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Effects of Silvicultural Practices on Engineering Properties of Northern Hardwood Species of the Great Lakes Region

A Literature Review

Yvette Dickinson
Xiping Wang
Jan Wiedenbeck
Robert J. Ross

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Abstract

This report summarizes technical and scientific literature on the relationship between silvicultural practices and engineering properties of wood from northern hardwood species grown in the Great Lakes Region. Knowledge of engineering properties is critical to the utilization of hardwoods in engineered wood products, including but not limited to wood composites and mass timber. In addition, this review revealed the following: (a) fundamental property information from research studies conducted in the early 20th century exists for many hardwood species indigenous to the Great Lakes Region; (b) several research studies have been conducted on the effects silvicultural practices have on tree form, log quality, and growth rate; (c) there is relatively little information regarding the effects silvicultural practices have on engineering properties in these species.

Keywords: silviculture, wood, mechanical properties, engineering properties, hardwoods

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A Literature Review

Yvette Dickinson, Assistant Professor
Michigan Technological University, Houghton, Michigan, USA

Xiping Wang, Research Forest Products Technologist
USDA Forest Service, Forest Products Laboratory, Madison, Wisconsin, USA

Jan Wiedenbeck, Supervisory Research Forest Products Technologist
USDA Forest Service, Northern Research Station, Princeton, West Virginia, USA

Robert J. Ross, Supervisory Research General Engineer and Research Professor
USDA Forest Service, Forest Products Laboratory, Madison, Wisconsin, USA, and
Michigan Technological University, Houghton, Michigan, USA

Introduction

Wood quality is an important determinant of its end use and therefore its value. The recent expansion of engineered wood products has created new potential uses for wood (Ross and Erickson 2005). However, a greater understanding of wood quality is needed to allow continued development of these wood products, some of which are novel and others are currently underutilized. For example, a number of tree species typical of northern hardwood forests such as sugar maple and yellow birch were previously utilized primarily for aesthetic applications and were therefore graded visually. However, the management of forests to produce high quality hardwood logs for aesthetic applications usually results in numerous smaller dimension, lower-grade logs as a co-product. Engineered wood products, including cross-laminated timber (CLT), could utilize these lower-grade hardwood timbers, providing new markets and potentially higher returns for these lower-valued materials. Furthermore, the mechanical properties of wood from most hardwood species is comparable with that of softwood species that are currently widely used in construction materials and engineered wood products. For example, static bending properties vary among hardwood species, as shown in Table 1, which compares clear wood samples from several species commonly used in the construction industry as well as common engineered wood products (FPL 2010).

Research examining the mechanical properties of softwood species has indicated that silviculture (cultural treatments used to manipulate forests) and growing environment (for example, climate and nutrient availability) can both have significant influence on engineering properties (Zobel and Van Buijtenen 1989, Barnett and Jeronimidis 2003, Shmulsky and Jones 2011). A smaller number of studies have investigated the engineering properties of hardwood species; therefore, it is presumed that less is known about the influence of silviculture and environment on the engineering properties of hardwood species specifically. Consequently, the scientific and technical literature should be reviewed to ascertain how much is currently known about the influence of silviculture and growing environment on hardwood engineering properties, and this knowledge should be synthesized to elucidate knowledge gaps for the purpose of developing hardwood use in engineered wood products. This is particularly true of northern hardwood species in the Great Lakes Region.

The objective of this report is to provide a thorough review of published literature pertaining to the influence of silviculture and growing environment on wood quality and engineering properties in northern hardwood species of the Great Lakes Region, including sugar maple (*Acer saccharum* Marshall), red maple (*Acer rubrum* L.), basswood (*Tilia americana* L.), yellow birch (*Betula alleghaniensis* Britton), paper birch (*Betula papyrifera* Marshall), American beech (*Fagus grandifolia* Ehrh.), black cherry (*Prunus serotina* Ehrh.), quaking aspen (*Populus tremuloides* Michx.), white ash (*Fraxinus americana* L.), American elm (*Ulmus americana* L.), and northern red oak (*Quercus rubra* L.). We will address the engineering properties of wood, specifically those physical and mechanical properties that are valued by manufacturers

Table 1—Static bending properties of different woods and wood-based composite materials (FPL 2010)

Material	Modulus of elasticity		Modulus of rupture	
	GPa	$\times 10^6$ lb/in^2	MPa	lb/in^2
Clear wood				
White oak	12.27	1.78	104.80	15,200
Red maple	11.31	1.64	92.39	13,400
Douglas-fir (coastal)	13.44	1.95	85.49	12,400
Western white pine	10.07	1.46	66.88	9,700
Longleaf pine	13.65	1.98	99.97	14,500
Panel products				
Hardboard	3.10–5.52	0.45–0.80	31.02–56.54	4,500–8,200
Medium-density fiberboard	3.59	0.52	35.85	5,200
Particleboard	2.76–4.14	0.40–0.60	15.17–24.13	2,200–3,500
Oriented strandboard	4.41–6.28	0.64–0.91	21.80–34.70	3,161–5,027
Plywood	6.96–8.55	1.01–1.24	33.72–42.61	4,890–6,180
Structural timber products				
Glued-laminated timber	9.00–14.50	1.30–2.10	28.61v62.62	4,150–9,080
Laminated veneer lumber	8.96–19.24	1.30–2.79	33.78–86.18	4,900–12,500
Wood–nonwood composites				
Wood plastic	1.53–4.23	0.22–0.61	25.41–52.32	3,684–7.585

of engineered wood products. Engineering properties are those that influence machining, fastening, or gluing of wood as well as affect the performance of end-products. A specific subset of these are mechanical properties, which are measurements of a material's reaction to applied external forces.

Approach

To review the state of the art, an extensive literature search was conducted on the effect silvicultural practices have on the mechanical properties of northern hardwoods. A number of scholarly databases were used through DigiTop navigator, which indexes many natural resource databases including CAB Abstracts, Web of Science, and Engineering Village. CAB Abstracts is an applied life sciences bibliographic database emphasizing agricultural literature that is international in scope. The database covers international issues in agricultural, forestry, and associated disciplines in the life sciences from 150 countries in 50 languages. In addition, further searches of publications available on the internet were undertaken using Google Scholar (Google LLC, Mountain View, CA, USA) and USDA Forest Service TreeSearch. A wide range of combinations of search terms were used, including searching for high-level key words and appropriate tree species, various wood properties, and specific silvicultural treatments. When multiple publications authored by a particular researcher were found, a further search for other relevant publications by that author was also undertaken. After the initial searches for publications using these databases, further publications were sought using "trickle-up" and "trickle-down" approaches. Trickle-up uses the functionality of databases and internet searches to find publications that cite those that we have already found. Alternatively, trickle-down involves searching for relevant publications that are cited within those that we have already found. Each relevant publication was read and summarized into an annotated bibliography, and their findings were synthesized.

Fundamental Engineering Properties of Hardwood Species of the Great Lakes Region

Foundational Research

Markwardt and Wilson (1935) undertook an extensive study designed to establish fundamental physical and mechanical property information on many species grown in the United States (Table 2a-c). The study was initiated in 1910 by the USDA Forest Service, Forest Products Laboratory. It involved testing several hundred thousand specimens from 164 tree species. The results reported were from tests made on clear wood, free from defects that affect the properties of wood products. It was developed to be used for (1) comparing properties among species, (2) calculating the strength of wood members, (3) establishing safe working stresses, and (4) grouping species into classes of approximately like properties for a variety of end uses.

Although the publication does not explicitly state that the data were from old-growth timber, we assumed that they represent baseline property information for timber that had not been subjected to intensive forest management activities. Table 2a-c includes information on the physical and mechanical properties of wood from the following Great Lakes Region species: black ash (*Fraxinus nigra* Marshall), aspen (*Populus tremuloides* and *P. grandidentata* Michx.), basswood (*Tilia americana* L.), birch (*Betula papyrifera* and *B. alleghaniensis*), elm (*Ulmus americana* and *U. rubra* Muhl.), hophornbeam (*Ostrya virginiana* (Mill.) K. Koch), and maple (*Acer rubrum*, *A. saccharinum* L., and *A. saccharum*). All of the information for these species were from trees harvested in Michigan and Wisconsin. The study reported on by Markwardt and Wilson (1935) did not include American beech, black cherry, white ash, and northern red oak from these two states. The experimental design used by Markwardt and Wilson (1935) examined five trees of a specific species from a single location.

Markwardt and Wilson (1935) reported the following physical properties: specific gravity, density, moisture content, and dimensional stability. Specific gravity is the ratio of the weight of a substance to that of an equal volume of water. Three specific gravity values for each species are reported in Table 2a; they correspond to volumes measured when the specimen was green (above fiber saturation), at 12% moisture content, and oven-dried (0% moisture content). All are based on the weight of the wood when oven-dried. Markwardt and Wilson (1935) also presented data for the following mechanical properties: static bending mechanical properties (modulus of rupture, modulus of elasticity, work to proportional limit, work to maximum load, total work/toughness), impact bending properties (stress at proportional limit, work to proportional limit, height drop of hammer), compression parallel to grain properties (stress at proportional limit, maximum crushing strength), compression perpendicular to grain (stress at proportional limit), hardness, shear parallel to grain (maximum shearing strength), cleavage, and maximum tensile strength perpendicular to grain.

The effect that fundamental wood structure characteristics have on engineering properties of wood can be significant. In addition to density differences between and within species, the structure of the cells that comprise wood and the manner in which cells are arranged in a tree have significant influence on the basic engineering properties of wood. A number of research studies have investigated these influences. For example, several studies have investigated the relationships between growth characteristics and the compressive properties of several species of wood (Bazhenov and others 1953, Bodig 1965, Kollmann 1960, Kunesh 1961, Schniewind 1959). Bazhenov and others (1953) and Kollmann (1960) are considered seminal works that focus on species indigenous to Europe. Bodig (1965) used wood from four species [red alder (*Alnus rubra* Bong.), Douglas-fir (*Pseudotsuga menziesii* (Mirb.) Franco), Oregon ash (*Fraxinus latifolia* Benth.), and western redcedar (*Thuja plicata* Donn ex D. Don)] to investigate the effect anatomy has on compressive modulus of elasticity and strength for (1) a diffuse-porous hardwood, (2) a softwood with wide summerwood bands, (3) a ring-porous hardwood, and (4) a softwood with narrow summerwood bands. He observed the stress versus strain relationships for small specimens tested in compression in both radial and tangential orientations. Likewise, Kunesh (1961) used a diffuse-porous hardwood (yellow-poplar (*Liriodendron tulipifera* L.)) to examine the compressive properties of wood perpendicular to the grain. Schniewind (1959) used small, clear specimens from California black oak (*Quercus kelloggii* Newberry) to examine the transverse isotropy of wood and its relationship to anatomical structure. All of these studies concluded that anatomical characteristics can significantly affect mechanical properties.

Furthermore, it has been shown that physical properties can vary significantly within a tree. Woodcock and Shier (2002, 2003), for example, observed radial variation in specific gravity among species. Red maple (*Acer rubrum*) and paper birch (*Betula papyrifera*) showed radial increases from the pith to bark in specific gravity, whereas American beech (*Fagus grandifolia*) and red oak (*Quercus rubra*) showed radial decreases. This variation is influenced by tree height and diameter. Therefore, radial increases associated with low values are an early-successional characteristic that may be in response to a need for mechanical support by the tree in response to wind loading. They did not observe radial increases with species that are late-successional or persistent in mature forests.

Growth Relationships

Growth rate is likely to be influenced by numerous factors including the quality of the site, environmental fluctuations, stand density, silvicultural treatments, and genetic inheritance. The relationships between these factors and growth rate are complex. Furthermore, a number of published studies have examined the impact of growth rate, and associated variation in ring width, on wood mechanical properties irrespective of the source of variation. Therefore, we chose to consider these studies separately from those that focused on the specific relationships among mechanical properties of wood, site quality, and silvicultural treatments.

Generally, it has been assumed that growth rate influences the mechanical properties of wood through changes to cellular structure. Furthermore, many have assumed that faster growth will lead to lower mechanical properties in all species; however, the published research suggests that this is not the case. Changes in mechanical properties with variation in growth are more nuanced, and fast growth rates do not necessarily result in lower mechanical properties, particularly with ring-porous hardwoods.

Table 2a—Properties of clear wood from Great Lake states hardwood species: Physical properties[a]

Common name	Scientific name	Place of growth for material tested	Moisture condition	Number of trees tested	Number of rings per inch	Percentage summerwood	Moisture content[b] (%)	Specific gravity		Weight per cubic foot (lb/ft^3)	Shrinkage (%)		
								Test	Oven-dry		Volumetric	Radial	Tangential
Ash, black	*Fraxinus nigra*	Ontonagon County, Michigan	Green	6	23.1	53	90.6	0.447	0.526	53	15.2	5.0	7.8
			Dry	1	–	–	9.1	0.500	–	–	–	–	–
		Marathon County, Wisconsin	Green	–	25.0	–	78.9	0.456	–	51	–	–	–
			Dry	–	–	–	11.6	0.497	–	–	–	–	–
Aspen	*Populus tremuloides*	Rusk County, Wisconsin	Green	5	8.5	–	106.6	0.360	0.422	46	11.1	3.3	6.9
			Dry	1	–	–	5.2	0.421	–	–	–	–	–
	Populus grandidentata	Sauk County, Wisconsin	Green	5	8.2	–	96.4	0.354	0.412	43	11.6	3.1	7.9
			Dry	2	–	–	8.0	0.404	–	–	–	–	–
Basswood	*Tilia glabra*	Marathon County, Wisconsin	Green	3	21.8	–	115.1	0.316	0.374	42	14.5	6.2	8.4
			Dry	1	–	–	9.2	0.348	–	–	–	–	–
Birch, paper	*Betula papyrifera*	Rusk County, Wisconsin	Green	5	5.5	–	72.0	0.473	0.600	51	16.3	6.6	8.8
			Dry	2	–	–	4.2	0.582	–	–	–	–	–
Birch, yellow	*Betula lutea*	Marathon County, Wisconsin	Green	5	19.7	–	71.8	0.545	0.661	58	17.0	7.9	9.0
			Dry	1	–	–	10.3	0.624	–	–	–	–	–
Elm, American	*Ulmus americana*	Marathon County, Wisconsin	Green	–	19.0	–	70.2	0.421	–	45	–	–	–
			Dry	–	–	–	10.8	0.469	–	–	–	–	–
Elm, slippery	*Ulmus rubra*	Sauk County, Wisconsin	Green	5	17.2	51	90.0	0.474	0.554	56	13.4	4.9	8.7
			Dry	2	–	–	7.7	0.531	–	–	–	–	–

Hophornbeam	*Ostrya virginiana*	Rusk County, Wisconsin	Green	5	28.8	–	52.0	0.632	0.762	60	18.6	8.2	9.6
			Dry	4	–	–	5.6	0.748	–	–	–	–	–
Maple, red	*Acer rubrum*	Marathon County, Wisconsin	Green	–	20.0	–	69.9	0.505	–	54	–	–	–
			Dry	–		–	12.1	0.548	–	–	–	–	–
Maple, silver	*Acer saccharinum*	Sauk County, Wisconsin	Green	5	7.1	–	65.7	0.439	0.506	45	12.0	3.0	7.2
			Dry	1		–	8.2	0.479	–	–	–	–	–
Maple, sugar	*Acer saccharum*	Marathon County, Wisconsin	Green	–	22.0	–	62.5	0.560	–	57	–	–	–
			Dry	–		–	12.5	0.621	–	–	–	–	–

[a]Markwardt and Wilson (1935).
[b]Based on original and oven-dry weights.

Table 2b—Properties of clear wood from Great Lake states hardwood species: Static and impact bending properties[a]

				Static bending			Work (in.-lb/in³)			Impact bending		
Common name	Scientific name	Place of growth for material tested	Moisture condition	Stress at proportional limit (lb/in²)	Modulus of rupture (lb/in²)	Modulus of elasticity (×10⁶ lb/in²)	Proportional limit	Maximum load	Total	Stress at proportional limit (lb/in²)	Work to proportional limit (in-lb/in³)	Height of drop causing complete failure (in.)
Ash, black	*Fraxinus nigra*	Ontonagon County, Michigan	Green	2,610	6,000	1.107	0.42	11.3	28.9	7,230	2.5	35
			Dry	10,340	16,130	1.975	2.05	17.9	43.6	–	–	44
		Marathon County, Wisconsin	Green	2,580	6,000	0.967	0.40	13.1	35.0	–	–	30
			Dry	6,310	11,620	1.395	1.64	13.1	27.3	12,160	5.3	27
Aspen	*Populus tremuloides*	Rusk County, Wisconsin	Green	2,940	5,280	0.840	0.65	6.9	16.0	6,880	2.5	28
			Dry	7,600	10,770	1.290	2.43	7.3		10,470	4.0	24
	Populus grandidentata	Sauk County, Wisconsin	Green	3,190	5,850	1.185	0.50	6.1	10.6	7,600	2.7	18
			Dry	7,140	10,890	1.635	1.83	6.7	13.5	15,100	7.0	27
Basswood	*Tilia glabra*	Marathon County, Wisconsin	Green	2,370	4,440	0.852	0.39	5.9	8.6	5,760	2.0	15
			Dry	5,640	7,280	1.696	1.05	3.2	4.4	6,390	1.8	8
Birch, paper	*Betula papyrifera*	Rusk County, Wisconsin	Green	2,920	5,770	1.013	0.49	15	36.9	7,780	2.7	45
			Dry	11,440	16,050	1.814	4.32	13.2	19.2	13,840	6.6	24
Birch, yellow	*Betula lutea*	Marathon County, Wisconsin	Green	4,190	8,390	1.597	0.62	14.2	33.7	11,080	3.8	36
			Dry	13,360	19,400	2.396	4.18	17.9	40.5	18,300	8.2	53
Elm, American	*Ulmus americana*	Marathon County, Wisconsin	Green	2,850	6,940	1.052	0.44	11.8	28.0	–	–	34
			Dry	6,790	12,140	1.504	1.75	13.4	21.0	14,620	7.4	35
Elm, slippery	*Ulmus rubra*	Sauk County, Wisconsin	Green	3,740	7,710	1.215	0.72	16.1	38.6	8,640	3.1	48
			Dry	9,690	15,110	1.556	3.50	17.9	42.5	17,980	9.6	46

Hophornbeam	*Ostrya virginiana*	Rusk County, Wisconsin	Green	4,540	8,540	1.153	1.02	13.3	39.1	10,580	3.5	73
			Dry	13,920	18,600	2.107	5.34	14.4	27.6	16,560	7.6	40
Maple, red	*Acer rubrum*	Marathon County, Wisconsin	Green	4,450	8,310	1.445	0.78	9.8	20.4	–	–	28
			Dry	8,650	13,420	1.761	2.37	12.4	19.0	17,030	8.5	31
Maple, silver	*Acer saccharinum*	Sauk County, Wisconsin	Green	3,120	5,820	0.943	0.61	11	22.3	6,830	2.6	29
			Dry	7,680	10,100	1.206	2.67	7.6	11.2	15,000	9.4	24
Maple, sugar	*Acer saccharum*	Marathon County, Wisconsin	Green	4,620	8,820	1.437	0.85	9.6	17.1	–	–	28
			Dry	9,110	14,830	1.930	2.41	13.8	21.3	17,440	8.5	29

[a]Markwardt and Wilson (1935).

Table 2c—Properties of clear wood from Great Lake states hardwood species: Compression, hardness, shear, cleavage, and tension properties[a]

Common name	Scientific name	Place of growth for material tested	Moisture condition	Compression parallel to grain: Stress at proportional limit (lb/in²)	Compression parallel to grain: Maximum crushing strength (lb/in²)	Compression perpendicular to grain, stress at proportional limit (lb/in²)	Hardness (lb): End	Hardness (lb): Side	Shear parallel to grain, maximum shearing strength (lb/in²)	Cleavage (lb/in of width)	Tension perpendicular to grain, maximum tensile strength (lb/in²)
Ash, black	*Fraxinus nigra*	Ontonagon County, Michigan	Green	1,720	2,340	409	610	552	866	266	490
			Dry	6,620	8,190	1,270	1,338	994	1,794	397	760
		Marathon County, Wisconsin	Green	–	2,260	452	565	490	854	292	490
			Dry	3,950	5,590	893	1,101	792	1,660	402	696
Aspen	*Populus tremuloides*	Rusk County, Wisconsin	Green	1,600	2,160	203	266	318	625	116	182
			Dry	4,320	6,440	552	848	420	890	224	380
	Populus grandidentata	Sauk County, Wisconsin	Green	2,210	2,720	269	443	366	813	216	394
			Dry	5,100	7,080	646	710	462	1,305	236	380
Basswood	*Tilia glabra*	Marathon County, Wisconsin	Green	1,180	1,830	191	283	220	554	146	286
			Dry	3,420	4,800	540	461	364	1,432	278	406
Birch, paper	*Betula papyrifera*	Rusk County, Wisconsin	Green	1,640	2,210	304	400	486	786	239	382
			Dry	6,140	9,470	912	1,487	1,278	1,627	–	–
Birch, yellow	*Betula lutea*	Marathon County, Wisconsin	Green	2,540	3,400	439	827	754	1,146	290	486
			Dry	7,160	9,560	1,340	1,542	1,280	1,428	490	1,112
Elm, American	*Ulmus americana*	Marathon County, Wisconsin	Green		2,700	292	536	486	825	–	578
			Dry	4,040	5,840	727	892	679	1,447	321	644
Elm, slippery	*Ulmus rubra*	Sauk County, Wisconsin	Green	2,660	3,180	468	715	653	1,090	373	614
			Dry	5,740	7,950	1,254	1,144	836	1,754	294	398

Hophornbeam	*Ostrya virginiana*	Rusk County, Wisconsin	Green	2,570	3,570	733	1,157	1,170	1,374	334	450
			Dry	8,890	11,750	2,303	3,148	2,394	2,114	–	–
Maple, red	*Acer rubrum*	Marathon County, Wisconsin	Green	–	3,680	605	766	748	1,232	267	–
			Dry	5,110	6,610	1,291	1,531	1,024	1,789	476	809
Maple, silver	*Acer saccharinum*	Sauk County, Wisconsin	Green	1,930	2,490	456	671	592	1,053	302	564
			Dry	5,640	6,600	1,181	1,376	746	1,714	353	489
Maple, sugar	*Acer saccharum*	Marathon County, Wisconsin	Green	–	4,020	870	965	–	1,434	–	–
			Dry	5,360	7,370	1,755	1,909	1,342	2,112	603	–

[a]Markwardt and Wilson (1935).

There are numerous published studies in the peer-reviewed literature that have examined the relationship between tree growth and mechanical properties across a wide variety of tree species and sites (for example, Radcliffe 1953, p. 26; Sajdak 1968; Maeglin 1974; Zhang 1995; Dunham and others 1999). These studies provide diverging evidence of the relationship between growth rate and mechanical properties. It is likely that these studies have resulted in varying conclusions caused by variation in study design and the metrics used to quantify growth rate. Furthermore, the relationship between growth rate and mechanical properties probably depends on species, tree age, and site characteristics (Zobel and Van Buijtenen 1989, chapter 5).

Variations in wood structure between ring-porous and diffuse-porous hardwoods probably influence the relationship between growth rate and mechanical properties of clear wood (Paul 1959, p. 23–42). Diffuse-porous woods in the northern hardwoods of the Great Lake states, such as sugar and red maple, basswood, yellow and paper birch, American beech, black cherry, and quaking aspen, have vessels that are distributed throughout their annual growth rings. In contrast, ring-porous woods such as white ash, American elm, and northern red oak have vessels concentrated predominantly in the earlywood, forming a ring of vessels within their annual growth rings. While working in species outside of the Great Lake states, Zhang (1995) found that of 16 Asian tree species studied, ring width had little effect on specific gravity, modulus of rupture, modulus of elasticity, and maximum compression of diffuse-porous species. In ring-porous species (and semiring-porous), these mechanical properties increased with increasing growth rate in some species and did not decline in any species. The increased mechanical properties may be explained by the inter-annual constancy of earlywood ring width in these species (Zobel and Van Buijtenen 1989, p. 174–177 and literature cited therein; Barnett and Jeronimidis 2003; Shmulsky and Jones 2011, p. 254). When ring-porous species grow slowly, the large pore space of the vessels are closer together with narrower latewood rings between them. Therefore, slower growing trees will have a greater proportion of pore space, lower wood density, and lower mechanical properties than faster growing trees.

Radcliffe (1953, p. 26) and Maeglin (1974) examined the relationship between growth rate and mechanical properties of sugar maple and northern red oak, respectively. Both studies drew conclusions that slow growth may increase mechanical properties in ring-porous species but have little impact in diffuse-porous species. For sugar maple, a diffuse-porous species, ring width had no effect on wood density, proportional limit, modulus of elasticity, or modulus of rupture (Radcliffe 1953, p. 26). Likewise, growth rate did not significantly influence the specific gravity of black cherry stump sprouts (Koch 1967) nor basswood and red maple (Paul 1959, p. 23–42). In contrast, in northern red oak (a ring-porous species), the proportion of fibers increased and proportion of ray and vessels decreased as growth rate increased (Maeglin 1974).

However, the conclusions of Sajdak (1968) directly diverged from the theory that growth rate does not influence mechanical properties of diffuse-porous species. Sajdak (1968) concluded that sugar maple with the highest diameter growth rates had platy bark characteristics and significantly lower specific gravity than slower growing trees without platy bark.

Although understanding the variation of clear wood mechanical properties is fundamental, wood utilized for engineered wood products includes other wood in addition to clear wood. Therefore, understanding mechanical properties of wood from throughout the whole tree is important. For example, reaction wood within a tree, including tension wood in hardwoods, has increased cell wall thickness probably in response to supporting the additional weight of branches, uneven tree architecture, or tree movement and sway. This increased cell wall thickness results in stronger tensile strengths in tension wood, but inhomogeneous properties across the woody stem may lead to dimensional instability. In addition, the juvenile wood laid down during rapid growth early in the life of a tree tends to have lower strength properties and dimensional instability and remains in the core at the base of the woody stem throughout the life of the tree. Furthermore, tree architecture and form vary among fast and slow growing trees, and therefore, the number and size of knots and the proportion of reaction wood may vary. Faster growing trees may have a higher proportion of juvenile wood (Shmulsky and Jones 2011). For example, Dunham and others (1999) found that fast growing birch with wider rings had lower modulus of rupture, but they concluded that this was probably because of increased knot area, increased slope of grain, and presence of juvenile wood in the fast growing trees.

Effect of Site Quality on Engineering Properties

When considering the influence of silviculture on wood engineering properties, it is important to also consider the concomitant influence of site. Site refers to the physical environment in which a tree or stand grows, including (but not limited to) the soil, climate, physiography, and biotic factors. These multifaceted factors interact with each other to influence the productivity of the growing tree or stand. And, therefore, site quality may influence the structure of the growing wood and its characteristics. Furthermore, site quality is known to influence the form and shape of the growing tree and will therefore influence log quality. Log quality is an important determinant of wood engineering properties, because it influences the size and distribution of knots and proportion of clear wood production (for example, black oak (*Quercus velutina* Lam.)) (Carmean and Boyce 1974). It has been suggested that variation in wood quality and mechanical properties of wood among trees of the same species may be greater than the variation between species (Zobel and Van Buijtenen 1989).

There are a variety of methods used to quantify the quality of a site. Although individual site factors may be quantified (for example, soil nutrition may be quantified by measuring content of individual nutrients), these measurements of each independent factor may not accurately reflect the overall quality of the site as a whole. Several methods for quantifying holistic site quality have been developed, including site index. Site index is defined as the height of the dominant or co-dominant trees growing on the site at a given base age for a species. Because height growth is predominantly influenced by the quality of the site rather than stand density or silvicultural practices, it is a relatively robust measurement of overall site quality. Dominant and co-dominant trees are taller on better quality sites (Brown and Gevorkiantz 1934).

Increased site quality in terms of site index has been associated with increased wood strength. In oaks, increasing site index is associated with higher proportions of wood fiber and decreased proportions of wood vessels, resulting in higher specific gravities (Hill 1954, Maeglin 1974, Maeglin and Quirk 1984). Furthermore, higher specific gravities were associated with stronger engineering properties, including higher modulus of elasticity, modulus of rupture, maximum compression strength, and maximum tensile strength (Hill 1954, Maeglin 1974, Maeglin and Quirk 1984). Although not in species found in the northern hardwoods of the Great Lake states, similar trends of increasing wood density with increased site index have been found in other North American hardwoods such as tulip tree (*Liriodendron tulipifera*) (Van Eck and Woessner 1964). Further supporting the influence of site characteristics on wood mechanical properties, Saucier and Taras (1966) found that specific gravity of red maple varied significantly among their study sites and Hamilton and others (2007) found that there were statistically significant but small differences between the specific gravity of northern red oak grown on limestone and sandstone parent materials.

In contrast, there are a number of published studies that have found inconsistent or no statistical relationship between site quality and wood engineering properties. In northern red oak, Van Eck and Woessner (1964) found that specific gravity decreased as site index increased in one forest but the opposite was found in another. In addition, soil type (an important factor of site quality) was found to have no effect on the specific gravity of trembling aspen (Wilde and Paul 1959). Furthermore, site factors did not significantly influence modulus of elasticity and modulus of rupture of clear wood samples of yellow birch and sugar maple, and variation among trees within each site was high (Duchesne and others 2016).

Effect of Silvicultural Practices on Engineering Properties

Trees generally grow slowly; thus, there are few studies spanning a sufficiently long time horizon to adequately address silvicultural influences on the mechanical properties of wood (Zobel and Van Buijtenen 1989). There are several excellent reviews generally examining the role of silviculture on engineering properties of wood (Zobel and Van Buijtenen 1989, chapter 7; Barnett and Jeronimidis 2003; Shmulsky and Jones 2011, chapter 11); however, these publications are principally focused on coniferous species, as is the majority of research to date. Two notable exceptions are Cutter and others (2004), which generally reviewed the effect of management activities on hardwood quality, and Kellison and others (1983), which focused on southern hardwoods. We draw on these publications, in addition to reviewing primary research focused on hardwood species of the Great Lakes Region.

Unmanaged Old-Growth Forests

The original old-growth northern hardwood forest stands in the Great Lakes Region did not receive any silvicultural treatments before their harvest; therefore, they represent the “base case” of wood engineering properties without silviculture. Understanding the difference between the unmanaged old-growth stands and second-growth stands will teach us the true impact of management on the mechanical properties of wood. Today, relatively few old-growth stands remain. Most were either harvested or burned shortly after European settlement in the Great Lakes Region. The majority of remaining old-growth stands are on state or federal forest reserves and are protected from future harvest. Although the specific management history is unknown for the samples listed in Table 2a-c, given the age of the study, it is likely that many came from unmanaged, old-growth stands.

There are relatively few studies that have specifically compared the engineering wood properties of old-growth stands to second-growth stands. However, old-growth sugar maple stands may have lower specific gravity and hardness than second-growth stands (Paul 1959, p. 23–42; 1963, p. 36–43) and a higher incidence of birdseye-figured wood patterns (Bragg and others 1997), which may influence wood properties.

Regeneration Method

One of the most basic decisions a silviculturist makes when managing a forest stand is the regeneration method. Regeneration method refers to the technique used to create a new cohort of trees and is typically part of a long-term, stand-scale forest management plan, often referred to as a silvicultural system. Regeneration methods can be divided into several categories based on the distribution of age classes that are present in a forest stand over the long-term. Systems in which the harvest removes all of the canopy cover at once, creating a stand with a single cohort of trees, are considered even-aged (for example, clearcut, shelterwood, and seedtree systems). Multi-aged systems disturb only a portion of the canopy cover, creating a stand with multiple age classes mixed together. In contrast, uneven-aged regeneration methods create stands with equal areas occupied by three or more cohorts, creating a reverse-J-shaped age distribution with many small regenerating trees and fewer large trees (for example, single-tree and group selection systems). Although uneven-aged management using a single-tree or group selection systems are common in northern hardwoods across the Great Lakes Region, other regeneration methods may be used (Tubbs 1977, DNR 2006). Given that the regeneration methods alter the growing resources available for the new developing trees in a variety of ways, it is likely that the choice of regeneration method may impact the mechanical properties of wood.

Although we found no published studies that directly examined the impact of regeneration method on mechanical wood properties of hardwood species of the Great Lakes Region, several published studies examined the impact of regeneration method on tree form and log or timber grades (Eyre and Zillgitt 1953, Erdmann 1986, Strong and Niese 1994, Strong and others 1995). In particular, silviculturists have been concerned about the development of epicormic branches after silvicultural manipulations that decrease tree density and temporarily increase tree stress in hardwood stands (DNR 2006, Cameron and others 1995). The development of epicormic branches results in knots and is therefore not desirable for wood product markets that are based on visual characteristics (for example, clear wood) and wood quality for engineered products.

In a foundational study of silviculture of northern hardwoods in the Great Lake states, Eyre and Zillgitt (1953) examined the impact of a range of partial cutting techniques on sugar maple and yellow birch quality specifically. They concluded that the greater the removal during harvest, the poorer the form of regeneration and the greater prevalence of epicormic branch growth in the residual trees (particularly in smaller size classes). Furthermore, yellow birch was more greatly impacted than sugar maple. The uncut, old-growth stand had the poorest quality mature trees after harvest and the lowest density regeneration but best form regeneration. Across all treatments, there was adequate regeneration of good form, including in the clearcut treatment.

Although both even- and uneven-aged stands can produce quality logs, even-aged systems will probably need follow-up tending and density management to produce many high quality log grades (Erdmann 1986). Furthermore, even-aged methods may not provide high enough densities of regeneration to provide adequate stem training and prevent epicormic sprouting (DNR 2006). The current silvicultural guidelines for northern hardwoods in the Great Lake states based on Eyre and Zillgitt (1953) recommends uneven-aged regeneration methods to maintain good tree form and produce high quality logs (Arbogast 1957, Tubbs 1977, DNR 2006). The impact of these recommendations on the mechanical properties of wood are not well understood.

Regeneration by coppicing is used for species that sprout vigorously after harvest. This is commonly used to regenerate trembling aspen via root suckering but can also be used to regenerate oaks and red maple via stump sprouting. Regeneration of oaks and red maple via stump sprouting may cause log form problems, particularly with j-shaped crook or sweep at the base and lopsided branching. This unbalanced tree form may induce tension wood, potentially influencing the mechanical properties of the wood (Zobel and Van Buijtenen 1989).

In addition to varying the regeneration method, varying the timing of regeneration harvests and rotation length may influence both wood and tree characteristics (Zobel and Van Buijtenen 1989, Shmulsky and Jones 2011). Rotation is the length of time between the establishment of a stand and its eventual harvest and regeneration. Longer rotations result in older trees at harvest and potentially larger diameter logs. In addition, as tree size increases, the proportion of juvenile wood decreases and the proportion of clear wood in the tree bole typically increases. Furthermore, in diffuse-porous hardwoods, wood density and fiber length increase with tree age (Shmulsky and Jones 2011). For example, specific gravity, modulus of elasticity, and modulus of rupture vary with age in aspen, with a juvenile period of 16 years and maturity not occurring until year 30 (Roos and others 1990).

Density Management

The control and manipulation of tree density through planting spacing and thinning may also influence tree form and therefore wood characteristics. Generally, wider spacing among trees tends to result in faster growth rates and therefore affects wood quality as previously described (see Growth Relationships). Wood density of ring-porous hardwoods increases with faster growth rates, suggesting that density will be higher when trees are more widely spaced. However, specific species, density, site conditions, timing (initial density, or thinned early or late), and magnitude of density changes are all likely to be influential (Zobel and Van Buijtenen 1989). Furthermore, it appears that planting densities within the range typically used by foresters have little influence on wood characteristics (Zobel and Van Buijtenen 1989). For example, Paul (1963, p. 36–43) found just a 1% increase in specific gravity with thinning in 50- to 65-year-old *Fraxinus* (a ring-porous species). Likewise, Savina (1956) (cited in Zobel and Van Buijtenen 1989) found lower porosity and longer fiber elements after thinning 35- to 55-year-old oaks (also ring-porous) but no effect in trees greater than 80 years old. In contrast, Ung and others (2011) found no relationship between stand characteristics (including density) and stress wave velocity (an indicator of wood stiffness) in sugar maple and yellow birch, which are both diffuse-porous species.

Both initial density and timing of changes in tree density are likely to influence wood quality. Wide initial tree spacing that results in fast growth early in the life of the tree is expected to produce wood with a larger proportion of juvenile wood (Shmulsky and Jones 2011). Likewise, early thinning may extend the period of juvenile growth and increase the proportion of juvenile wood (Shmulsky and Jones 2011). Wide spacings may also increase the development of heartwood (Shmulsky and Jones 2011).

The influence of initial tree density on stem form, and therefore log quality, has been much more widely studied, and guidelines for northern hardwoods have been developed (Arbogast 1957, Tubbs 1977, DNR 2006). It is generally accepted that wider tree spacing results in larger diameter trees with deeper tree crowns, lower live branches, larger branches, and greater stem taper. This finding can lead to lower grade lumber because there are more and larger knots as well as lower sawing yields caused by the relatively high taper. Conversely, narrower initial spacing results in smaller diameter trees with smaller crowns, self-pruning of lower branches, smaller branches and knots, and lower stem taper. Generally, spacing has a negligible effect on tree height of the tallest trees in the stand, but high tree densities may result in greater variation in tree height with some trees remaining relatively short. For example, Paul and Baudendistel (1945) found that sugar maple grown at very low densities (open-grown) had faster growth and superior machining properties but short clear logs between branches.

Thinning to decrease tree density may decrease the likelihood of self-pruning lower branches. Furthermore, thinning may induce epicormic branching, thereby increasing crown depth, size and density of knots, and proportion of tension wood. Both size and density of knots and proportion of tension wood influence the engineering properties of wood. For example, Conover (1958) found increased forking of stems in American elm and sugar maple after thinning. Furthermore, thinning yellow birch increased diameter growth but also induced epicormic branches, potentially decreasing stem and log quality (Erdmann and Peterson 1972; Erdmann and others 1975a, 1975b). In contrast, Marquis (1969), McCauley and Marquis (1972), and Roberge (1975) concluded that thinning in sugar-maple-dominated northern hardwoods increased tree diameter without adversely influencing tree form or quality.

The impacts of partial cutting on changes to log quality can also be influenced by the type and severity of the thinning. For example, Strong and Niese (1994) found that heavy and medium single-tree selection in northern hardwoods in Wisconsin provided greater improvements in tree quality during a 40-year period compared with crop tree release treatments, diameter-limited cutting, or not cutting. Likewise, Swift and others (2013) concluded that thinning improved tree quality in northern hardwoods of New Brunswick, Canada, and that increased thinning severity increased the growth response of residual trees, including increases in veneer and sawlog-grade trees.

Therefore, silvicultural recommendations for producing high quality hardwood sawlogs generally advocate establishing trees at higher densities in even-aged regeneration methods or under canopy in uneven-aged regeneration methods to slow initial growth, control the proportion of juvenile wood, and induce good tree form. This should be followed by moderate thinning to increase growth rates after juvenile growth has ended (Tubbs 1977, DNR 2006, Shmulsky and Jones 2011).

Fertilization and Irrigation

As with density management, it is likely that the response of wood mechanical properties to fertilization and irrigation are context dependent, and making generalizations is difficult (Zobel and Van Buijtenen 1989). The specific fertilizer, species, tree age, site quality, timing, frequency, and dosage all probably interact with each other and influence the response. Furthermore, in forests, fertilization is frequently applied in combination with other types of silvicultural treatments, such as thinning, which modify response of trees (Zobel and Van Buijtenen 1989).

Generally, the use of fertilization and irrigation are uncommon in the Great Lakes Region. However, fertilization and irrigation may be used to increase availability of required growing resources if levels are depleted, thereby increasing growth rates. Therefore, fertilization and irrigation probably have an effect on wood mechanical properties similar to the growth relationships previously described. On poor sites, adding nutrients or water probably increases growth rates and consequently the wood density of ring-porous hardwoods (Shmulsky and Jones 2011). For example, Mitchell (1971) fertilized northern red oak (ring-porous), yellow-poplar (diffuse-porous), and white ash (ring-porous) with nitrogen for 5 years and observed increased growth in the first year. This fertilization resulted in observed increases in specific gravity and growth rates 27 years later, and machining properties of the wood were similar to that of unfertilized trees. In contrast, Einspahr and others (1972) observed increases in volume and decreased specific gravity in 6-year-old quaking aspen with the addition of nitrogen, phosphorous, potassium, calcium, magnesium, and irrigation after

3 years. The aspen's fiber lengths were also shortened with irrigation. Likewise, the application of fertilizer is likely to increase the proportion of juvenile wood if applied early (Zobel and Van Buijtenen 1989, Shmulsky and Jones 2011). Furthermore, the increase in growth rates is likely to result in increases in wood volume (Zobel and Van Buijtenen 1989). In addition, fertilization may increase fiber length (Shmulsky and Jones 2011). However, Foulger and others (1972) found that adding nitrogen to white ash seedlings increased vessel width and decreased fiber length. The impact of fertilization is probably short-lived, lasting only 3 to 5 years until the added nutrients are fully utilized (Shmulsky and Jones 2011). And, on moderate or high quality sites without depleted resources, there is likely to be little change to growth rates or wood mechanical properties with the addition of fertilizer or irrigation.

In addition to influencing growth rates and wood mechanical properties, the addition of fertilizer may alter tree form and epicormic growth and therefore would affect log quality and increase the presence of knots (Zobel and Van Buijtenen 1989). Although Auchmoody (1972) found that the addition of nitrogen, phosphorous, and potassium fertilizer increased the vigor of epicormic growth in northern red oak and yellow-poplar, Erdmann and others (1975a) found no impact of combinations of thinning and fertilization on yellow birch tree form.

Artificial Pruning

As with fertilization and irrigation, artificial pruning is currently uncommon in the Great Lakes Region. However, artificial pruning in forest stands can be used to achieve a number of objectives, including improving forest aesthetics and recreational value, decreasing risk of fungal pathogens in the understory, and increasing the production of clear wood by removing lower branches. Generally, it is assumed that clear wood without knots and associated defects has improved mechanical wood properties. However, pruning also directly decreases the photosynthetically active surface area of a tree and therefore may decrease the growth rate of a tree and influence the mechanical properties of the wood. The effect of pruning on wood properties probably varies among species and site qualities and depends on the severity of the pruning.

Generally, silvicultural guidelines recommend pruning less than one-half to one-third of the crown at a time because more severe pruning is likely to decrease growth rate. Furthermore, excessive pruning that rapidly and suddenly decreases the photosynthetic area of a tree is likely to induce epicormic growth and therefore decrease wood quality, particularly in maples and black cherry (Books and Tubbs 1970, Tubbs 1977, Grisez 1978, Zobel and Van Buijtenen 1989). Furthermore, silvicultural pruning guidelines suggest removing branches completely while they are small leaving the swelling at the base of the branch to ensure a small scar and faster healing (Tubbs 1977). Poor pruning techniques that create large scars or leave branch stubs may lead to occlusions and defects that degrade wood quality. Furthermore, if the goal is to decrease the "knotty core" and promote clear wood development, recommendations are generally to prune early while the tree is still relatively small and prune again relatively frequently.

Studies in yellow birch specifically demonstrated that pruning approximately 50% of the crown generally has little or no effect on the growth rate (Skilling 1959). Furthermore, the growth rate may slow in the first year following pruning, but pruned trees grew faster in the second year (Solomon and Blum 1977). Although moderate pruning had little effect on the growth rate, it increased the length of the clear stem and therefore improved log quality of the butt log (Skilling 1959). It is recommended that yellow birch be pruned to approximately 50% of the total tree height (Skilling 1959, Solomon and Blum 1977).

Concluding Comments

Based on our review of the available literature, we conclude the following:

Physical and mechanical property information generated in research studies conducted in the early 20th century exists for many hardwood species indigenous to the Great Lakes Region. However, much of these data were probably derived from old-growth stands.

Several research studies have been conducted that examined the effect silvicultural practices have on tree form, log quality, and growth rate.

It is likely that silvicultural treatments influence the structure of wood and therefore the engineering properties of northern hardwoods growing in the Great Lakes Region. However, there is relatively little information regarding the specific effect of silvicultural practices on the engineering properties of individual species.

Recommendations for Research

Areas identified for research include the following:

Research needs to be conducted on the effect silvicultural practices have on important physical and mechanical properties of hardwoods growing in the northern hardwoods region. Specifically, baseline information needs to be developed on the relationship between silvicultural practices and the engineering properties of hardwood species. This information will be useful in assessing the impact of utilizing hardwoods in engineered wood products.

Research is needed that focuses on examining the relationship between property information originally developed in the early 20th century and current property information.

Research is needed on the use of modern nondestructive assessment technologies for evaluating engineering properties in standing trees.

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