridge and MacGregor 2007). However, the majority of forestland is owned by a diversity of private owners whose "working forests" provide timber and wood products, jobs, and environmental services but face competition for conversion to agriculture, urban and suburban development, and infrastructure. To survive, working forests must generate sufficient revenue to cover costs of management and ownership and provide adequate return as an incentive for the landowner to not sell for conversion.

Because many costs, such as meeting legal mandates to provide habitat and other services, are largely beyond a landowner's control, the main option to be profitable and remain competitive with alternative land uses is to increase revenue. One opportunity to increase revenue is to sell forest services, such as recreation fees and licenses, and to engage in emerging markets for carbon credits and bioenergy. A second opportunity is to create additional timber volume by increasing productivity through genetic improvement and intensive silviculture. Recognizing that timber value reflects fiber quality as well as growth, yield, and tree size, a third opportunity is to improve quality to increase yields of higher value products. Enhancing value through fiber quality or wood quality, terms considered synonymous, is the focus of this article.

Fiber Quality Definition and Measurement

Before developing a research gap analysis of fiber quality, a framework within which it is defined, methods for assessing it are reviewed, and changes and future challenges are identified. Given this context, it

Received May 21, 2009; accepted October 30, 2009.

David Briggs (dbriggs@u.washington.edu) is Professor, University of Washington, School of Forest Resources, Box 352100, Seattle, WA 98195. *The author acknowledges the US Forest Service Washington Office and Southern Research Station.*

will be easier to identify fiber quality research gaps and their linkage to the issue of enhancing forest productivity.

Defining Fiber Quality

Quality is generally defined as "suitability for a use" (Briggs and Smith 1986). Further precision requires statement of a specific product and the key performance requirements of that product in service. Given these product performance requirements, the physical, mechanical, and chemical properties of wood that contribute to the requirements can be identified (Gartner 2005). These wood properties, which arise from the biology of tree growth, have a hierarchical structure ranging in scale from meters to nanometers (Figure 1; Moon 2008). At the "macroscale" are knots, growth rings, juvenile wood (JW), and mature wood (MW) [1] etc., and at the "microscale" are fibers and chemical structures. Given the product, performance requirements, and linkage to the governing properties at the appropriate scale, one can assess how silvicultural practices may alter wood properties and subsequent product performance. Table 1 consolidates information, adapted from Gartner's (2005) approach, with respect to the performance requirements of a floor joist. For each performance requirement, Table 1 lists governing wood properties and indicates how intensive silviculture that reduces rotation age, with corresponding increases in JW and sapwood content, may change the wood properties with subsequent changes in joist performance.

In practice, logs can be converted into a spectrum of "wood elements" (Figure 2) reflecting points along the hierarchical scale of Figure 1. Wood elements can be tested and sorted and combined with adhesives and other materials in the design and manufacture of engineered wood products (EWP) that meet specific performance requirements with low variability between items. Depending on the wood element chosen for designing an EWP, the point along the hierarchical structure and the scale both change. For example, if a log is converted into fiber for paper or fiberboard, macroscale organizational patterns such as growth rings, sap/heart and JW/MW zones, knots, and so on, are largely destroyed and comingled so they contribute relatively little to product variability, which then is mainly governed by the microscale aspects such as specific fiber types, fiber geometric structure, and chemistry. If a log is sawn into a lumber, many aspects of the macroscale remain and contribute to variability between the pieces. Wood properties are a result of the structure interactions within and between these scales. Consequently, to fully understand the response of a bulk wood product to a load or environment situation, the properties and response characteristics must be understood across all scales (Moon et al. 2006).

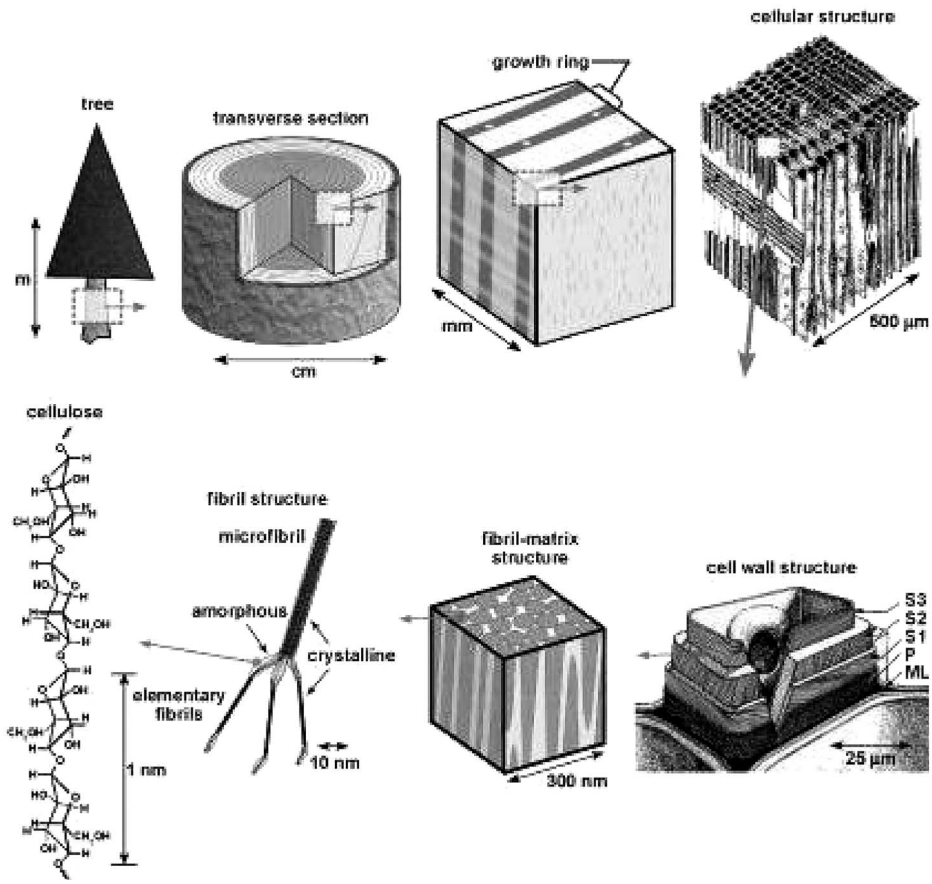

Figure 1. Hierarchical structure and scales of wood. (Moon 2008)

Measuring Fiber Quality

Forestry has well-developed sampling procedures, widely used technology for measuring trees, and software models for estimating stem volume and projecting growth, size, and yield. Development of counterparts for fiber quality has lagged far behind. Consequently, there has been little progress in developing fiber quality models. With the shift to intensive planning of growth and yield and marketing, a more diverse mix of products from forests, the need for technology to measure and monitor fiber quality, is becoming more important. Inability to measure, monitor, and predict quality has costly ramifications. First, it is very expensive for a manufacturer to purchase and process timber with low yields of products with the performance requirements expected by customers. Value is also lost when timber with potential to yield high value products is misallocated to a lower use. Second, wood variability increases the risk of product failure in service with subsequent replacement and possible litigation costs. Conservative design can reduce risk of failure but is inefficient and costly in terms of wood use. Alternatively, frustrated users may decide to choose a nonwood product instead. Third, inability to routinely monitor fiber quality characteristics and integrate it into forest planning may lead to choices of cultural practices that fail to maintain or improve quality or meet future needs.

Fiber Quality Assessment

Visual Fiber Quality Assessment

Visual grading relies on the human eye or imaging observation of external quality characteristics on the surfaces and ends of trees, logs, and products. For trees, the number, diameter and pattern of branches or branch indicators, evidence of decay, to name a few, observed on the bark surface are common quality indicators. These observa-

Table 1. Floor joist—Performance requirements, influencing biological and chemical wood properties, and effects of shorter rotation.

Performance property	Influencing biochemical wood properties	Effect of shorter rotation: On juvenile wood[a]	On sapwood[b]	Net effect on performance
Stiffness and strength	Knots	Increase	?	Lower stiffness and strength
	Density	Decrease	?	
	Microfibril angle	Increase	?	
	Slope of grain	Increase	?	
Dimensional stability (warp)	Slope of grain	Increase	?	Poorer stability and more warp
	Microfibril angle	Increase[c]	?	
	Extractives content	?	Decrease	
Treatability	Sapwood percent	?	Increase	Easier to treat

[a] Juvenile wood refers to the growth rings at the center of a cross-section.
[b] Sapwood refers to the growth rings just under the bark that are actively conducting water and nutrients from the soil to the crown.
[c] Depends on the pattern of growth rate
?, Effect uncertain.

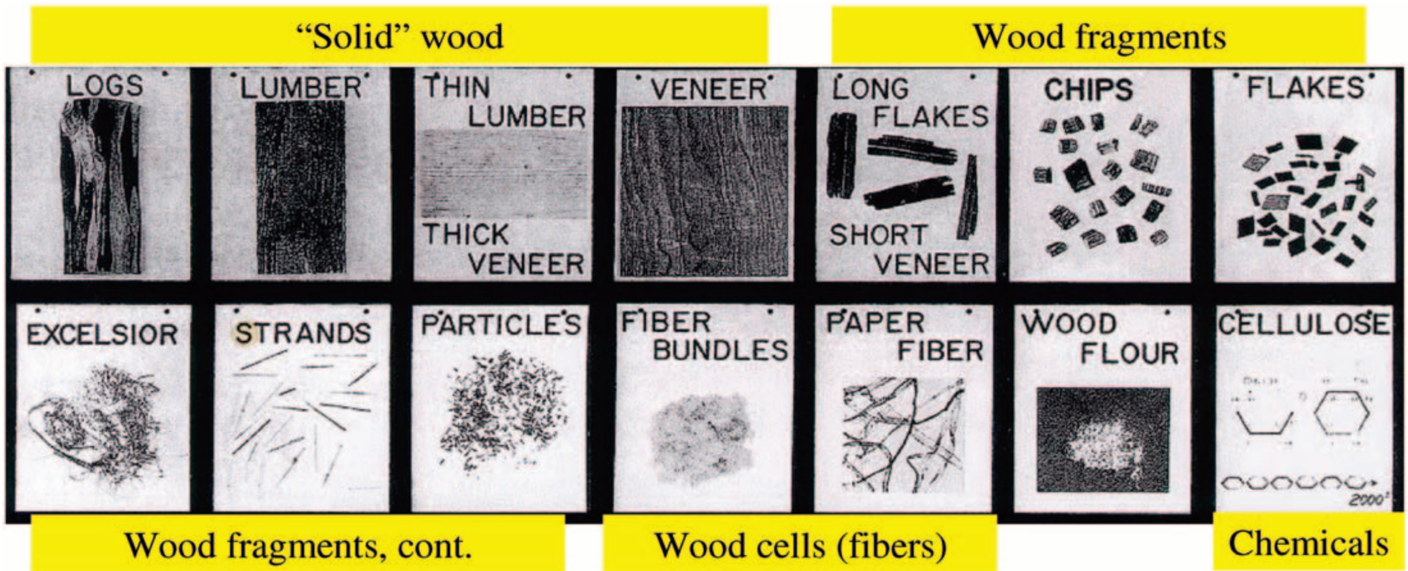

Figure 2. Wood element progression of scales from large-scale solid wood to chemical components.

tions may be combined with tree diameter and age to estimate growth rate. Similar clues are used on logs but bark may be removed and exposure of log ends allows growth rate and latewood, sapwood, and JW/MW content to be taken into account. For products such as lumber and veneer, the specific placement of knots and other defects exposed by processing can also be considered. Visual grading presents a number of issues. First, to keep visual approaches manageable for the human eye and brain, only a small number of broad grades occur for trees, logs, and products. Second, although visual grades partition the overall variability into more homogeneous groups, much variability remains within a grade. Third, because of the difficulty and expense of training and certifying graders, grade definitions tend to be inflexible with respect to changing customer needs. Fourth, there are issues with misclassification due to human error and the poor correlation between visually assessed external characteristics and actual internal properties. Consequently, visual methods do not provide precise, accurate estimates of properties. For example, the peeler-sawlog log grading system used in the Pacific Northwest for Douglas-fir places 85% of logs in two grades: grade 2 and grade 3 sawlog (H & W Saunders, Ltd., 2001). These two log grades respectively allow knot diameters up to 2.5 or 3.0 in., have minimum small end diameter limits of 12 and 6 in., and have no growth rate restriction. Logs of vastly different quality occur in each of these grades and studies commonly show no relationship between recovered product quality and these grades (e.g., Fahey et al. 1991) and in one case the relationship was inverted (Sonne et al. 2004). Similar issues occur for visual grading of lumber and veneer (MacPeak et al. 1990, Biblis et al. 1993). Madsen (1992) noted for visual grading of dimension lumber that "we do have a lot of strong material in the sawmill production but that our present grading system does not enable us to economically identify the strong pieces." A number of factors are challenging traditional visual grading rules as a reasonable method for assessing quality and matching the resource to product performance requirements.

Domination by Construction. Construction of buildings and their repair and remodel activities constitute the primary use of wood in the United States. Much of the construction wood is lumber that must be long, deep, and straight as well as stiff and strong. As the timber resource shifted from large old-growth to second growth and then to intensively managed plantations (IMP), the "small-diameter tree" and the "short-rotation tree" problems emerged.

Small Diameter. The small-diameter tree arises from various situations. First, there was the shift from the legacy of large-diameter old-growth to relatively unmanaged "second growth that was harvested when trees were younger and smaller. Second, second growth has been replaced by IMPs that commonly produce small, but harvestable, trees in less time; these trees also have the short-rotation problem discussed later in this article. Third, a large acreage of old, small-diameter timber occurs in the interior west. Small-diameter trees produce small logs from which it is difficult to obtain products with the required length and cross-section dimensions.

Short Rotation. IMPs can produce fast-growing trees that reach harvestable size at a younger age. In addition to relatively small size, short-rotation trees have a high proportion of low stiffness/strength JW compared with MW that would accumulate over longer rotations. Fast-growing trees produce large knots, further reducing product strength and stiffness. Quality of IMP trees contrasts with that of older similar-size trees from the Interior West. The contrasting quality of such extreme versions of small-diameter trees challenges the ability of visual grading systems to reliably segregate products into categories with accurate, precise, and consistent properties.

Emergence of EWPs. To overcome the small-diameter tree and variable quality issues, there has been a trend to meet product performance requirements through EWPs. EWPs can be considered as falling into two broad classes. In one class that includes glulam beams, laminated veneer lumber, and I-beams and joists, wood elements for use in product design and manufacturing are commonly stress rated and sorted. In the other class that includes oriented strandboard, oriented strand lumber, wood–plastic composites, to name a few, wood elements are generally not stress rated before sorting. These latter EWPs rely on mixing specific size wood elements with other materials and densification during manufacturing to achieve targeted product properties. Advantages of EWPs are that large-size products can be manufactured from small elements, overcoming tree size and low yield limitations; nondestructive testing (NDT) technology can be used to measure properties of individual wood elements so they can be sorted and used intelligently in product design; and the wood elements can be combined with other materials to enhance performance.

Quantitative Fiber Quality Assessment

Visual grading may be useful for assessing aesthetic features of products but does not provide accurate, precise quantitative measurements of properties. NDT is "the science of identifying the physical and mechanical properties of a piece of material without altering its end use capabilities and then using this information to make decisions regarding appropriate applications" (Pellerin and Ross 2002). The evolution of the theory and practice of NDT is well documented in a series of international symposia that began in 1963 with the most recent in 2007 (Ross et al. 2008). NDT provides either direct or indirect quantitative measures of properties. For example, lumber stiffness can be measured by mechanically measuring deflection due to a load or by measuring the speed of sound through the piece. NDT provides accurate, precise estimates of a property and the ability to adapt equipment settings to respond to changing requirements, thus overcoming the inflexibility of traditional grades. NDT grades can have much higher resolution and lower variability improving manufacturers' ability to source and sort raw material and design and manufacture products that more accurately and precisely meet performance requirements. Table 2 lists examples of NDT used at various scales, some of which are discussed in the remainder of this section.

Macroscale (Meter to Centimeter) Technologies

Perhaps the first commercial application of NDT was the 1963 introduction of machine stress rating (MSR) to measure lumber stiffness and sort pieces into stress grades (Galligan and Kerns 2002). MSR initially involved mechanical devices complemented by a visual assessment. Acoustic technologies also began to emerge in the 1960s (Brashaw 2002). Initially developed for stress rating of veneer and lumber and to assess integrity of building structures, acoustic technologies advanced with the rapid growth of EWPs (Divos et al. 2008, Ross 2008). The success of NDT for lumber and veneer stimulated development of acoustic tools to assess logs for their potential yield of stress-rated lumber or veneer (Ridoutt et al. 1999; Ross et al. 1997, 1999; Wang et al. 2007a, b). The success of the log tools led to more recent development of tools to assess standing trees, thereby connecting predictions of modulus of elasticity (MOE) along the tree-to-product chain (Dickson et al. 2004; Knowles et al. 2004; Carter et al. 2005; Wang et al. 2007a, b). Tree tools enable preharvest assessments for harvest planning, can be used to monitor the stiffness in developing forest stands, (Briggs et al. 2005) and to evaluate the opportunities for genetic improvement of stiffness (Cherry et al. 2008). There are related acoustic tomography techniques for detecting and mapping internal decay and other features through tree cross-sections (Gocke et al. 2008).

Microscale (Millimeter to Nanometer Scale) Technologies

X-ray densitometry, using the transmission through and absorbance of X-rays by a material, has been used for approximately 50 years to obtain the width and density of whole rings and their earlywood and latewood components. Silviscan was developed within the past 20 years by Australia's Commonwealth Scientific and Industrial Research Organization (Evans 1994, 1999). Silviscan integrates (1) image analysis that measures radial and tangential fiber width, ring orientation, and ray orientation; (2) X-ray densitometry that gathers the ring width and density data; and (3) X-ray diffraction that measures microfibril angle, fiber orientation, and crystallite data. These direct measurements permit estimation of other fiber (wall thickness, coarseness, and specific surface area) and wood (stiffness, wood shrinkage, and reaction wood) properties. Advantages include simultaneous measurement of many more properties from a sample and obtaining data 100–1,000 times faster than was previously possible. Presently, only three Silviscan systems exist (Australia, Canada, and Sweden). Near-infrared spectroscopy (NIRS) uses the near-infrared region of the electromagnetic spectrum (from about 800 to 2500 nm) to probe bulk material and measure various properties. NIRS has been used to predict physical (density, microfibril angle, and tracheid length), mechanical (MOE and modulus of rupture), and chemical content (glucose, lignin, and extractives) wood properties (Kia et al. 2003, Kludt 2003, Kelley et al. 2004, Jones et al. 2005, Schimleck et al. 2005). NIRS advantages are relatively lower cost instrumentation, need for relatively little sample preparation, and rapid spectra collection (So et al. 2004).

Data from these technologies has been used to develop estimates of the transition from JW to MW, to test for effects of silvicultural treatments (thinning, fertilization,

Table 2. Examples of NDT technologies for macro- and microscale wood property evaluation.

Technology	Property	Method	Scale
Acoustic: Stress wave	MOE	Impale two transducers into piece, propagate sound with hammer blow, measure transit time between transducers	Macro
Acoustic: Ultrasonic	MOE	Propagate sound with short duration, high-voltage pulse rather than hammer blow	Macro
Acoustic: Longitudinal vibration	MOE	Propagate sound with hammer blow to end of piece, measure resonant frequency between ends	Macro
Acoustic tomography	Map decay and other features	Impale multiple transducers into piece, propagate sound with hammer blows, measure transit time between transducers	Macro
Transverse vibration	MOE	Generate an oscillation in a piece suspended between two supports, measure resonant frequency	Macro
X-ray tomography	Knots, decay, rings, and so on	X-rays through cross-section create virtual images of internal structure	Macro
Synchotron tomography	Cellular structure	Synchrotron radiation through wood section creates virtual images of cellular organization and cell wall structure	Micro
X-ray densitometry	Wood density	X-rays through cross-section strip create pith to bark patterns of within and between ring width and ring density	Micro
Resistograph	Wood density, decay	Use resistance to drilling through a cross-section to create pith to bark patterns of ring width and ring density	Micro
Silviscan	Physical[a] and mechanical[b] properties	Combines X-ray densitometry, X-ray diffraction, and image analysis	Micro
NIRS	Physical,[a] mechanical,[b] and chemical[c] properties	Approximately 800–2500 nm of the electromagnetic spectrum, principle of electromagnetic radiation interacting with matter and transferring energy	Macro, Micro

[a] Physical properties include wood density, microfibril angle, and cell dimensions.
[b] Mechanical properties include MOE and modulus of rupture (MOR).
[c] Chemical properties include cellulose, lignin, extractives, and so on.
Macro, meter to centimeter scale; Micro, millimeter to nanometer scale.

and pruning), as a screening tool for genetic selection, and to develop models that predict growth ring properties as a function of age and growing condition variables. In the United States, the most intensive efforts for measuring and modeling patterns of wood properties have been focused on loblolly pine (Clark et al. 2004, 2006; Jones et al. 2005; Jordan et al. 2005, 2008; Schimleck et al. 2005, Mora et al. 2007; Isik et al. 2008). The formation of the Wood Quality Consortium at the University of Georgia in 1999 has provided much of the impetus for this work. Others have used these technologies to measure chemical content (cellulose, lignin, pentosans, extractives, to name a few) of pulp and pulp yield (Wright et al. 1990, Mitchell 1995, Terdwongworakul et al. 2005). Use of NIRS to measure wood density has been investigated for potential incorporation into harvesting machines to improve bucking stems into logs (Acuna and Murphy 2006).

In the future, nanotechnology, the science of understanding and control of matter at dimensions of approximately 1–100 nm (10^{-9} m), may become a key new technology. The nanoscale is the scale of atoms and molecules, the fundamental building blocks of materials. At this level scientists can measure and directly affect physical, chemical, and biological properties of wood products. Possibilities include making wood products harder or softer, stronger and stiffer, more durable, different in color, and changing the fundamental structure of the chemical components of wood, leading to new forms of wood products (Moon et al. 2006, Moon 2008). As nanotechnology develops, the forestry sector must understand the creative opportunities that it offers in enhancing existing or developing new products and the subsequent implications for wood properties that will be needed from genetic selection and tree-growing processes in the future.

Effect of Silviculture, Genetics, and Location and Climate on Fiber Quality

Many studies have been conducted on the effects of stand age and silvicultural treatments on the direction and magnitude of change of wood properties, the delineation of JW from MW, and impacts on product properties (e.g., Briggs and Smith 1986; Megraw 1985, 1986; Larson et al. 2001; Gartner 2005, Bowyer et al. 2007). The most commonly studied species in the United States have been conifers, mainly Douglas-fir and loblolly pine, with a growth habit that produces an abrupt transition from earlywood to latewood. Information on conifers with a gradual earlywood to latewood growth habit and hardwoods is limited. Although past research has contributed greatly to understanding basic principles governing the direction and magnitude of effects, quantitative models that have the potential for integration with growth and yield models have only recently emerged (Clark et al. 2004, 2006; Jones et al. 2005; Jordan et al. 2005, 2008; Mora et al. 2007; Kantavichai et al. 2010).

Surveys in the West (US Forest Service 1965a, Maeglin and Wahlgren 1971) and South (US Forest Service 1965b, Jordan et al. 2008) indicate wide geographic variation of wood density. Because wood density is correlated with many other wood properties, similar variation in these other properties can also be expected. Such spatial information would permit geographic information system (GIS) integration of wood density with other forest inventory information and could be updated as stands age, respond to treatments, and are replaced with new stands. Managers could use this information for planning silviculture, harvest, and market activities in the context of how fiber quality influences value of traditional products, carbon, and bioenergy. Future mapping of density may be improved by supplementing or replacing static location variables (latitude, longitude, and elevation) with climate (typically defined as the mean of the last 30 years) and weather (short term, often available at a monthly resolution) and soil data. Recent studies of Douglas-fir used local weather and soil data to calculate soil moisture deficit that was found to be an important predictor of wood density on droughty sites (Bower et al. 2005, Kantavichai et al. 2010). Historically, forest growth and yield models have not included climate and weather effects but Stage et al. (1999) hold that the assumption of stable weather over time is no longer tenable and a number of researchers (Wensel and Turnblom 1998, Hill 2008) have incorporated climate and weather into growth models to reduce bias. Because an objective of future models will be to integrate fiber quality and growth and yield models, coordination of these efforts will be critical.

Information on the role of genetics in controlling and improving fiber quality is more limited. Although many have estimated heritability of various properties, very little is known about how genetics may be used to alter the within-tree patterns of wood properties, how genetically improved trees respond to silvicultural treatments, or how they respond across a range of site conditions. Isik et al. (2008) developed a model for the pattern of microfibril angle for 14 loblolly pine families, a rare step in this direction.

Fiber Quality Research Gaps

Developing markets for carbon storage and bioenergy, shifting of the pulp and paper industry to biorefineries, and the potential of new technologies, such as nanotechnology, present the forest sector with exciting transformative opportunities and challenges and integrating these changes with traditional products can increase value along the forest to end-use chain of custody. Research using life-cycle analysis has shown the environmental benefits of wood products and substituting them for nonwood materials that consume more energy and produce more greenhouse gases and other pollutants (Perez-Garcia et al. 2005). The forest sector already produces significant bioenergy and can readily expand to capitalize on the new market opportunities and environmental benefits of using forest biomass. However, although technical issues related to conversion of biomass into energy and new products are important, success in the conversion arena will be meaningless if concerns about sustaining the economic, social, and environmental values provided by forest ecosystems are ignored. Evaluating the impacts of biomass production and use includes assessment of (1) biomass growth and inventory; (2) landowner supply capability; (3) biomass harvest and transport alternatives; (4) effects of biomass removal on environmental values including nutrient depletion, long-term productivity, forest health, carbon storage, pest and fire risk reduction, habitats, and water; and (5) effects of forest biomass products on the economy, formation of green jobs, global warming, and social and cultural values. An integrated, science-based systems approach to inform society and policymakers on these five areas is urgently needed and will require long-term interdisciplinary investigation with substantial financial commitment.

Although fiber quality is not explicit in the preceding paragraph, the issue of what fiber quality will be needed to meet requirements across a more diversified set of markets is an important question. Those who grow and those who use forest biomass products will need improved understanding and communication to ensure that biomass quality matches customer needs. Without this understanding and communication value will be lost and investments may be misdirected. Although single-purpose plantations for a specific biomass product, such as energy, can be created by conversion of agricultural lands or by conversion of existing forests, integrated production of traditional and new biomass products from existing forests is likely to produce synergies, more value opportunities, and redefine how fiber quality is considered. Collectively, these changes and challenges lead to the following fiber quality research gaps:

1. The first gap is the poor understanding of the relationships between the properties of wood across various scales depicted in Figures 1 and 2 and their effect on product performance. Higher-scale quality properties of trees and logs, such as wood density, knots, and JW content, are often identified as critical components of product performance and many empirical studies (e.g., Fahey et al. 1991) have related these properties to the yield and value of recovered product grades. Although these studies provide some linkage, their utility is constrained by the product line obtained during the study and by use of traditional grades. A more useful approach would be to conduct research to understand the governing principles and relationships among properties of wood elements across different scales. This research would form the basis for models of fundamental processes and principles to predict the behavior and performance of wood products composed of elements from various scales.
2. The second gap is the lack of understanding of how physiological processes, genetics, silviculture treatments, and growing environment conditions affect properties at different scales as exhibited within trees, logs, and products. Past research has provided a good conceptual understanding of the general direction and magnitude of these effects but quantitative prediction models that are on par with and could be integrated with growth and yield models are lacking. Crown models are used in some growth models to predict knot size and distribution along stems (e.g., Maguire et al. 1999) and the log knot index, a predictor of product recovery and grade yield (Fahey et al. 1991), has been linked to a standing tree knot measure (Briggs et al. 2005, 2007). Others have developed models for the patterns of wood density (Mora et al. 2007) and microfibril angle (Jordan et al. 2005) with age. However, current models are largely descriptive rather than process driven and are disconnected across various species, genetics, treatments, and growing environments. Consequently, a model for multiple fiber quality properties of a species is lacking. Knowledge of, and the ability to predict, wood properties of a species across space and time would provide the opportunity to create and update GIS layers of fiber quality to enhance planning activities. Modeling of fiber quality in stands across landscapes must avoid bias by including appropriate

growing environment variables. A number of recent studies (e.g., Larson et al. 2001, Wilhelmsson et al. 2002, Jordan et al. 2008, Kantavichai et al. 2010) have found important effects of latitude, longitude, elevation, precipitation, temperature, and water balance on wood properties.

3. The third gap is the weak scientific infrastructure to address gaps 1 and 2. Wood science education; research infrastructure; and R & D investments at universities, in industry, and in federal laboratories have become smaller or disappeared and much of what remains lacks adequate equipment and funding. In contrast, technologies to measure and model fiber quality are advancing elsewhere. Why, e.g., does the United States, the world's largest wood producer and consumer, not have a Silviscan system? A further infrastructure issue is the need to refine wood quality measurement technologies to make them more robust and affordable for use in operational field settings rather than in specialized laboratories. Enabling more individuals along the chain of custody with the capability to routinely measure and monitor wood properties will further enhance understanding and permit the use of more flexible, customized sorting systems that can add value.
4. Gap 4 is the lack of models that integrate fiber quality into decision support systems that can be used to improve planning of investment, silviculture, harvest, and marketing activities. Because the value of a timber stand and products derived from it depends on fiber quality as well as tree size and volume per acre, planning models that incorporate only growth and yield projections from growth models may produce information leading to biased analyses and inferior decisions. Filling gap 4 can be viewed as having two main components. The first is to integrate fiber quality model outputs of gaps 1–2 with growth and yield models and enable mapping of fiber quality attributes of stands across landscapes. The second component is to incorporate this capability into a decision support system that can be used to improve investment, silvicultural, operational, and market and harvest planning. The decision support system should be designed to incorporate other forest services and values (carbon, water, habitat, to name a few) providing analysts and decisionmakers with the opportunity to assess tradeoffs. Integration in a decision support framework combines knowledge and establishes the linkages across the dimensional scales and across the technologies providing improved understanding as well as identification of important gaps requiring additional research in the future.

Looking at the potential opportunities for the forest sector and the fiber quality research gaps identified in this article, the question of how to successfully move forward must be addressed. Because the opportunities and issues involve all components of the forest sector, from landowners to manufacturers, this is a complex topic that transcends regions and organizations. It will require formation of some group to define and set priorities, establish funding, and organize and oversee the research program. Models for conducting such large-scale, complex endeavors, such as AGENDA 2020 and Consortium of Research for Renewable Industrial Materials (CORRIM) have been and continue to be successful. Some organization will need to be formed to be the catalyst for addressing the fiber quality research gaps.

Endnote

[1] Properties of wood formed in young growth rings at the center of a tree cross-section are often changing rapidly compared to subsequent older rings where properties are more stable. "Juvenile" wood is often used to describe the period of rapid change, when many properties are often considered to be inferior, and "mature" wood is often used to describe the subsequent more stable period when properties are often considered to be more desirable.

Literature Cited

ACUNA, M.G.M. 2006. Use of near infrared spectroscopy and multivariate analysis to predict wood density from chain saw chips. *For. Prod. J.* 56(11/12):67–72.

BARBOUR, J. 2007. The role of wood products in meeting ecological objectives of sustainable forest management. P. 39–38 in *Proc. of Forest Products and environment: A productive symbiosis, IUFRO All Div. 5 Conf.*, Oct. 29–Nov. 2, 2007.

BIBLIS, E.J., R. BRINKER, H.F. CARINO, AND C.W. MCKEE. 1993. Effect of stand age on flexural properties and grade compliance of lumber from loblolly pine plantaion timber. *For. Prod. J.* 43(2):23–28.

BOWER, A.D., W.T. ADAMS, D. BIRKES, AND D. NAILE. 2005. Response of annual growth ring components to soil moisture deficit in young, plantation-grown Douglas-fir in coastal British Columbia. *Can. J. For. Res.* 35: 2491–2499.

BOWYER, J., R. SMULSKY, AND J.G. HAYGREEN. 2007. *Forest products and wood science: An introduction*, 5th Ed. Blackwell Publishing. Oxford, U.K. 558 p.

BRASHAW, B. 2002. Ultrasonic veneer grading, Chap. 8. P. 129–134 in *Nondestructive evaluation of wood*, Pellerin, R.F., and R.J. Ross (eds.). Forest Products Society, Madison, WI.

BRIGGS, D.G., AND W.R. SMITH. 1986. Effects of silvicultural practices on wood properties–A review. P. 108–117 in *Douglas-fir: Stand management for the future*, Oliver, C.D., D.P. Hanley, and J.A. Johnson (eds.). Contribution no. 55, June 18–20, 1985, College of Forest Resources, Univ. of Washington, Seattle, WA.

BRIGGS, D.G., E.C. TURNBLOM, AND B.B. BARE. 2005. Non-destructive methods and process capability analysis to assess conformance of Douglas-fir stands to customer quality specifications. *N.Z. J. For. Sci.* 35(2/3):170–188.

BRIGGS, D.G., R. KANTAVICHAI, AND E.C. TURNBLOM. 2008. Effect of pre-commercial thinning followed by a fertilization regime on branch diameter in coastal Douglas-fir plantations. *Can. J. For. Res.* 38:1564–1575.

BRIGGS, D.G., L. INGARAMO, AND E.C. TURNBLOM. 2007. Number and diameter of breast-height region branches in a Douglas-fir spacing trial and linkage to log quality. *For. Prod. J.* 57(9):28–34.

CARTER, P., D.G. BRIGGS, R.J. ROSS, AND X. WANG. 2005. Acoustic testing to enhance western forest values and meet customer wood quality needs. P. 121–129 in *Productivity of western forests: A forest products focus*, Harrington, C.A., and S.H. Schoenholz (eds.). US For. Serv. Gen. Tech. Rep. PNW-GTR-642, PNW Res. Stn., Portland, OR.

CHERRY, M.L., V. VIKRAM, D.G. BRIGGS, D.W. CRESS, AND G.T. HOWE. 2008. Genetic variation in direct and indirect measures of wood stiffness in coastal Douglas-fir. *Can. J. For. Res.* 38:2478–2496.

CLARK, A., III, B.F. BORDERS, AND R.F. DANIELS. 2004. Impact of vegetation control and annual fertilization on properties of loblolly pine wood at age 12. *For. Prod. J.* 54(12):90–96.

CLARK, A., III, R.F. DANIELS, AND J.H. MILLER. 2006. Effect of controlling herbaceous and woody competing vegetation on wood quality of loblolly pine. *For. Prod. J.* 56(2):40–46.

DICKSON, R.L., A.C. MATHIESON, B. JOE, J. ILIC, AND J.V. OWEN. 2004. Acoustic segregation of *Pinus radiata* logs for sawmilling. *N.Z. J. For. Sci.* 34(2):175–189.

DIVOS, F., P. DIVOS, AND G. DIVOS. 2008. Acoustic techniques from seedling to wood structures. P. 3–12 in *Proc. of the 15th Int. symp. on Nondestructive testing of wood, Duluth, MN, Sept. 10–12, 2007*, Ross, R.J., X. Wang, and B.K. Brashaw (eds.). Forest Products Society, Madison, WI.

EVANS, R. 1994. Rapid measurement of the transverse dimensions of tracheids in radial sections from *Pinus radiata*. *Holzforsch.* 48:168–172.

Evans, R. 1999. A variance approach to the x-ray diffractometric estimation of microfibril angle. *Appita J.* 52:283–288, 294.

Fahey, T.D., J.M. Cahill, T.A. Snellgrove, and L.S. Heath. 1991. *Lumber and veneer recovery from intensively managed young-growth Douglas-fir.* US For. Serv. Res. Pap. PNW-RP-437, PNW Res. Stn., Portland, OR. 25 p.

Galligan, W., and J. Kerns. 2002. Mechanical grading of lumber, Chap. 7. P. 93–128 in *Nondestructive evaluation of wood*, Pellerin, R.F., and R.J. Ross (eds.). Forest Products Society, Madison, WI.

Gartner, B.L. 2005. Assessing wood characteristics and wood quality in intensively managed plantations. *J. For.* 103:75–77.

Gocke, L., S. Rust, U. Weihs, T. Gunther, and C. Rucker. 2008. Combining solic and electrical impedance tomography for nondestructive testing of trees. P. 31–42 in *Proc. of the 15th Int. Symp. on Nondestructive testing of wood*, Ross, R.J., X. Wang, and B.K. Brashaw (eds.). Forest Products Society, Madison, WI.

Helms, J.A. (ed.). 1998. *The dictionary of forestry*. Society of American Foresters, Bethesda, MD. 210 p.

Hill, A. 2008. *Improving diameter prediction of Douglas-fir in Eastern Washington State, USA, by incorporating precipitation and temperature*. PhD dissertation, College of Forest Resources, Univ. of Washington, Seattle, WA. 213 p.

H & W Saunders, Ltd. 2001. *Critique of cross-border comparisons relating to British Columbia in the Department of Commerce's Preliminary Determination*. In the matter of Countervailing duty investigation of certain softwood lumber products from Canada. Joint Rep. by H&W Saunders, Ltd., and Wesley Rickard, Inc., to Province of British Columbia and the BC Lumber Trade Council. 29 p. plus appendices.

Isik, F., M. Gumpertz, B. Li, B. Goldfarb, and X. Sun. 1008. Analysis of cellulose microfibril angle using a linear mixed model in *Pinus taeda* clones. *Can. J. For. Res.* 38:1676–1689.

Jones, P.D., L.R. Schimleck, G.F. Peter, R.F. Daniels, and A. Clark, III. 2005. Nondestructive estimation of *Pinus taeda* L. wood properties for samples from a wide range of sites in Georgia. *Can. J. For. Res.* 35:85–92.

Jordan, L., R.F. Daniels, A. Clark, III, and R. He. 2005. Multilevel nonlinear mixed-effects models for the modeling of earlywood and latewood microfibril angle. *For. Sci.* 51(4):357–371.

Jordan, P.D., A. Clark, III, L.R. Schimleck, D.B. Hall, and R.F. Daniels. 2008. Regional variation in wood specific gravity of planted loblolly pine in the United States. *Can. J. For. Res.* 38:698–710.

Kantavichai, R., D.G. Briggs, and E.C. Turnblom. 2010. Effect of thinning, biosolids, and weather on annual ring specific gravity and carbon accumulation of a 55 year-old Douglas-fir stand in western Washington. *Can. J. For. Res.* 40(1):72–85.

Kelly, S.S., T.G. Rials, R. Snell, L.H. Groom, and A. Sluiter. 2004. Use of near infrared spectroscopy to measure the chemical and mechanical properties of solid wood. *Wood Sci. Tech.* 38:257–276.

Kia, B.K., T.F. Schupe, L.H. Groom, M. Stine, and C.L. So. 2003. Multivariate modeling of density, strength ans stiffness from near infrared spectra for mature, juvenile and pith wood of longleaf pine (*Pinus pulustris*). *J. Near Infrared Spect.* 11:365–378.

Kludt, K.D. 2003. *Use of near infrared spectroscopy for predicting bending properties of clear wood specimens.* MSc thesis, Washington State Univ., Pullman, WA. 86 p.

Knowles, R.L., L.W. Hansen, A. Wedding, and G. Downes. 2004. Evaluation of nondestructive methods for assessing stiffness of Douglas-fir logs. *N.Z. J. For. Sci.* 34(1):87–101.

Larson, P.R., D.D. Kretschmann, A. Clark, III, and J.G. Isebrands. 2001. *Formation and properties of juvenile wood in southern pines: A synopsis*. FPL-GTR-129, US For. Serv., Forest Products Laboratory, Madison, WI. 42 p.

MacPeak, M.D., L.F. Burkhart, and D. Weldon. 1990. Comparison of grade, yield and mechanical properties of lumber produced from young fast-grown and old slow-grown planted slash pine. *For. Prod. J.* 40(1):11–14.

Madsen, B. 1992. *Structural behavior of timber*. Timber Engineering, Ltd., North Vancouver, BC, Canada. 464 p.

Maeglin, R.R., and H.E. Wahlgren. 1971. *Western wood density survey*. Rep. 2, Res. Pap. FPL-183, US For. Serv., Forest Products Laboratory, Madison, WI. 24 p.

Maguire, D.A., S.R. Johnson, and J. Cahill. 1999. Predicting branch diameters on second-growth Douglas-fir from tree-level descriptors. *Can. J. For. Res.* 29(12):1829–1840.

Megraw, R.A. 1985. *Wood quality factors in loblolly pine: The influence of tree age, position in tree and cultural practices on wood specific gravity, fiber length, and fibril angle*. TAPPI Press, Atlanta, GA. 88 p.

Megraw, R.A. 1986. Douglas-fir wood properties. P. 81–96 in *Douglas-fir: Stand management for the future*, Oliver, C., D. Hanley, and J. Johnson (Eds.). Institute of Forest Resources Contribution 55, College of Forest Resources, Univ. of Washington, Seattle, WA.

Mitchell, A.J. 1995. Pulpwood quality estimation by near infrared spectroscopic measurements on eucalypt woods. *Appita J.* 48(6):425–428.

Moon, R.J. 2008. Nano materials in the forest product industry. P. 225–228 in *McGraw-Hill Yearbook of Science and Technology*, McGraw-Hill, New York.

Mora, C.R., H.L. Allen, R.F. Daniels, and A. Clark. 2007. Modeling corewood-outerwood transition in loblollypine using wood specific gravity. *Can. J. For. Res.* 37:999–1011.

Partridge, C., and B. MacGregor. 2007. *The future of Washington's forests*. Washington State Department of Natural Resources, Olympia, WA. 100 p.

Pellerin, R.F., and R.J. Ross. 2002. *Nondestructive evaluation of wood.* Forest Products Society, Madison, WI. 210 p.

Perez-Garcia, J., B. Lippke, D. Briggs, J. Wilson, J. Bowyer, and J. Meil. 2005. The environmental performance of renewable building materials in the context of residential construction. *Wood Fiber Sci.* 37:3–17.

Ridoutt, B.G., K.R. Wealleans, R.E. Booker, D.L. McConchie, and R.D. Ball. 1999. Comparison of log segregation methods for structural lumber yield improvement. *For. Prod. J.* 49(11/12):63–66.

Ross, R.J. 2008. Transverse vibration techniques—Logs to structural systems. P. 13–16 in *Proc. of the 15th Int. Symp. on Nondestructive testing of wood*, Ross, R.J., X. Wang, and B.K. Brashaw (Eds.). Forest Products Society, Madison, WI.

Ross, R.J., K.A. McDonald, D.W. Green, and K.C. Schad. 1997. Relationship between log and lumber modulus of elasticity. *For. Prod. J.* 47(2):89–92.

Ross, R.J., S.J. Willits, W. Von Segen, T. Black, B.K. Brashaw, and R.F. Pellerin. 1999. A stress wave based approach to NDE of logs for assessing potential veneer quality. Part 1. Small diameter ponderosa pine. *For. Prod. J.* 49(11/12):60–62.

Ross, R.J., X. Wang, and B.K. Brashaw. 2008. *Proc. of the 15th Int. Symp. on Nondestructive testing of wood, Duluth, MN, Sept. 10–12, 2007.* Forest Products Society, Madison, WI. 271 p.

Schimleck, L.R., O.D. Jones, A. Clark, R.F. Daniels, and G.F. Peter. 2005. Near infrared spectroscopy for the nondestructive estimation of clear wood properties of *Pinus taeda* L. from the southern United States. *For. Prod. J.* 55(12):21–28.

So, C.L., B.K. Kia, L.H. Groom, L.R. Schimleck, T.F. Schupe, S.S. Kelley, and T.M. Rials. 2004. Near-infrared spectroscopy in the forest products industry. *For. Prod. J.* 54(3):6–16.

Sonne, E., E. Turnblom, D. Briggs, and G. Becker. 2004. Log and lumber quality and value from a low-site, 55 year old Douglas-fir stand in western Washington 20 years after thinning and biosolids fertilization. *West. J. Appl. For.* 19(1):1–8.

Stage, A.R., D.L. Renner, and J.A. Moore. 1999. Searching for robust silvicultural options in the context of uncertain climate. P 77–88 in *First Int. Conf. on measurements and quantitative methods and management and the 1999 southern forest mensurationists meeting*, Cziewski, C.J. (ed.). Univ. of Georgia, Jekyll Island, GA.

Tedwongworakul, A., V. Punsuwan, W. Thanapase, and S. Tsuchikawa. 2005. Rapid assessment of wood chemical properties and pulp yield of Eucalyptus camaldulensis is Thailand tree plantations by near infrared spectroscopy for improving wood selection for high quality pulp. *J. Wood Sci.* 51:167–171.

US Forest Service. 1965a. *Western wood density survey, report 1.* Res. Pap. FPL-27, US For. Serv., Forest Products Laboratory, Madison, WI. 58 p.

US Forest Service. 1965b. *Southern wood density survey, status report.* Res. Pap. FPL-26, US

For. Serv., Forest Products Laboratory, Madison, WI. 42 p.

Wang, X., P. Carter, R.J. Ross, and B.K. Brashaw. 2007a. Acoustic assessment of wood quality of raw materials—A path to increase profitability. *For. Prod. J.* 57(5): 6–14.

Wang, X., R.J. Ross, and P. Carter. 2007b. Acoustic evaluation of wood quality in standing trees. Part I. acoustic wave behavior. *Wood Fiber Sci.* 39(1):28–38.

Wensel, L.C., and E.C. Turnblom. 1998. Adjustment of estimated tree growth rates in northern California conifers for changes in precipitation levels. *Can. J. For. Res.* 28:1241–1248.

Wilhelmsson, L., J. Arlinger, K. Spangberg, S.-O. Lundqvkist, T. Grahn, O. Hedenberg, and L. Alsson. 2002. Models for predicting wood properties in stems of *Picea abies* and *Pinus sylvestris* in Sweden. *Scand. J. For. Res.* 17:330–350.

Wright, J., M. Burkett, and M. Gamgino. 1990. Prediction of pulp yield and cellulose content from wood using near infrared reflectance spectroscopy. *TAPPI J.* 73:164–166.