REVIEW

Uses and Desirable Properties of Wood in the 21st Century

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ABSTRACT

The desirability of specific wood properties is driven by a number of social, economic, and environmental factors that influence wood-use trends. This article discusses current continuing commercial uses of wood, significant new or emerging commercial uses, and desirable wood properties indicated by projected changes in wood use. Emerging issues and applications such as carbon markets/carbon sequestration, production of renewable energy, chemical feedstock production, and production of nano-enabled materials and products are expected to increasingly shape wood use as the 21st century progresses. However, current uses of wood are projected to remain the dominant uses for decades to come, and many desirable wood properties recognized as important to today's products will continue to be important. Projected expansion in US timber harvest will be matched by expansion of wood output from plantations. Advances in biotechnology will enable tailoring wood properties of plantation trees and short-rotation woody crops for specific end uses.

Keywords: wood utilization, wood properties, forest productivity, research needs, future resource needs

Changing needs for products to meet the needs of daily living will shape the uses of wood in the 21st century as they have in the past. Changing needs and uses of wood are driven by social, economic, and environmental factors generally beyond the control of forest sector managers and policymakers. Driving forces include growing world population and human needs for packaging, furnishings, energy, and shelter; the need to mitigate and adapt to climate change; increased competition from globalization of markets; the need to adapt products and uses; shifting demographic patterns; and the need to adapt to rapid technological change.

With that context, this article describes (1) continuing changes in markets for current commercial products, with notes on generally desirable wood properties for those products; (2) drivers of change in commercial uses that may shift the emphasis of desirable properties; and (3) significant new or emerging commercial uses and their desirable wood properties. The intent is to provide information that will be important in considering strategies for improving wood properties. However, this article suggests only in a general way alternative possible strategies to consider for attaining desirable properties given end-use market development (such as seeking many desirable properties in "generalist" trees or seeking fewer very special properties in "specialist" or "purpose grown" trees).

On a tonnage basis, the United States produces more forest products than any other country but is also the world's largest importer of forest products. Anticipating future needs in wood characteristics and volumes is critically important because US producers face increasing competition from an expanding global forest product industry. With higher imports between 1990 and 2005, the domestically produced share of US consumption decreased for paper and paperboard, wood-based panels, hardwood and softwood lumber, wood furniture, wood flooring, and molding (Figure 1). Economic globalization and associated loss of market share to imports have dampened revenues to US forests and impacted the ability to maintain socioeconomic benefits of forest management (Ince et al. 2007). Thus, sustaining global competitiveness is the one major challenge faced today by the entire US forest sector.

Anticipating future needs in wood properties and volumes is also important because primary forest products have end uses with demanding performance requirements or engineering specifications. Examples are engineered wood products, such as structural wood trusses and I-joists made from

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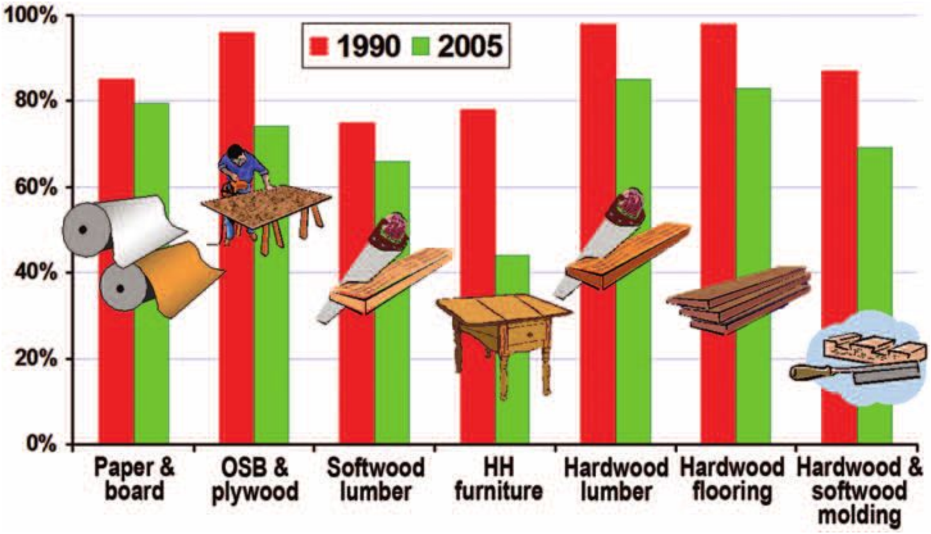

Figure 1. Domestically produced shares of US consumption for selected wood-based products, from 1990 and 2005. (Source: Ince et al. 2007.)

lumber and wood panels, and corrugated shipping containers made from paperboard. The performance of both primary and end-use products depends on wood properties. Forest products contribute basic materials to important sectors that generate more than a trillion dollars in the US economy each year, in building construction, furniture, publishing and print media, packaging and shipping, sanitary products, transportation, and communication. Management of forests to anticipate future needs helps maintain this economic contribution.

Drivers of Change

Drivers of change in forest products consumption include population and economic growth as well as shifts within forest product demand. For example, there was a general shift of growth in goods manufacturing from North America to other global regions, most notably to Europe and Asia, reducing North American consumption of paper and paperboard and use of wood in manufacturing.

Changes in forest products output depend also on supply side drivers, including infrastructure, labor costs, and wood raw material costs. Capital investment in automation has helped sustain productivity in the United States, but global access to capital and automated production technology contributed to expansion of production in regions with lower labor costs. Trade liberalization, open policies for capital investment, and low currency exchange rates attracted capital investment and capacity expansion to low-wage countries, especially for labor-intensive industries such as wood furniture. Over one-half of US wood furniture consumption is now imported, and China has become the leading source of US wood furniture imports (Ince et al. 2007).

Wood costs remain a large fraction of total production costs for forest products, and wood costs are influenced by timber supply, timber growth, and yield. Growth and yield are typically highest for select species grown uniformly in plantations, such as southern pine species widely planted in the US South. Other fast-growing trees, such as select eucalyptus species, are widely planted in tropical or semitropical regions of Latin America, Asia, and Africa.

These and other drivers of change have contributed to a shift in global expansion in forest products output from North America to mainly Asia, Europe, and Latin America. Figure 2 shows, e.g., global trends in paper and paperboard production and wood-based panel production from 1970 to 2005 among principal global regions (United Nations Food and Agriculture Organization 2008)

Projected Uses of Wood for Current Products and Desirable Wood Properties for those Products

Current uses of wood and their trends in the US economy were analyzed and projected in the recently published US Forest Service Resource Planning Act timber assessment update (Figure 3; Haynes et al. 2007). Consumption of roundwood from US forests for products is projected to grow at generally slower rates than experienced in some earlier decades, partly because of the ongoing shift of growth in wood product output to other world regions. Use of wood for sawlogs, pulpwood, and composite panels such as oriented strand board (OSB) will remain important. Harvest of veneer logs is projected to continue declining because of declining output of plywood and veneer. Projected expansion in US timber harvest for lumber, pulp, and OSB is matched by projected expansion in timber output from managed plantations. Projected growth in softwood use will be met primarily from pine plantations in the US South. Toward 2030, with maturing timber inventories and changing landownership, available hardwood pulpwood supplies from natural forests are projected to become more limited and cultivation of hardwood short-rotation woody crops (SRWCs) becomes economically feasible. This results in expansion of hardwood SRWC supply for pulpwood toward the end of the projection period (equivalent to several million acres of SRWC plantations by 2050), further displacing hardwood pulpwood supply from natural forests. However, the expansion of hardwood plantations may be limited by competition from wood imports from fast-growing plantations in the Southern Hemisphere.

Despite longer-term projections for increased wood from plantations, in the shorter term, slow projected growth in conventional wood uses and the current economic recession appear to be inhibiting expansion or new investment in timber plantations. Nevertheless, only modest expansion of plantation area along with likely productivity gains would be expected to meet timber needs for conventional products. Expanded future wood energy use (e.g., biofuels, wood pellets, and more) could, of course, eventually propel further expansion of timber plantations.

Because conventional uses of wood are projected to remain the largest uses for decades to come, wood properties currently recognized as important will continue to be important. Higher uniformity of chemical, mechanical, and physical properties and higher specific gravity (density) are among the properties of wood that will remain desirable. Uniformity contributes to more efficient processing and more uniform end-product quality, whereas higher specific gravity increases pulp throughput and is correlated with higher strength properties in

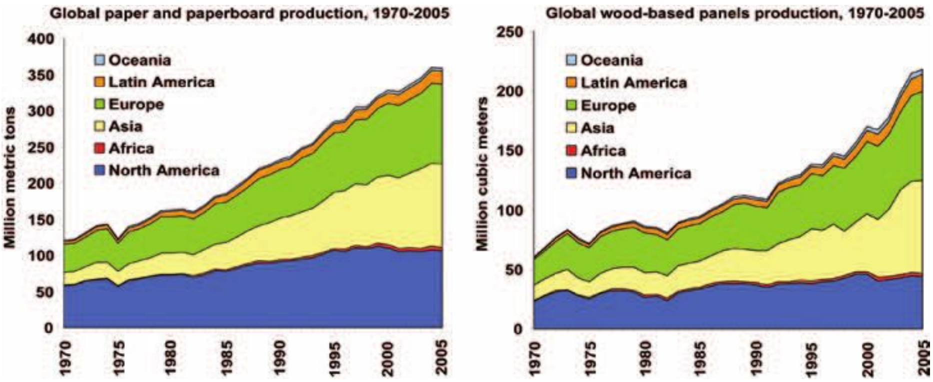

Figure 2. Global production of paper and paperboard and wood panels by principal (continental) region, from 1970 to 2005. (Source: UNFAO 2008.)

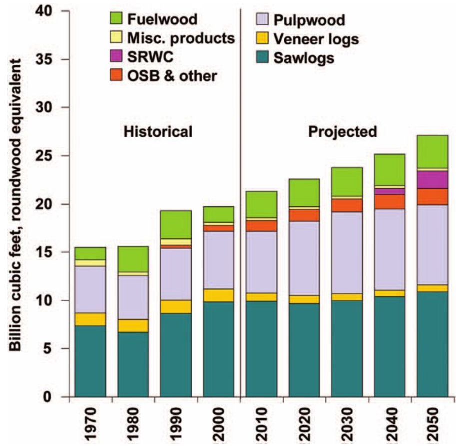

Figure 3. Roundwood equivalent of wood use in the United States by product, historical and projected, from 1970 to 2050. (Source: Haynes 2007.)

solid-sawn wood products. Higher specific gravity is also related to higher carbon and energy content per unit volume, which are likely to be of increasing value, as discussed in subsequent sections on wood energy and carbon sequestration. Lower microfibril angle, less juvenile wood, and longer, more flexible tracheids also contribute to strength and efficiency in products. Higher cellulose content and lower or modified lignin content can improve pulp yield and pulping efficiency. These properties are also better for making ethanol by hydrolysis and fermentation. Improved stem form and more desirable wood color are properties that will be of value for sawlogs and veneer logs.

The ability of the forest products industry to adopt new technologies and adapt to different resources should not be overlooked. The history of OSB stands as an example of how the forest products industry changed and adapted to resource conditions. Before commercial production of OSB in the late 1970s, the structural panel market was dominated by softwood plywood that was produced almost exclusively from Douglas-fir and southern pine veneer logs. Development of OSB permitted use of other wood species for wood panels, particularly low-density hardwoods such as poplars. More recently, OSB production has expanded in the US South, based largely on availability of southern pine pulpwood. As a result, the OSB industry has the ability to use a range of timber species—from low-density hardwoods (such as aspen) to softwoods. Relative to softwood plywood, OSB greatly increased raw material flexibility, in terms of not only species diversity but also size classes of trees (i.e., pulp logs as opposed to larger veneer logs). Furthermore, the plywood industry has now adopted technology that enables more efficient use of smaller-diameter veneer logs.

The focus of efforts in silviculture, tree genetics, tree propagation, and tree productivity improvement should continue to be improvement of wood raw material properties that are currently recognized as important and desirable in forest products:

- Greater uniformity and predictability of chemical, mechanical, and physical properties.
- Higher specific gravity (density) of wood.
- Lower microfibril angle.
- Higher cellulose content.
- Decreased or modified lignin content.
- Higher growth and yield (lower cost per ton delivered or per ton carbon).
- Improved stem form (for sawlogs and veneer logs).
- More desirable wood color.
- Longer and more flexible tracheids (fibers).
- Less juvenile wood.
- Lower moisture content (lower transport costs).

However, ongoing changes in wood use and new technologies lead to questions regarding desirable wood properties for the future in areas such as wood energy, carbon sequestration, biorefining, and nanotechnology.

Wood Energy and Biofuels

Interest in producing energy from wood has been growing in the United States and globally. Wood is the largest component of biomass energy in the United States, encompassing residential fuelwood consumption, wood energy use in the manufacture of forest products (including energy from wood residues and spent pulping liquors), and wood fuel use for combined heat and power, or cofiring with coal. In 2007, US wood energy consumption was 2,146 trillion Btu (US Department of Energy, Energy Information Administration [USDOE EIA] 2009), the energy equivalent of 118 million dry short tn of wood per year (at 17.9 million Btu per dry ton of wood). Figure 4 shows that wood remains a relatively small fraction of energy consumption relative to the total from fossil fuels and nuclear power. However, wood energy use is expected to expand in several ways.

One expanding area of commercial development is use of wood pellet fuel to produce heat or electric power. Wood pellets are typically produced from dried finely divided wood (such as hammer-milled wood or sawdust) by a mechanical compression and extrusion process. The small, uniform pellets are typically sold in bags or in bulk. Specialized wood pellet stoves are used increasingly to burn wood pellets for space heating in homes or cabins (most commonly in rural areas). Wood pellets can also be used as a commercial fuel in larger energy facilities and may be used as a substitute for coal in power boilers.

The Pellet Fuels Institute (PFI), an association of pellet producers in North America, reports that 1 million tn of pellets were shipped in 2005, an increase of 61% over 2000, and many additional pellet mills have been built since 2005. Two grades of wood pellet fuel are available for pellet stoves—premium and standard (PFI 2007). The difference between the two is their percentage of inorganic ash content. Thus, desirable properties of wood important for the pellet

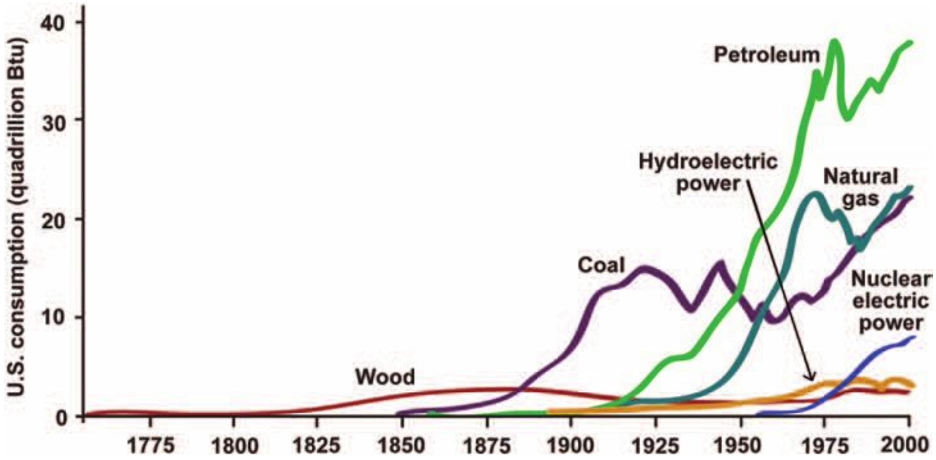

Figure 4. US energy consumption by source, from 1775 to 2000, in quadrillion British thermal units. (Source: USDOE EIA 2008b.)

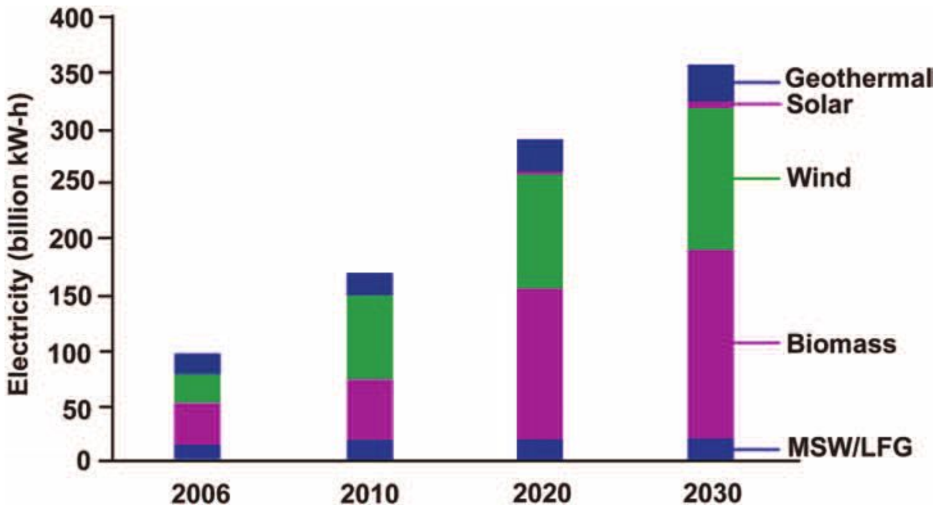

Figure 5. Nonhydroelectric renewable electricity generation by energy source, 2006 to 2030, in billion kilowatt-hours (MSW/LFG refers to municipal solid waste and landfill gas). (Source: USDOE EIA 2008a.)

fuel industry and producers of heat or electric power include low cost (i.e., delivered costs at less than or equal to pulpwood) and low ash content (i.e., low bark content or bark removal). Wood pellets are produced from both hardwood and softwood species, and pellet fuel can also be produced from other lignocellulosic biomass (i.e., agricultural residues).

Other areas of expanding commercial use of wood energy include cofiring of wood biomass with coal at coal-fired power plants or increased substitution of wood residues for fossil fuels at forest product manufacturing facilities, such as pulp mills and sawmills. Figure 5 shows that biomass combustion is projected to be the leading US source of nonhydroelectric power generation in the decades ahead, and wood is the leading source of biomass used for combustion in the United States. Industrial wood energy consists primarily of wood and bark residues burned for energy at forest product mills, including combustion at pulp mills of spent pulping liquors (containing lignin and carbohydrate residuals removed in the pulping process). Wood residues and spent pulping liquors account for most US industrial and commercial wood energy use, but use of wood that is grown and harvested specifically for energy may increase in the future. In this case, purpose-grown trees with properties such as higher bulk density (to reduce transport costs), low ash content, and higher energy content per unit volume may be in demand (Table 1).

Technologies to produce liquid biofuels from forest biomass are being developed, and early commercial demonstration projects have been funded in part by government energy programs (USDOE 2007b). Liquid biofuels that can be produced include cellulosic ethanol (via fermentation of wood sugars), diesel (via gasification and catalytic synthesis), and an array of other alcohols or alkane fuels. Glucose fermentation is an established means of producing fuel ethanol in large volumes from corn grain. Glucose is readily and cheaply produced from starch in corn grain, making corn grain ethanol production a low-cost commercial option for producing fuel ethanol. However, ethanol from wood can become more economical with improvements in hydrolysis of cellulose, hemicellulose extraction, and fermentation of wood sugars. Properties of wood that are important in this biochemical pathway to biofuels include high cellulose and/or hemicellulose content, lower lignin content, more readily separable lignin, and lower delivered cost for the wood (Table 1).

The alternative thermochemical pathway to make biofuels (and chemicals) from forest biomass involves gasification into syngas (carbon monoxide, hydrogen, and other gases) and syngas conversion to liquid fuels by catalytic reforming. The range of potential fuels includes mixed alcohols and mixed alkane fuels (Fischer–Tropsch liquids), their derivatives, or pyrolysis to bio-oil. The thermochemical approach is analogous to coal-to-liquid technology. Forest biomass has higher hydrogen content than coal and provides higher conversion ratios to mixed alcohols or alkane fuels. However, challenges in biomass gasification include the formation of tars (primarily from lignin derivatives) and carbon char, which inhibit catalytic reforming. Research is focused on achieving more efficient biomass gasification, with less tar and char, and more efficient catalysts. All components, including the lignin fraction, leaves and needles, and bark, can be used in the thermochemical process. Lignin can not be converted in the biochemical (sugar fermentation) process, and bark tannins inhibit fermentation. The thermochemical approach is likely to be more tolerant of variable wood properties (and bark content) than the biochemical approach, although lower lignin content may be desirable in gasification if it contributes to decreased tar formation. It should also be noted that wood typically has much lower ash content than most agricultural residues. Therefore, forest biomass may be preferred for the thermochemical pathway.

A prerequisite for a competitive biofuel industry based on woody biomass is the development of desirable wood properties and high biomass productivity under sustainable

Table 1. Desired wood properties and product category.

Product category	Forest wood sources	Desired wood properties
Current wood products	Commercially important hardwood and softwood species from plantations and natural stands	Higher uniformity of chemical and physical properties
Structural lumber (softwoods)	Sawlogs	Higher specific gravity (density)
Appearance lumber (softwoods)	Veneer logs	Lower microfibril angle
Hardwood lumber	Pulpwood	Higher cellulose content
Plywood		Higher growth and yield (lower cost per ton delivered or per ton carbon)
Composite panels (e.g., OSB, MDF, particleboard)		Decreased/modified lignin content
Paper, paperboard, and other pulp fiber-based products		Improved stem form (for sawlogs and veneer logs)
		More desirable wood color
		Longer and more flexible tracheids (fibers)
		Less juvenile wood
		Lower moisture content (reducing transport costs)
Biofuels/electric power/heat—Gasification/pyrolysis/direct combustion	Hardwood and softwood species from plantations and natural stands	Higher growth and yield (lower cost per ton delivered or per ton carbon)
	Pulpwood	Higher specific gravity (i.e., higher energy density)
	SRWCs	Low ash content
	Biomass–slash/thinnings (with bark)	Lower moisture content (reducing transport costs)
		Low degrade in storage
Biofuels—Biochemical conversion	Hardwood and softwood species from plantations and natural stands	Higher growth and yield (lower cost per ton delivered or per ton carbon)
	Pulpwood	Higher cellulose content (six-carbon sugars)
	SRWCs	Higher specific gravity (density)
	Biomass–slash/thinnings (with bark removed)	Lower recalcitrant cellulose (i.e., crystalline cellulose)
		Higher six-carbon sugars in hemicelluloses
		Higher syringyl lignin ratio (S/G ratio)
		Lower moisture content (reducing transport costs)
Chemical feedstocks/pharmaceuticals	Hardwood and softwood species from plantations and natural stands	Higher growth and yield (lower cost per ton delivered or per ton carbon)
	Pulpwood	Higher cellulose content (six-carbon sugars)
	SRWCs	Lower recalcitrant cellulose (i.e., crystalline cellulose)
	Biomass—slash/thinnings (with bark for thermal conversion routes; without bark for biochemical routes)	Higher six-carbon sugars in hemicelluloses
		Higher syringyl lignin ratio (S/G ratio)
		Lower moisture content (reducing transport costs)
Nanomaterials from wood	Hardwood and softwood species from plantations and natural stands	Trees with uniform size cellulose nanocrystals and cell wall nanostructures
	Clean wood or chips (no bark)	Trees with selected cell wall nanostructures important for commercial use
		Trees with reactive sites on nanostructures (e.g., for attaching chemicals)
Carbon sequestration/carbon offsets—Sequestration in forests; sequestration in products; carbon emission offsets from substitution	Hardwood and softwood species in plantations and natural stands	Higher growth and yield, higher specific gravity (carbon density) and resistance to disturbances that cause carbon loss (e.g., insects, disease, and fire)
		Durability and recyclability of wood to extend its use life
		Solidwood—Increased wood strength and durability to replace emission intensive materials
		Paper—Wood properties that decrease energy and emissions to make paper

MDF, medium density fiberboard; OSB, oriented strand board; SRWC, short-rotation woody crops.

low-input conditions (USDOE 2006). Major agricultural crops grown today for food and feed have not been bred for biofuels. Thus, many selected traits in food and feed crops, such as a high ratio of seed to straw production (harvest index), may be disadvantageous in biofuel production. To the extent that tree crops have been bred and developed specifically for maximum cellulosic fiber yield and recovery, their development may be more compatible with biofuels. In general, wood specifically bred for biofuels and adapted to a range of different soil types and climatic conditions is likely to be needed in the future.

Trees, especially fast-growing trees such as hybrid poplars, are important potential feedstocks for bioenergy and bioconversion. Such trees have a range of potential uses, including ethanol production to biomass gasification to whole-tree combustion. Genomics is an important technology that should tip the scales in the competition among various lignocellulosic feedstocks such as poplar, switchgrass, and mescanthus. To make poplar a feedstock of choice for biochemical conversion to fuels will require increasing syringyl lignin relative to guaiacyl lignin (S/G ratio) [1], increasing cellulose content, and decreasing five-carbon sugars (xylans and arabinans [2]), which would result in a higher proportion of six-carbon sugars. For gasification, higher wood density, low ash content, and low moisture content are desirable traits. To lower transportation costs, higher specific gravity and lower moisture content are also desirable. For whole-tree combustion, increased caloric content, lower ash content, and lower moisture content lead to greater energy production (Table 1).

Chemical Feedstocks and Pharmaceuticals

A potential growth area for wood-based materials is the production of chemical feedstocks and pharmaceuticals. The US chemical industry is the world's largest, producing 26% of the world's chemicals (USDOE 2009, American Chemistry Council 2007). The chemical industry uses fossil fuels for power generation and as raw materials for the manufacture of organic chemical products (USDOE 2007a). As the chemical industry seeks to reduce its environmental footprint, it is interested in using renewable raw materials as feedstock, reducing energy consumption, and implementing the concepts of green chemistry and engineering (Anastas and Warner 1998, Biomass Technical Advisory Committee 2002, Jenck et al. 2004, Garcia-Serna et al. 2007). As a result, renewable materials are expected to become increasingly used as feedstocks, and estimates by the USDOE project that the chemical industry will (1) increase use of renewable biomass materials fivefold by 2020 and another fivefold again by 2050 and (2) renewable biomass will reach use parity with fossil hydrocarbons by 2050 (USDOE 1999). The DOE identified 12 building block chemicals that can be produced from biomass via biological or chemical conversions (Werpy and Petersen 2004). This represents an important opportunity for wood-based materials, because the value of chemical products from renewable raw materials in 2020 is estimated to be over $400 billion. Moving the concept of forest biomass to chemical feedstocks forward requires significant technological improvements to economically fractionate wood into its constituent components at high yield without deleterious byproduct production.

The production of chemical feedstocks is likely to occur in a forest biorefinery that would very likely include production of liquid biofuels (discussed previously; Winandy et al. 2008). The forest biorefinery is a processing and conversion facility that (1) efficiently separates forest lignocellulosic biomass raw material into individual components and (2) converts these components into marketable products. An array of building blocks, secondary chemicals, intermediates, pharmaceuticals, and products can be produced. The forest biorefinery is enhanced if higher-value chemical materials can be produced. However, just about all aspects of forest biomass production, collection, and conversion processing need to be further developed, with the goal of making production economically viable. As for biochemical production of biofuels, desirable wood properties for production of many types of chemical feedstocks include increased syringyl lignin, increased cellulose content, and decreased xylans and arabinans to increase six-carbon sugars content (versus five-carbon sugars). Higher specific gravity and lower moisture content are desirable to lower transport costs per unit of biomass. It is also desirable (1) to manipulate cellulose chain morphology and molecular weight/degree of polymerization to allow for more complete saccharification of cellulose to sugars and (2) to manipulate polymeric components so that they have uniform molecular weight.

It is important to note there are a number of different conversion pathways and permutations of pathways for both chemical feedstock and biofuels production. Of the desirable wood properties identified here, the most important ones will differ depending on which conversion pathway or pathways are ultimately proven to be commercially viable (Table 1).

Wood-Based Nanomaterials and Nano-Enabled Products

Nanotechnology is an emerging area of science and technology that will revolutionize materials use in the 21st century (Nanoscale Science, Engineering, and Technology 2007, Saxton 2007) and holds the promise of transforming the forest products industry (Atalla et al. 2005). Because forestry provides the key materials platform for production of renewable, recyclable, and environmentally preferable feedstocks and because nanotechnology is the next leap forward in materials technology, the merging of these two critical areas is a significant new opportunity. Nanotechnology will tap the enormous undeveloped potential that trees possess—as photochemical "factories" that produce nanomaterials. By harnessing this potential, nanotechnology can provide benefits that extend well beyond fiber production into the areas of energy production, storage, and use. Novel ways to produce energy and other innovative products and processes from this renewable, domestic resource base will address major issues, including energy security, global climate change, air and water quality, and global industrial competitiveness. Potential uses for nanotechnology include developing intelligent wood- and paper-based products with an array of nanosensors built in to measure forces, loads, moisture, temperature, pressure, attack by wood decay fungi, and other factors. Building functionality onto lignocellulosic surfaces at the nanoscale will open opportunities for new pharmaceutical products, self-sterilizing surfaces, and electronic lignocellulosic devices. Use of nanodimensional building blocks will enable the assembly of functional materials and substrates with substantially higher strength properties and lighter weight products with less energy requirements.

Significant improvements in surface properties and functionality will make current wood products multifunctional and more effective. Nanotechnology can be used to improve processing of wood-based materials by improving water removal; eliminating rewetting; reducing energy usage in drying; and tagging fibers, flakes, and particles to allow customized property enhancement in processing. The exact economic impacts and opportunities for wood as a nanomaterial are unknown, but it is expected that all nanomaterials and nano-enabled products will grow to exceed a trillion dollars per year as the technology is further developed during the 21st century (Hullmann 2006).

Wood as a nanomaterial and its interaction with other nanomaterials is largely unexplored (Moon 2008). The strategy for incorporating nanotechnology and nanomaterials into forest products encompasses two pathways. The first pathway is for nanotechnologies and nanomaterials developed in other industry sectors to be adopted and deployed into materials, processes, and products used in or produced by the current forest products industry. The expected gains of this will be improved processing efficiencies, improved end-use performance, and new product development using much of the existing capital infrastructure. The second pathway is the development of completely new materials or product platforms using wood-derived nanoscale structures and properties. This second approach will lead to radically different products, processing techniques, and material applications. Nanotechnology will better use all the components that are available in wood and wood-based materials. New methods for liberating the nanodimensional constituents of wood (e.g., nanocrystals and nanofibrils) and macromolecules will be needed. The opportunities are great because wood has a nanofibrilar/nanocrystalline structure, is self-assembled, has piezoelectric properties (i.e., the ability to generate an electric potential in response to an applied mechanical stress) greater than those of quartz, and can be made multifunctional.

The value chain for wood-based nanomaterials is the same as for any other material. It is based on being able to profitably produce products that are economically viable in the marketplace. Although the focus of nanotechnology may seem to be on the nanoscale, it is really nanotechnology-enabled macroscale end products that are most important. Because of this, nanotechnology must be viewed as an enabling technology versus an end in itself. Examples of nanotechnology-enabled end-use products include lumber with built in nanosensors to record and react to static and dynamic loading; multifunctional siding that generates electricity, is self-cleaning/sterilizing, and never needs painting; and smart paper that functions as a computer and accepts downloaded information. Among first applications for nanotechnologies in forest products will be barrier coatings, architectural coatings, and preservative treatments.

The highest priority forestry research needs with respect to nanotechnology are to develop the science and technology to produce commercially important nanoscale architectures and constituents in trees, such as nanocrystalline cellulose, and to produce hierarchal assemblies within the tree itself (Atalla et al. 2005, Moon 2008). For nanocrystalline cellulose, there is a need to have trees grow cellulose nanocrystals of uniform size and shape with selected aspect ratios (length/diameter) and to increase the weight of cellulose nanocrystals per unit volume. For cell wall nanoscale architecture, trees with selected uniform nanoscale cell wall architecture that builds into larger structures with superior properties (such as cell wall layers, microfiber angle and structure, polymeric constitutive materials, and tracheid length) will be desired. There is also a need to create multiple reactive sites on nanostructures where chemicals may be added that would provide additional properties (e.g., decay resistance; Table 1).

Carbon Sequestration and Carbon Emission Offsets

Carbon sequestration in forests is recognized as a key pathway to mitigate carbon accumulation in the atmosphere. The Kyoto protocol led to the establishment of markets where credits for carbon increase for afforestation and reforestation projects can be purchased. Several voluntary carbon markets have been established in the Unites States where forestry projects can earn and sell carbon credits.

The Intergovernmental Panel on Climate Change (IPCC) 4th assessment report on mitigation of the effects of climate change cites seven key mitigation technologies and practices (IPCC 2007). One of the seven is "afforestation; reforestation; forest management; reduced deforestation; harvested wood product management; and use of forestry products for bioenergy to replace fossil fuel use." As part of this category, the report projects that by 2030 there will be "tree species improvement to increase biomass productivity and carbon sequestration."

Although the IPCC recognizes the importance of trees species improvement to increase productivity and carbon sequestration, the ways to count carbon accumulation in markets are still evolving. The Kyoto protocols provide two mechanisms to credit carbon accumulation. These are (1) the clean development mechanism (CDM) where Annex I countries (developed countries) invest in projects in non-Annex I countries (developing countries) and (2) the joint implementation (JI) mechanism where Annex I countries invest in projects in other Annex I countries and trading of assigned amount units where Annex I countries trade assigned CO_2 reduction amounts. CDM and JI activities approved in 2006 were valued at about $5 billion (€3.8 billion), but the contribution from forestry projects has been limited (World Bank 2007).

Although storage of carbon in harvested wood products was not recognized as a way of offsetting emissions under the Kyoto Protocol it is recognized as important in the IPCC guidelines for countries to report greenhouse gas emissions and sinks under the United Nations Framework Convention on Climate Change (IPCC 2006) and by the granting of credit for such storage under forest management protocols by the Chicago Climate Exchange (Chicago Climate Exchange [CCX] 2009).

At least three developing carbon markets in the United States could involve carbon credit payments for forest growth and storage in harvested wood products (World Bank 2007):

- The voluntary but legally binding CCX.
- The developing Regional Greenhouse Gas Initiative in the Northeastern states.
- California Assembly Bill 32, establishing a statewide cap on emissions.

Although not currently recognized under carbon market protocols, carbon emissions are also offset when wood or paper products substitute for alternative products that generate more carbon emissions during manufacture. For example, carbon emissions are decreased when lumber is used in place of steel or concrete in buildings (Lippke et al. 2004).

It will be desirable to have tree species and genotypes that enhance carbon sequestration in forests by growing rapidly and by resisting losses from insects and disease. Properties that enhance storage in products include durability and recyclability—particularly for long-lived structures that will extend carbon storage time. Properties that enhance carbon offsets from solidwood products include greater strength and durability to replace steel or concrete in more applications. For paper products offsets are increased if paper production requires less energy and emissions than plastics or other substitutes (Table 1).

Biotechnology as a Tool for Manipulating Desirable Properties

Genomics research with forest trees is accelerating, fueled by increased federal funding, by the dramatic reduction in sequencing costs, and by an increase in ability of bioinformatics to manipulate large date sets. Following the sequencing of the *Arabidopsis*, tomato, and poplar genomes, genes are now known for traits that influence branch angle, stem thickness, lignin content, and plant competition. Genes that control wood color are being identified and will allow for their potential control and manipulation. Other traits that could be altered through future genomics work and are highly desirable for the secondary forest products industry include longer and more flexible tracheids, reduction in the difference between properties of earlywood and latewood, reduction in the amount of juvenile wood, decrease in microfibril angle in secondary walls, increase in wood density for improved product strength, higher specific gravity, increased growth and yield, increased uniformity of fiber characteristics within stands, increased durability of sapwood, and higher uniformity of physical and chemical properties. In addition, enhanced insect and disease resistance through use of genetic modification or selection of stock for cloning should lead to forest products with fewer wood defects caused by damaging agents.

Longer-term domestication of forest trees will lead to trees that have less competition among each other through a change in root architecture, similar to agronomic row crops. These trees will have more anchor roots and less fibrous roots. Other domesticated trees will be optimized for their photoperiodic response, leading to trees with fewer side branches and greater apical dominance and a shift in crown and tree architecture leading to improved stem form and fewer defects from shed branches. Still, other tree crops will have a shift in carbon allocation from roots to the stem, thus allocating carbon to the desirable portion of the tree. In other cases, specialty trees may be modified in their ability to increase carbon sequestration.

The needs of the commercial wood market in the 21st century will determine some of the objectives of hardwood and softwood genetic improvement programs, but the ability to quickly achieve changes in desirable traits to meet market and societal demands will depend on whether those traits are controlled by a few genes or by complex quantitative genetic interactions. For example, enhanced insect and herbicide resistance, increase in cold tolerance, or production of a novel pharmaceutical ingredient or industrial catalyst might be achieved by genetic modification with one or several genes, but consistent changes in wood color may well only be achieved by sophisticated genetic recombinations that can be complicated by environmental influences. In many cases, the ability to alter tree biology to achieve improved raw material is not going to keep pace with market desires. Technological advances that can manipulate woody materials to achieve the desired end product may well have a competitive advantage.

Productivity Gaps

Important productivity gaps for wood and for needs for wood productivity research will be determined by which wood-using technologies are developed and used in the 21st century, and, in turn, our ability to improve wood productivity (improved characteristics) will influence long-run development of wood-using technologies in the 21st century. Higher productivity in terms of more uniform wood properties at higher growth rates will certainly be important for most existing and likely future technologies, and such productivity improvements may spell the difference between marginal and more competitive and profitable economic performance of these technologies. In addition, more specialized improvements in desirable wood properties will be relevant to specific product categories, as summarized in Table 1. Foresters and others who grow trees for future markets will need to contemplate the benefits of potential productivity gains, which may be more rapidly advanced via plantation forestry, tree selection, or genetic improvement. Forest landowners may consider two broad strategies concerning their forest management for future products: (1) seek to grow "generalist" trees that have higher productivity and a number of desirable properties and many uses or (2) seek to grow "specialist trees" based on the promise of special high-value markets for very specific properties. Each strategy will entail different risks and rewards that should be further identified and evaluated. However, in the near term—until new emerging markets develop further—a reasonable strategy would be to provide enhanced generalist trees, trees that allow for a range of end-use applications. Monitoring the development of emerging markets will be important to help judge when specialist trees may become economically viable.

Summary

Wood and wood-based materials and products are expected to be as important to society in the 21st century as they have been in the 20th century. Economic drivers internal and external to the forestry community inevitably come to bear, and users of wood-based materials will continue to change and evolve. Traditional forest products will likely continue to be produced in large volumes, but traditional forest products may evolve to become more multifunctional and durable without losing the ability to be recycled and reused. In addition, emerging applications such as renewable energy, chemical feedstock production, and sustainable production of nano-enabled materials and products likely will increasingly shape the use of wood as the 21st century progresses, although the eventual size of emerging markets is quite uncertain. These changes in use of wood will, in turn, serve to drive forest productivity needs and wood property requirements. Table 1 summarizes wood quality and productivity needs by product category, including principal current and future uses of wood. Despite marketplace uncertainties, it will be important to develop the science and technology needed to manipulate wood properties to meet end-use performance needs and to produce uniform wood at high growth rates and short rotations.

Endnotes

[1] Lignin has three general components that are called phenylpropanoids. These are *p*-hydroxphenyl (H), guaiacyl (G), and syringyl (S) phenylpropanoids. Gymnosperms have lignin high in G, and angiosperms are a mixture of S and G. The G component is difficult to deal with in pulping and other chemical conversion processes.

[2] Xylans and arabinans are polymeric carbohydrates derived from the hydrolysis of wood.

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