Structural lumber from dense stands of small-diameter Douglas-fir trees

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Abstract

Small-diameter trees growing in overstocked dense stands are often targeted for thinning to reduce fire hazard and improve forest health and ecosystem diversity. In the Pacific Northwest and Intermountain regions, Douglas-fir can be a predominant species in such stands. In this study, mechanical properties and grade yield of structural products were estimated for 2 by 4 lumber cut from logs of small-diameter Douglas-fir trees from a stand in northern California. The results indicate that 70- to 90-year-old suppressed Douglas-fir has excellent potential for the production of all structural lumber products. Grade recovery was determined using five grading systems. When graded as Structural Light Framing, 68 percent of the lumber made Select Structural as Light Framing, 74 percent made Construction grade, 89 percent made STUD grade, 90 percent made 2400Fb-2.0E under machine stress rating rules, and 46 percent would qualify as stock for glue laminated beams. Care must be taken in kiln-drying to avoid the commonly observed problem of twist.

Douglas-fir (*Pseudotsuga menziesii*) is one of the world's most important and valuable species. Its latitudinal range is the largest of any commercial conifer of the western United States (Burns and Honkala 1990), extending from the Rocky Mountains to the Pacific Coast and from Mexico to central British Columbia. Two varieties are recognized botanically: Coast (*P. menziesii* [Mirb.] Franco var. menziesii) and Rocky Mountain (*P. menziesii* var. glauca [Beissn.] Franco). Douglas-fir grows under a large variety of climate and soil conditions, reaching its best growth on deep well-aerated soils with pH ranging from 5 to 6. In these conditions, Douglas-fir trees reach a height of 250 feet (76.2 m), with a diameter at breast height (DBH) up to 6 feet (1.8 m). This species is classified as intermediate in shade tolerance. First-year seedlings survive and grow best under light shade, but older seedlings require full sunlight.

Approximately 302,900 × 10^6 ft^3 (8577 × 10^6 m^3) (net) of softwood growing stock exists in the western United States, excluding Alaska and the Great Plains (USDA 2002). At approximately 114,300 × 10^6 ft^3 (3237 × 10^6 m^3), Douglas-fir is by far the largest component of this western resource **(Table 1).** About 15 billion (10^9) ft^3 (450 million m^3) of this Douglas-fir is from trees 5 to 10.9 inches (127 to 277 mm) in diameter, and about 24 percent of these trees are growing in overstocked stands. Of the 130 × 10^6 acres (52.6 × 10^6 ha) of western timberland not reserved for timber harvest and meeting minimum productivity standards, it has been suggested that 29 × 10^6 acres (11.7 × 10^6 ha) are high priority areas for fuel reduction treatments **(Fig. 1).** (High priority areas are classified as Fire Regime Condition Class 3, areas at risk for losing key ecosystem components in a fire.) California alone has 5.5 × 10^6 acres (2.2 × 10^6 ha) of timberland in Class 3 areas (USDA 2003). Most trees in these high priority treatment areas are in diameter classes below 10 inches (250 mm) DBH. However, the majority of the biomass falls in diameter classes above 10 inches (250 mm) DBH. This increase in the number of small trees and the resulting increase in harvesting and processing

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Table 1. — Net volume of softwood growing stock in three western U.S. regions (USDA 2002).[a]

Species	All diameters		Diameter of 5.0 to 10.9 inches (127 to 277 mm)	
	($\times 10^6$ ft^3)	($\times 10^6$ m^3)	($\times 10^6$ ft^3)	($\times 10^6$ m^3)
Douglas-fir	114,281	3,236.1	15,908	450.5
True firs	48,827	1,382.6	11,224	317.8
Ponderosa pine[b]	37,352	1,057.7	6,185	175.1
Lodgepole pine	28,420	804.8	17,657	500.0
Western hemlock	20,894	591.7	3,808	107.8
Engelmann spruce[c]	19,477	551.5	4,194	118.8
Western redcedar	7,736	219.1	1,252	35.5
Western larch	5,984	169.4	1,586	44.9
Redwood	4,631	131.1	242	6.9
Incense cedar	3,611	102.3	399	11.3
Sugar pine	3,372	95.5	139	3.9
Western white pine	1,227	34.7	174	4.9
Sitka spruce	328	9.3	10	0.3
Other softwoods	6,763	191.5	1,591	45.1

[a]Pacific Northwest, Pacific Southwest, and Intermountain West regions
[b]Includes Jeffrey pine.
[c]Includes other spruces except Sitka.

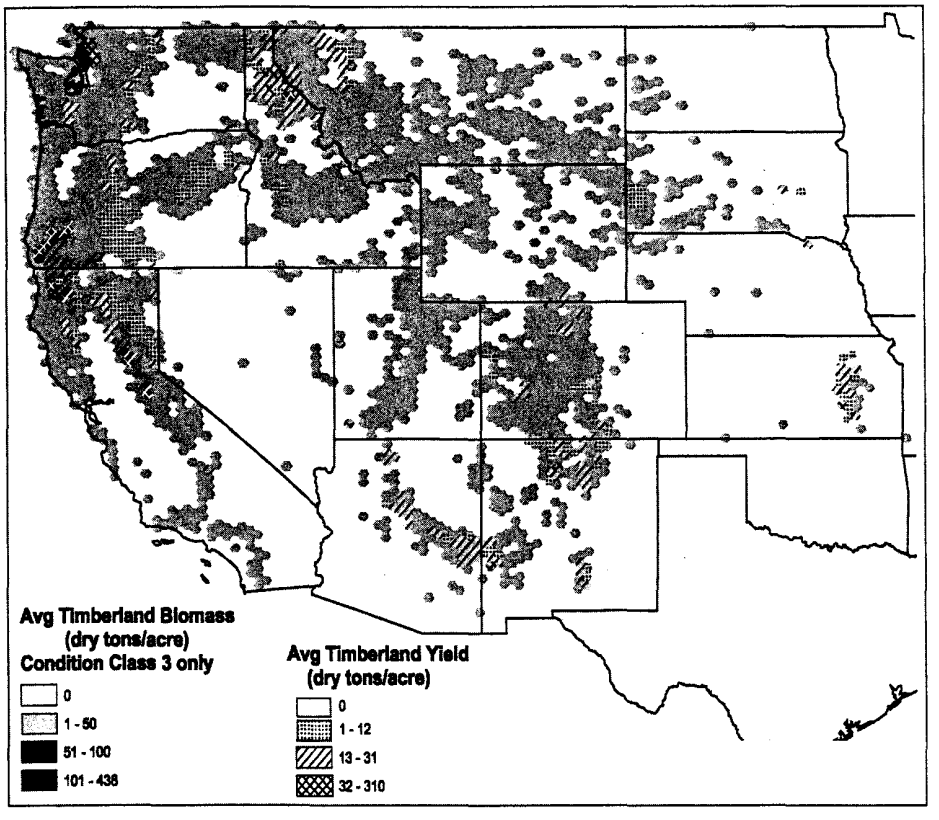

Figure 1. — Potential opportunities for high-priority fuel reduction thinning on timberland in the western United States (Vissage and Miles 2003).

costs are largely responsible for the accumulation in western forests (Barbour 1999). Douglas-fir represents one of the largest segments of small-diameter trees between 5 and 11 inches (127 and 279 mm) DBH in northern California.

In 1999, a study was initiated to evaluate the yield and economic value of structural and nonstructural products from Douglas-fir trees 10 inches (250 mm) and less in diameter growing in dense overstocked stands in northern California. The objective of this paper is to provide estimates of the grade yield and properties of structural lumber products from this resource. Future papers will present information on other wood quality aspects.

Procedures

Log selection and processing

Logs were obtained from the Hayfork Ranger District in the Shasta-Trinity National Forest. The stands in this forest are predominantly mixed conifers with some hardwoods. Predominant softwood species include Douglas-fir and ponderosa pine (*Pinus ponderosa* Dougl. ex Laws.), as well as some sugar pine (*P. lambertiana* Dougl.), white fir(*Abies concolor* [Gord. & Glend.] Lindl. ex Hildebr.), and incense-cedar (*Libocedrus decurrens* Torr.). Hardwoods include Pacific madrone (*Arbutus menziesii* Pursh), California black oak (*Quercus kelloggii* Newb.), and Oregon white oak (*Quercus garryana* Dougl. ex Hook). Most softwood trees are "pole size," defined as 5 to 11 inches (127 to 279 mm) DBH; a few larger diameter trees are scattered throughout the stand **(Table 2).** The understory is often dominated by Douglas-fir that is typically 4 to 20 inches (100 to 560 mm) in diameter and 70 to 150 years of age. Such suppressed Douglas-fir may have 15 or more rings per inch (25.4 mm) and few large knots.

On the Trinity portion of the Shasta-Trinity National Forest, about two-thirds of trees less than 10 inches (250 mm) DBH are Douglas-fir **(Table 3).** The logs for this study were taken from the 67-acre Farmer Ridge sale. The stands on Farmer Ridge are primarily even-aged Douglas-fir, approximately 150 years old, with a small component of ponderosa pine and sugar pine and some mixed hardwoods. This is site class 3 to 4 land, with canopy closure as high as 80 to 90 percent. The objectives of the sale were to thin the understory to break up fuel ladders and to maintain or improve forest health. The stocking density of these stands was 900 to 1,000 stems/acre (0.4 ha). The goal was to thin the stands to 100 to 150 stems/acre with approximately 20 by 20 feet (6 by 6 m) between dominate trees.

The sample design consisted of five 1-inch- (25-mm-) diameter class increments ranging from 5 to 10 inches (127 to

Table 2. — Size and age distribution of conifers on Shasta-Trinity National Forest (WRTC 1999).

Size category	Diameter		Age	Percentage of board foot volume
	(in)	(mm)	(yr)	
Seedlings, saplings	0 to 5	0 to 127	0 to 30	9
Poles	5 to 11	127 to 279 mm	30 to 80	8
Small sawtimber	11 to 24	280 to 610 mm	80 to 180	69
Large sawtimber	>24	>610 mm	>180	14

Table 3. — Estimated amount of small-diameter conifers available from thinnings on Trinity National Forest (WRTC 1999).

	Volume	Percentage of total volume
	($\times 10^3$ BF)	
Mixed conifers[a]	1,983,983	95.5
Douglas-fir	20,791	1.0
	73,624	3.5

[a]70 percent Douglas-fir; 30 percent ponderosa. sugar, and Jeffery pines.
[b]Planted by Forest Service: 80 percent ponderosa pine, 20 percent Douglas-fir.

Table 4. — Experimental design for initial tree and log sampling.[a]

Diameter classes for trees		Trees	Logs
(in)	(mm)	(*n*)	(*n*)
5	127	37	54
6	152	45	88
7	178	43	107
8	203	43	126
9	229	45	148
10	254	7	25

"Some additional mill length logs were later selected at the mill to provide more 2 by 6's for a future study.

Table 5. — Log dimension breakdown for Economizer sawmill.

Small-end diameter of log outside bark		Lumber size[a]
(in)	(mm)	
4.0 to 5.0	102 to 127	2 by 4
5.0 to 6.5	127 to 165	2 by 4
6.5 to 7.25	165 to 184	2 by 4
7.25 to 10.0	184 to 254	2 by 6

[a]2 by 4 is nominal 2 by 4 inches, standard 38 by 89 mm; 2 by 6 is nominal 2 by 6 inches. standard 35 by 140 mm.

254 mm). Each diameter class contained approximately 40 trees, for a total sample of 220 trees **(Table 4).** Several 10-inch (254-mm) DBH trees were also selected. Physical measurements were taken on all trees and logs were sampled for use in other phases of the analysis: trees were numbered to assure tracking of lumber and logs to the trees from which they were cut. After harvest, tree-length logs were cut at the sawmill into 12-foot (0.42-m) lengths, including 6 inches (150 mm) of trim. The final length of the top log of the tree was as short as 10 feet (3 m).

Measurements of log dimensions, defects, and other characteristics were taken. These measurements included marking the first 20 annual rings as a general indication of the extent of juvenile wood (Senft et al. 1985, DiLucca 1989, Abdel-Gadir et al. 1993). To supplement the number of 2 by 6's (nominal 2 by 6 inches, standard 38 by 140 mm) available for future study, some additional trees in the largest diameter class were selected. The butt logs of these trees furnished 2 by 6 lumber and the upper logs provided some 2 by 4 lumber (nominal 2 by 4 inches, standard 38 by 89 mm). The logs were sawn into lumber on an Economizer' portable mill. The width of the lumber was dependent on the small-end diameter of the log **(Table 5).** The lumber was kiln-dried and surfaced according to industry standards.

Grading and testing

After surfacing, the lumber was shipped to the Forest Products Laboratory in Madison, Wisconsin, and placed in a conditioning room at approximately 73°F (23°C) and relative humidity of 65 percent for several months. The 2 by 4 lumber was then graded by a retired quality supervisor of the West Coast Lumber Inspection Bureau. Each 2 by 4 was graded by several structural grading systems (Structural Light Framing, Light Framing, STUD). for the visual requirements of machine stress rated (MSR) lumber, and for laminating grades (AITC 1993, WCLIB 1993). If the grade of the lumber could be increased by trimming 2 to 4 feet (0.6 to 1.2 m) from the end, the trimmed grade and trimmed length were also recorded.

Modulus of elasticity (MOE) was determined by transverse vibration (E_{TV}) using a DynaMOE (Tip Murphy Trading Company, Riverside, IL) machine with specimens in the flatwise orientation and supported at their ends. Specimens were then tested on edge to failure using third-point loading and a span-to-depth ratio of 21:1 following the procedures of ASTM D 198 (ASTM 2002). The rate of loading was approximately 2 inches (51 mm) per minute. Properties determined were MOE and modulus of rupture (MOR). After testing, ovendry moisture content (MC) and specific gravity (SG) based on ovendry weight and ovendry volume were determined from sections taken near the failure region (ASTM D 2395 and D 4442) (ASTM 2002).

Because there is interest in using this type of Douglas-fir lumber for flooring (Niemiec and Brown 1995), hardness tests were conducted on a randomly selected subset. The procedure followed was that of ASTM D 143 (ASTM 2002), except that the unbroken ends of the 2 by 4's were used as test specimens. Thus, the lumber was only 1.5 inches (38 mm) thick instead of the prescribed 2-inch- (51-mm-) thick material. Nonetheless, the thickness used should provide results comparable with those from the standard thickness because the lumber exceeded the minimum thickness of 1 inch (25.4 mm) prescribed in ASTM D 1037 (ASTM 2002).

Because tests were conducted on 2 by 4 lumber, specimens were oriented only in the radial direction. It is generally assumed that there is little difference between radial and tangential values, and ASTM D 143 specifies that hardness should be determined from the average of two penetrations each on the

[1] Formerly manufactured by Canadian Mill Systems, Inc., New Westminster, BC. A similar machine is available from MicroMill Systems, Inc., Summerland, BC.

radial and tangential faces. For 1,258 dry Douglas-fir hardness specimens in the clearwood databank (USDA 1999), the average difference in hardness between matched radial and tangential pairs (radial-tangential) is only −32 pounds (-14.5 kg), with the difference between radial and tangential pairs ranging from +380 pounds (+172 kg) to −454 pounds (−206 kg). Even for dry red oak, the difference between pairs of radial and tangential hardness values is only −29 pounds (−13 kg), with a range of +580 pounds (+263 kg) to −897 pounds (−407 kg).

MSR simulation

Simulations of MSR grades were conducted for a range of potential grades having MOE values ranging from 1.0 to 2.4 × 10^6 psi (6.9 to 16.5 GPa). The simulations were conducted as if only one grade were to be produced at a time. This approach helps potential producers in assessing the resource quality with respect to MSR production. This does not imply that each of these grades is commonly produced, or that it is undesirable to produce other grades. Normally at least two MSR grades are produced at once. Simultaneous production of more than four grades of Douglas-fir MSR is not common. The visual grades of lumber that do not qualify for the mix of MSR grades produced are also an important economic consideration. Mill managers typically select a mix of grades that optimizes the value of their production over all grades and grading systems. This optimization considers such factors as knowledge of the characteristics of the available resource. information on current markets, purchase orders on hand, and technical capabilities of the mill. The optimum grade mix might change continuously in response to a change in any of these considerations. More information on MSR lumber may be found in Galligan and McDonald (2000) and the Summer 1997 issue of *Wood Design Focus* (FPS 1997). Supplemental discussions of marketing considerations in MSR lumber production and an example of simulating the simultaneous production of two MSR grades are given in Green et al. (2000).

Individual pieces in the simulation of MSR grades had to meet three criteria to qualify for a specified grade: 1) fifth percentile (minimum) MOE; 2) fifth percentile (minimum) MOR; and 3) grade average MOE. Traditionally, for mechanically graded lumber, the fifth percentile nonparametric point estimate must equal 82 percent of the target average MOE value (i.e., 0.82* average grade MOE). This limits the variability of the lower half of the MOE distribution of the grade to a coefficient of variation (COV) of 11 percent. Thus, the minimum MOE for a 1.3E grade would be 0.82* 1.3 = 1.07 × 10^6 psi (7.4 × 10^6 GPa). The minimum MOR value would be 2.1 times the allowable bending strength (Fb) for the specified grade. For a given sample size, ASTM D 2915 (ASTM 2002) shows how many pieces are allowed to be below the specified MOR value to estimate the fifth percentile at the 75 percent confidence level used in our simulation. In addition to the MOE and MOR requirements, for various Fb values knots (and a few other defects) partially or wholly at the edges of the piece may not occupy a set proportion of the net cross section:

0 to 900 Fb	not more than 1/2 the net cross section
950 to 1450 Fb	not more than 1/3 the net cross section
1500 to 2050 Fb	not more than 1/4 the net cross section
2100 Fb	not more than 1/6 the net cross section

Laminating grades

Another traditional structural use for Douglas-fir is the production of glued-laminated timbers. Two types of grades are used in production of Douglas-fir glulam: visually graded and E-rated. The rules for visual rating are entirely based on the characteristics that are readily apparent to the human eye, such as knot size, slope of grain, and wane. The following tabulation is an example of the knot size limitations for visual glulam grades:

Grade	Maximum knot size
L1	1/4 width
L2	1/3 width
L3	1/2 width

Lumber for the L1 grade of Douglas-fir must qualify as dense. E-rated lumber is graded by a combination of lumber stiffness and visual characteristics. These grades are expressed in terms of MOE followed by limiting knot size. Thus, a 2.0E-1/6 grade has an MOE of 2.0 × 10^6 psi (13.8 GPa) and a maximum edge knot size of 1/6 the width. For lamination grades, MOE is measured flatwise with the specimen supported at the ends.

Glulam manufacturers generally purchase visually graded lumber and regrade it according to laminating requirements such as wane, skip, and warp. Special tension lamination grades are selected for use in the outer 5 percent of the laminations of bending members (AITC 1993). These grades must meet strict requirements on strength-reducing characteristics such as knots, slope of grain, and density.

Results and discussion

The 220 trees sampled in this study ranged from 15 to 109 years old, with an average age of 66.6 years. Because these trees have generally been growing underneath larger trees, the juvenile core on the butt logs has been suppressed, with the first 20 rings occupying only about 20 percent of the log diameter. For most of the lumber, the number of growth rings was typically 10 to 15 per inch (25.4 mm). The knots were also relatively small on these logs. The average knot on the butt logs was about 0.2 inch (5 mm) and on the top logs 0.5 inch (13 mm). These two characteristics, knot size and amount of juvenile wood, have been shown to be good predictors of the yield of both visually graded and mechanically graded lumber from small-diameter Douglas-fir trees (Fahey et al. 1991). Log taper was also generally less than might be expected for small-diameter trees growing in more open conditions. Note that in closed stands Douglas-fir is exceedingly slow to self-prune because even small dead limbs are resistant to decay and persist for a very long time (Bums and Honkala 1990). On the average, Douglas-fir growing in natural stands is not clear to a height of 17 feet (5 m) until it is 77 years old and a height of 33 feet (10 m) until 107 years. Thus, such trees are not likely to produce many clear cuttings and may be particularly suitable for structural products.

Side hardness

Table 6 gives side hardness values determined on the 120 pieces of 2 by 4 lumber from suppressed trees. The SG of 0.49 is typical for Douglas-fir. The hardness value of 864 pounds (3.84 kN) is higher than the species average and probably reflects the slow growth rate of this material. Although the hardness of Douglas-fir is lower than that of some traditional hardwood species that have been used for flooring, it is in the vi-

Table 6. — Side hardness of lumber from small-diameter Douglas-fir logs.

Species	Moisture content	Specific gravity[a]	Side hardness		Reference
	(%)		(lb)	(kN)	
Douglas-fir	12	0.49	864	3.84	This study
Douglas-fir					
Coast	12	0.48	710	3.16	FPL 1999
Interior west	12	0.50	660	2.94	FPL 1999
Interior north	12	0.48	600	2.67	FPL 1999
Longleaf pine	12	0.51	870	3.87	FPL 1999
Western larch	12	0.52	830	3.69	FPL 1999
Sugar maple	12	0.63	1,450	6.45	FPL 1999
Oak					
Northern red	12	0.63	1,290	5.74	FPL 1999
Eastern white	12	0.68	1,360	6.05	FPL 1999
California black	7	NR	1,034	4.60	Niemiec and Brown 1995
Oregon white	8	NR	1.866	8.30	Niemiec and Brown 1995
Pacific madrone	7	NR	1,564	6.96	Niemiec and Brown 1995

[a]Based on ovendry weight and volume at indicated moisture content. NR = not reported.

Table 7. — Grade yield of 2 by 4 lumber.

Grade	Full length			Trimmed		
	n	Board feet	Yield (%)	*n*	Board feet	Yield (%)
Structural light framing						
Select structural	544	4,256	60.7	605	4,640	67.8
No. 1	55	421	6.0	63	473	6.9
No. 2	128	992	14.1	160	1,179	17.2
No. 3	52	401	5.7	43	316	4.6
Economy	122	946	13.5	30	233	3.5
No. 2 and better	727	5,669	80.8	828	6,292	91.9
Light framing						
Construction	608	4,738	67.5	667	5,118	74.4
Standard	128	991	14.1	159	1,177	17.1
Utility	53	411	5.8	43	323	4.7
Economy	113	885	12.6	33	257	3.8
STUD						
STUD	726	5,639	80.2	801	6,123	88.7
Economy	176	1,385	19.8	101	781	11.3

cinity of the hardness of other softwood species used for flooring.

Visually graded structural lumber

In this paper, grade yield is based on the total volume of 2 by 4's produced from the logs rather than the volume of wood in the entire logs. This was done to make the results more applicable to mills that use other equipment to saw lumber. A subsequent paper will evaluate recovery and grade yield for the Economizer portable sawmill. The yield of lumber in the Structural Light Framing grading system is shown in **Table 7.** Based on trimming to improve grade, 68 percent of 2 by 4 lumber made Select Structural and almost 92 percent made No. 2 & better. Although the grade of "dense" is no longer utilized, all the lumber would have qualified as dense by ASTM D 245 criteria (ASTM 2002). With the full-length pieces, the primary cause of failure to make grade was the presence of wane; 23 percent had wane as the grade-controlling defect prior to trimming. Warp, specifically twist, can be a problem with lumber sawn from small-diameter suppressed-growth Douglas-fir (Shelly and Simpson 2000). A consistent amount of twist was observable in 2 by 4's produced for this study. However, only 4 percent of the lumber had twist sufficiently severe to limit the grade assignment. Drying recommendations for suppressed-growth Douglas-fir are given in the paper by Shelly and Simpson (2000).

Barbour and Parry (2001) investigated the yield of Structural Light Framing from 20- to 100-year-old Douglas-fir grown on managed plantations. Such stands would be expected to have larger knots and a higher percentage of juvenile wood than does suppressed Douglas-fir in dense stands. The yield of higher grade lumber from these managed stands increased with the average age of the stand at harvest **(Table 8).** The yield of No. 2 and better lumber from the older trees in the managed plantations was within 5 percent of that from the suppressed trees **(Table 7),** but much more of the lumber from the suppressed trees made Select Structural compared to trees from the managed stands.

The properties of the lumber sampled in this study are summarized for the Structural Light Framing grades in **Table 9.** The samples shown in **Table 9** were slightly smaller than those shown in **Table 7** because some 2 by 4's were used in a separate study of finger-joint strength, to be reported separately. SG values are typical of those shown in the *Wood Handbook* for dry Douglas-fir, which range from 0.48 to 0.50 (USDA 1999). Both MOE and MOR were significantly higher than the values adjusted to 12 percent MC for Douglas-fir 2 by 4's tested in the In-Grade program (Evans and Green 1987). Mean MOE values for Select Structural and No. 2 grade lumber in the In-Grade program were 1.91 and 1.64 × 10^6 psi (13.2 and 11.3 GPa), respectively, and mean MOR values were 6.22 and 3.77 × 10^3 psi (42.9 and 26.0 MPa), respectively. The values for No. 1 grade shown in **Table 9** are not in line with those of Select Structural and No. 2. This perhaps is a reflection of the small sample size.

In the Light Framing grading system, 74 percent of the lumber made Construction grade when trimmed **(Table 7)** and almost 92 percent made Standard and better. For all the pieces, 17.1 percent of the untrimmed pieces were grade-limited for wane and 3.2 percent for warp (mostly twist). As studs, 88.7 percent of the trimmed pieces made STUD grade **(Table 7).** Again, wane was the primary grade-controlling defect.

Table 8. — Yield of visually graded lumber from managed stands of small-diameter Douglas-fir (adapted from Barbour and Parry 2001).[a]

Analytical group	Age	Treatment	Grade					
			SS	No. 1	No. 2	No. 3	Econ.	No. 2 and better
	(yr)							
Port Blakely	95	UT	21	20	46	10	4	87
		TH	25	17	45	14	4	87
	80	UT	17	21	46	11	5	84
		TH	17	19	48	12	5	83
Stand Management Cooperative	21 to 40	--	5	15	53	19	8	73
	41 to 60	--	5	12	51	22	11	67
	61 to 80	--	16	20	47	12	5	83
	81 to 100	--	25	21	43	9	4	89

[a]SS = Select Structural; Econ. = economy; UT = unthinned; TH = thinned.

Table 9. — Mechanical properties of structural light framing grades for 2 by 4 lumber.[a]

Grade	*n*	MC	SG	MOE				MOR					
				Mean		SD		Mean		SD		5th percentile	
				(×10⁶ psi)	(GPa)	(×10⁶ psi)	(GPa)	(×10³ psi)	(MPa)	(×10³ psi)	(MPa)	(×10³ psi)	(MPa)
SS	594	12.2	0.49	2.27	15.6	0.32	2.2	10.78	74.3	2.4	16.4	6.94	47.9
No. 1	61	12.0	0.48	1.90	13.2	0.28	1.9	7.96	54.9	2.0	13.9	5.01	34.5
No. 2	158	12.4	0.50	2.20	15.1	0.32	2.2	10.38	71.6	2.4	16.1	6.81	47.0
No. 3	43	12.4	0.52	2.06	14.2	0.34	2.4	9.66	66.6	2.7	18.5	5.24	36.1
Econ.	28	13.7	0.51	2.08	14.3	0.47	3.2	9.82	67.7	3.1	20.7	4.02	27.7

[a]SG is based on ovendry weight and volume at MC shown.

Mechanically graded structural lumber

As expected, the relationship between MOE by static test and MOE by transverse vibration (E_{TV}) was very good (r^2 = 0.82) **(Table 10).** The relationship between MOR and MOE is typical of that found for most lumber (r^2 = 0.57). Therefore, there is nothing to suggest that this lumber cannot be mechanically graded.

Table 11 shows the number of pieces selected for MSR lumber from the computer simulation based on trimming the lumber for grade yield. For example, for grades of 1650Fb-1.5E and less, 92.8 percent of the pieces qualified as MSR lumber. Even for a potential grade of 3000Fb-2.4E, approximately 64 percent of the lumber would qualify. **Table 11** also shows the visual falldowns in the Structural Light Framing grading system for each MSR grade simulated. This is an important economic consideration for an MSR producer. According to current guidelines, any lumber that fails to make an MSR grade (called falldowns) may be sold as visually graded lumber provided that the assigned Fb for the visual grade of the falldown is less than that of the MSR grade for which the lumber fails to qualify. For example, the Fb value for Douglas-fir Select Structural 2 by 4's is 2.25 × 10³ psi (15.5 MPa). Eleven pieces of Select Structural lumber failed to make 2250Fb-1.9E MSR. Thus, these pieces would have to be sold as No. 1 visual grade, which has an allowable Fb value of 1.5 × 10³ psi (10.3 MPa). Ten pieces of No. 1 grade lumber failed to make 2250 Fb. Because the assumed property for No. 1 lumber is 1500 Fb, they may retain their visual grade. Thus the total number of No. 1 falldowns shown in **Table 11** is 21. Again, we must caution that we simulated a very wide range of potential grades to help illustrate the potential of this resource. Not all the grades given in **Table 11** are ever produced by a commercial operation. Generally, the lowest grade produced is about 1450 Fb and the highest about 2850 Fb.

Table 70. — Property relationships for 2 by 4 lumber.[a]

Property	*X*	*n*	Property = *A* + *B* * *X*			
			A	*B*	r^2	RMSE
MOE	E_{TV}	884	0.963	0.194	0.82	0.147
MOR	MOE	884	−1.718	5.484	0.57	1.643

"RMSE is square root of mean square error. MOE is given in millions of pounds per square inch (1 psi = 6.894 kPa). MOR is given in thousands of pounds per square inch.

As with visually graded lumber, the yields of MSR lumber from suppressed trees would be expected to be higher than those of lumber from stands managed to optimize the volume of wood fiber produced. In the study by Barbour and Parry (2001), the anticipated yield of 2100 Fb lumber for the oldest age classes was 25 to 30 percent. For suppressed Douglas-fir of a similar age, yield is anticipated to be over 90 percent **(Table 11).**

Laminating grades

Table 12 shows the distribution of number of pieces by MOE obtained by transverse vibration (E_{TV}) and edge knot displacement for the 884 2 by 4's tested in this study. For most pieces, edge knots occupied only 116 or less of the width of the member. For these pieces, the mean MOE value was 2.11 × 10⁶ psi (14.5 GPa). Most of this lumber is potentially suitable for the highest laminating grades and for E-rated grades having an allowable edge knot of 116 of the cross section.

Table 11. — Estimated yield of machine stress rated 2 by 4s.

Grade	Yield		Visual grade assignment (n) of falldowns[a]				
			SS	No. 1	No. 2	No. 3	Econ.
	(*n*)	(%)					
1200Fb-1.2E	821	92.8	0	0	0	35	28
1450Fb-1.3E	821	92.8	0	0	12	23	28
1650Fb-1.5E	821	92.8	0	6	6	23	28
1800Fb-1.6E	820	92.7	0	7	6	23	28
1950Fb-1.7E	818	92.5	0	9	6	23	28
2100Fb-1.8E	809	91.5	0	15	8	24	28
2250Fb-1.9E	801	90.6	0	21	10	24	28
2400Fb-2.0E	786	88.9	20	13	13	24	28
2700Fb-2.2E	728	82.3	50	28	26	24	28
2850Fb-2.3E	697	78.8	70	32	31	26	28
3000Fb-2.4E	565	63.9	160	44	57	30	28

[a]Values indicate the final assignment of visual grade for falldowns after required reduction (see text).

Table 12. — Distribution of flatwise MOE values by knot size class for 2 by 4 lumber.

E_{TV}		No. of pieces. by edge knot displacement class[a]		
		1/6	1/4	1/2
(10^6 psi)	(GPa)	----------(%)----------		
1.2	8.3	1	0	0
1.3	9.0	3	0	0
1.4	9.7	8	0	1
1.5	10.4	12	0	0
1.6	11.0	39	I	1
1.7	11.7	40	0	2
1.8	12.4	57	0	3
1.9	13.1	97	0	3
2.0	13.8	98	1	1
2.1	14.5	102	1	2
2.2	15.2	87	0	1
2.3	15.9	79	0	0
2.4	16.6	66	0	1
2.5	17.3	53	0	0
2.6	18.0	36	0	0
2.7	18.7	31	0	1
2.8	19.3	4	0	0
2.9	20.0	4	0	0
3.0	20.7	1	0	0
3.1	21.4	1	0	0
Mean E,, value for knot		2.11	1.89	1.94
COV of E_{TV}		14.9	14.3	15.6

[a]Percentage of cross section occupied by edge knot.

In conducting the grade sort, we first determined if the piece would make one of the three tension lamination grades. If not, then we asked if the piece would qualify for one of the visual "L" grades. The distribution of E_{TV} values for pieces qualifying for laminating grades is shown in Table 13. Almost 35 percent of the lumber qualified for 302-24, the highest grade of tension lamination (tension lam); 46 percent made a tension lam grade, and another 22 percent made an L grade. The 34 percent that did not make one of the laminating grades could still be sold as visually graded structural lumber. **Table 13** also shows the number of pieces that did not make a laminating grade for the Structural Light Framing grading system. Laminating plants typically purchase lumber as L3 and better, with the expectation that the mix of grades will yield certain levels of L1 and 302-tension laminating grades. No published information is available for the expected yield, but recent communication with a laminating plant indicated that the 66 percent yield observed in our study for the L1 and 302-tension lam grades combined was extremely high.

To evaluate if the material properties of these laminating grades meet the requirements of the American Institute of Timber Construction (AITC) manufacturing standard (AITC 1993), we calculated MOE values for grades having a significant sample size **(Table 14).** The AITC requires that the L1 and 302-tension lam grades have a mean MOE value of 2.0×10^6 psi (1 3.8 GPa), based on nominal 2 by 6 dimensions. The results in **Table 14** show that our nominal 2 by 4 lumber achieved these levels. The E,, values reported by Marx and Evans (1986, 1988) for Douglas-fir were higher than those found in our study. However, the SG values reported by Marx and Evans were higher than those typically reported for Douglas-fir (USDA 1999).

Relative economic value

To get some idea of the relative economic value of sorting lumber by the various grading systems presented in this paper **(Tables 9, 11,** and **13),** the following prices (in $/MBF) were obtained for Douglas-fir 2 by 4 lumber from the February 13, 2004 issue of Random Lengths (2004): No. 1 and better, $480; No. 2 and better, $465; No. 3/Utility, $253; Standard and better, $460; STUD (9-ft [2.7-m] length), $455; Economy, $135; 1800F MSR, $500; and 2400F MSR, $565. Prices paid for laminating stock are not generally reported in Random Lengths. Lamstock is generally purchased as either L3 and better or L 1 and better grades.

A cooperator in several research studies provided the following approximate values for lumber:

Lumber	$/MBF
Structural Light Framing with No. 2 and better pricing	444
Structural Light Framing with No. 1 and better pricing	452
Light Framing	43 8
STUD	438
MSR, 1800f, plus falldowns	491
MSR, 2400f, plus falldowns	548
Lamstock, with L3 and better pricing	567
Lamstock, with L1 and better pricing	629

Using these assumed prices, the value of L3 and better lumber is $600/MBF and that of L 1 and better is $725/MBF. Only about 5 percent of the lamstock market involves transactions of L1 and better. This usually occurs when laminators from the eastern United States order Douglas-fir lamstock from the West Coast.

Although the prices that can actually be obtained by a particular mill at any given point in time may vary considerably from these figures, this comparison helps illustrate the value of looking for a higher value market. Compared to simply settling for the No. 2 and better price, a premium of $8/MBF could be obtained by finding a customer who would pay for

Table 13. — Distribution of flatwise MOE values by glulam grade for 2 by 4 lumber.

		Tension laminations			L-grades			Visual grades of rejects				
E_{TV}		302-24	302-22	302-20	L1	L2	L3	SS	No.1	No.2	No.3	Econ.
(10^6 psi)	(GPa)											
1.0	6.9	0	0	0	1	0	0	0	0	0	0	0
1.1	7.6	0	0	0	0	0	0	0	0	0	0	0
1.2	8.3	0	0	0	0	0	0	1	0	0	1	1
1.3	9.0	1	0	0	0	0	0	2	0	0	0	0
1.4	9.7	0	0	0	4	0	0	2	3	1	0	0
1.5	10.4	1	0	2	2	0	0	1	4	4	0	0
1.6	11.0	1	6	2	16	3	0	4	2	8	1	0
1.7	11.7	3	7	3	18	0	0	6	6	2	1	1
1.8	12.4	13	5	1	19	0	0	12	5	5	3	1
1.9	13.1	23	11	4	30	2	0	26	3	3	1	2
2.0	13.8	38	14	4	16	0	2	11	4	11	2	1
2.1	14.5	36	13	2	20	6	0	15	4	11	3	0
2.2	15.2	49	10	0	11	1	0	12	0	8	1	1
2.3	15.9	32	8	2	11	3	1	14	1	9	1	1
2.4	16.6	33	4	0	9	3	1	7	0	9	2	1
2.5	17.3	36	2	0	4	2	0	5	1	1	3	1
2.6	18.0	14	1	1	4	4	0	6	0	5	1	1
2.7	18.7	22	1	0	6	0	0	2	0	2	0	0
2.8	19.3	3	0	0	0	0	0	2	0	0	0	0
2.9	20.0	2	0	0	1	0	0	0	0	1	0	0
3.0	20.7	0	0	0	0	0	0	1	0	0	0	0
3.1	21.4	0	0	0	0	0	0	0	0	1	0	0
Total												
n		307	82	21	172	24	4	129	33	81	20	11
Percent		34.7	9.3	2.4	19.5	2.7	0.4	14.6	3.7	9.2	2.3	1.2

Table 14. — Transverse vibration MOE values for laminating grades of Douglas-fir lumber from small-diameter trees.

	Current study			Marx and Evans (1986, 1988)		
Grade	*n*	Mean	COV	*n*	Mean	COV
		(10^6 psi)	(%)		(10^6 psi)	(%)
302-24	307	2.24	12.0	362	2.43	17.0
302-22	82	2.04	12.2	--	--	--
L1	172	1.95	14.8	357	2.14	17.0

the large amount of No. 1 and better material lumber in this sample. Selling the lumber as STUD, or Light Framing, reduced the value by $6/MBF. Producing higher value MSR grades offered a higher return, with 1800f offering a premium of $47/MBF and 2400f a premium of $104/MBF. Of course, production costs would also be higher for MSR. The highest returns were for lamstock. Simply selling the lumber as grade L3 and better, with the rest sold as visually graded lumber, produced a premium of $123/MBF relative to the price for No. 2 and better, but looking for a buyer to purchase the lumber as L1 and better offered a premium of $185/MBF. These figures illustrate the value of marketing lumber to higher value users instead of just selling for commodity prices.

Conclusions

Our results indicate that 2 by 4's sawn from 70- to 90-year-old suppressed Douglas-fir trees 10 inches (254 mm) or less in diameter have excellent potential for the production of structural lumber.

- Logs from these trees were generally tight-ringed, with small knots and a small portion of juvenile wood.
- SG was typical of that of older trees, and hardness values were superior for Douglas-fir.
- When graded as Structural Light Framing, 68 percent of 2 by 4's graded as Select Structural and 92 percent as No. 2 & better. This is about the same yield of No. 2 & better, but a higher yield of Select Structural lumber, than would be expected from logs of similar age and diameter from a managed plantation.
- Ninety percent of 2 by 4's would make 2400Fb-2.0E machine stress rated (MSR) lumber.
- When graded as lamstock, 46 percent of 2 by 4's would qualify as tension laminations and an additional 22 percent as an "L" grade. When graded as laminating grades, 67 percent of 2 by 4's qualified as L1, or 302-tension laminating grades.
- Mean MOE values of L1 and 302-tension laminating grades met the AITC requirement of 2.0 × 10^6 psi (13.8 GPa).

Care should be taken in drying suppressed-growth Douglas-fir. The lumber has a tendency to twist. This tendency was usually not a grade-controlling defect for the structural lumber in this study, but it could pose a problem with thinner boards.

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