MOE DISTRIBUTION IN VISUALLY GRADED PONDEROSA PINE LUMBER HARVESTED FROM RESTORATION PROGRAMS IN SOUTHERN OREGON AND NORTHERN CALIFORNIA

*Sina Jahedi**†
Graduate Research Assistant
E-mail: jahedisina@gmail.com

Lech Muszynski†
Professor
E-mail: lech.muszynski@oregonstate.edu

Mariapaola Riggio†
Associate Professor
Department of Wood Science and Engineering
Oregon State University
Corvallis, OR 97331
E-mail: mariapaola.riggio@oregonstate.edu

Benjamin Brice Blengino
Undergraduate Student
Ecole Supérieure du Bois
Nantes, France
E-mail: benjamin.blengino@etu.es-campus.fr

Sujit Bhandari†
Graduate Research Assistant
Department of Wood Science and Engineering
Oregon State University
Corvallis, OR 97331
E-mail: sujit.bhandari@oregonstate.edu

(Received December 2021)

Abstract. Every year, restoration programs in Southern Oregon and Northern California produce large amounts of low-value ponderosa pine, *Pinus ponderosa* (PP) lumber. This material has a limited market in the United States. Engineered wood products, such as cross-laminated timber (CLT) and glulam, are expected to provide a value-added market to offset the high costs of restoration programs. However, restoration program lumber has larger amounts of juvenile wood and visual grades are reported to show lower mechanical properties compared with commercially harvested material, on which the National Design Specification (NDS) design values are based. This research addresses a knowledge gap on the impact of juvenile wood and visual strength-affecting characteristics on the mechanical performance of PP lumber generated in the region of interest. The purpose of this study was to assess this impact based on dynamically measured MOE of samples of visually graded and ungraded restoration program PP lumber. The material used in this study was intended for fabrication of CLT for another project, hence it could not be used for destructive tests to measure MOR. The results were compared with previous studies and published values for commercially harvested PP as reflected in the NDS Western Woods (WW) species group. The results show that characteristic MOE values of visual grade Nos. 1 and 2 of PP from restoration programs were lower than respective design values for NDS WW group. However, the mean MOE values of all groups considered individually as well as pooled together were higher than NDS WW grade No. 3. MOE

---

* Corresponding author
† SWST member

Wood and Fiber Science, 54(2), 2022, pp. 90-98
https://doi.org/10.22382/wfs-2022-10

distributions for all groups, except for the visual grade No. 1, were remarkably similar. The average MOE of PP harvested in Southern Oregon and Northern California were higher than those reported for Columbia PP harvested in North Idaho.

Keywords: Forest restoration programs, ponderosa pine, juvenile wood, visual grades, modulus of elasticity.

INTRODUCTION

The forestlands in Western United States are prone to catastrophic wildfires and pest outbreaks. Restoration programs are implemented to prevent or mitigate such events. USDA Forest Service is seeking value-added markets for logs harvested from thinning operations to offset the high costs of these programs. While utilization in structural engineered products have been proposed (Hernandez et al 2005; Larkin 2017; Lawrence 2017a, 2017b), most such products require lumber graded for structural uses. There are two common lumber grading systems used in the United States (Entsminger et al 2020). The first is visual grading, where the grade is assigned based on the characteristics that are visible to the naked eye, eg size and location of knots, grain angle, wane, etc. This task is done by either a trained lumber grader or an automated scanning system. The second system is machine grading which includes machine stress rated (MSR) and machine evaluated lumber. For machine grading system, a property of the material, commonly MOE, or density is measured as a predictor of other properties of the material, in combination with some visual limiting criteria, eg rejecting pieces with large edge knots (Entsminger et al 2020). In addition to machines that bend lumber to measure stiffness, other machines use dynamic measurements, including transverse vibration to measure stiffness from the fundamental frequency of the flatwise vibration of a piece of lumber supported at the ends.

The most common approach for restoration programs is "thinning from below," meaning that the lower crown classes or canopy layers are harvested to preserve upper crown classes or layers (Powell 2013). Pacific Northwest restoration programs consist of removing trees smaller than 0.5 m (22 in.) in diameter as well as dead trees (Smith 2021). The lumber obtained from these small diameter trees contains substantial presence of knots, wane, warp, and twist, which results in lower fractions of the higher structural grades, compared with the yield from commercial stands (Erikson et al 2000; Hernandez et al 2005; Smith 2021).

One of the species harvested in forest restoration operations in substantial quantities is ponderosa pine, *Pinus ponderosa* (abbreviated as PP in this paper; Shinneman et al 2016). Commercially harvested PP is listed among structural softwoods in the National Design Specification (NDS) supplement handbook (FPL 2010). Substantial portion of the material harvested in Southern Oregon and Northern California does not meet the requirements of structural grade lumber and is turned into chips to be used as biofuel or for fabrication of hardboards and particleboards (Smith 2021). A comparison of visual grade yield of PP in typical restoration programs to commercial harvest is presented in Table 1. One of the main causes of reduced mechanical properties in small diameter logs is the high amount of juvenile wood, which has higher microfibril angle and thinner cell walls, resulting in higher longitudinal shrinkage, lower specific gravity, and lower strength compared with mature wood (FPL 2010). The transition from juvenile wood to mature wood is gradual (Moore and Cown 2017), and it is not easy to determine the proportion of juvenile wood content in individual pieces of lumber by macroscopic visual clues. Currently, the presence of juvenile wood is not among grade-defining criteria in visual grading systems (WWPA 2017); hence, the effect of juvenile wood on the design characteristics of graded lumber is not considered. Those characteristics are mainly determined based on commercially harvested logs and cannot represent the properties of the lumber obtained from small diameter trees having high contents of juvenile wood.

Table 1. Typical ponderosa pine visual grade yield in "thinning from below" operations and comparison with commercial harvest.

References	Region	Grade No. 2 or better	Grade No. 3	Other
Erikson et al (2000)	Grangeville, ID (thinning)	47.4%	3.2%	49.4%[a]
Hernandez et al (2005)	Flagstaff, AZ (thinning)	34.0%	32.2%	33.7%[a]
This study	Lakeview, OR (thinning)	50.0%[b]	34.0%	16.0%[c]
Smith (2021)	Lakeview, OR (commercial)	70.0%	20.0%	10.0%[a]

[a] Includes economy.

[b] Includes 2% No. 1.

[c] Includes ungraded lumber.

The characteristic values of MOE and MOR of commercially harvested PP lumber were determined as a part of in-grade testing programs (Green and Evans 1987). These data were collected from approximately 80 specimens for each grade obtained from various mills around the country. No information could be found on specific locations the specimens were obtained from. Also, NDS supplement handbook provides the design values of commercially harvested PP lumber grouped with similar species as Western Woods (WW). The design values for the whole group were derived based on the weakest species for that specific property. Applying WW design values or in-grade data to restoration program PP lumber that contains a high proportion of juvenile wood is likely to result in overestimating mechanical properties. The major design values used for engineering purposes include MOE, bending strength (F_b), tension strength parallel to grain (F_t), shear strength parallel to grain (F_v), and compression perpendicular to grain ($F_{c\perp}$). Although among these properties only MOE can be measured nondestructively, it is commonly accepted that there are correlations between MOE and other properties (Green and Kretschmann 1991). As per ASTM D2915, the sample mean is used for deflection-related design values, while a 5th percentile tolerance limit is considered for derivation of strength-related design values.

A study on PP lumber obtained from restoration programs in Arizona showed that MOE of straight grained small clear specimens increases with cambial age, which is an indication of the amount of juvenile wood present in the material (Vaughan et al 2021). Detrimental effects of juvenile wood on material mechanical properties are confirmed for other pine species. A study on Loblolly pine lumber with high content of juvenile wood showed that approximately 20% of the material did not conform to the design values (MOE and ultimate tensile stress) of the assigned visual grades in NDS (Kretschmann and Bendtsen 1992). Another study collected data on 2 × 4 PP lumber harvested from restoration programs in North Idaho (Erikson et al 2000) and the results showed that PP lumber from thinning operations visually graded as No. 2 had lower MOE compared with the data published for that grade of commercially harvested PP. The subspecies (PP subsp. *ponderosa*, Columbia ponderosa pine) studied by Erikson et al 2000 is different from Pacific PP trees growing in West Oregon and Northern California (PP subsp. *critchfieldiana* Callaham, subsp. nov., Pacific ponderosa pine) investigated in this study (Callaham 2013). However, regardless of the potential differences between subspecies, there seems to be mounting evidence that the design values established for commercially harvested ponderosa pine may overestimate the actual properties of the lumber obtained from forest restoration thinning. The magnitude of the effect for PP lumber generated in the region of interest is the research gap addressed partially in this study.

A study on utilization of thinning program PP lumber (Hernandez et al 2005) showed that approximately 28% of the material can be used to produce a new PP glulam beam combination better than all PP L3-grade combinations published in the standards. The authors of this study reported that the major factors for rejection of lumber were wane and skip. A study conducted at Oregon State University suggested that lumber harvested in restoration programs in the Pacific Northwest could also be used for production of cross-laminated timber (CLT), adding to the diversity and resilience of the current schemes of utilization (Lawrence 2017a). CLT is a massive, engineered wood panel consisting of three or more orthogonally arranged plies of lumber bonded with an adhesive. ANSI APA PRG-320 (ANSI/APA 2019) specifies the requirements for fabrication, performance, and quality assurance of CLT panels in North America. Experimental studies (Larkin 2017; Lawrence 2017b) demonstrated that acceptable structural performance may be achieved in hybrid CLT layups including low-value PP lumber in the cores, however both studies failed to meet the resistance to cyclic delamination criteria. An example of the interest in using PP in construction may be a small-scale CLT manufacturer in Colorado fabricating non-structural restoration program PP panels since 2018, with the prospect to produce structural panels in the near future (Timber Age 2018).

Using restoration program PP lumber in all laminations of CLT is intended to maximize the utilization of the material in the value-added structural product. However, to predict the design properties of such layups, the design values of PP lumber generated in restoration program thinning in the Pacific Northwest must be known first. The necessary step toward structural utilization of this material is collecting representative data on the properties of the lumber. The objective of this study was to determine the distribution of the MOE in visually graded and ungraded PP lumber harvested from restoration programs in Southern Oregon and Northern California. This study is part of a broader project aimed at utilizing ungraded restoration program PP lumber in all laminations of structural CLT. The target use of the proposed CLT layup is in low-rise modular construction, identified as a potential market for such large outlet of restoration program lumber (Bhandari et al 2020).

Limitation

The PP lumber obtained for this study was intended for fabrication of CLT, performance tests on CLT elements, and construction of a demonstration CLT unit in parallel projects conducted at the Oregon State University. This precluded destructive test procedures, such as determination of MOR. Therefore, in this study, only the MOE and specific gravity distributions, which could be measured nondestructively, were determined and used for comparisons and analysis.

MATERIALS AND METHODS

While the common species harvested in Southern Oregon and Northern California restoration operations include White Fir (*Abies concolor*), and PP, only PP was the focus of this project. The lumber for this project was obtained from "thinning from below" harvest, aimed at preserving the healthy trees with a diameter larger than 560 mm. The material was harvested, sawn to 2 × 6 nominal dimension lumber (actual dimension 38 mm by 152 mm), kiln-dried to 19% MC, and visually graded by Collins Co. (Lakeview, OR). The length of the lumber was 2.44, 3.05, 3.66, or 4.88 m (8, 10, 12, or 16 ft.).

Out of the 18 units of PP lumber donated for the fabrication of prototype CLT layups for a parallel project conducted at OSU, seven units were randomly selected for nondestructive testing. A total of 810 pieces was obtained from the units, of which 84% were visually graded by the lumber company based on the standard (WWPA 2017) as following: No. 1 (2%), No. 2 (48%), and No. 3 (34%), while the rest (16%) remained ungraded (last row of Table 1). The ungraded lumber was mostly blue-stained pieces acquired from dead trees. Although this portion of the material potentially could be visually graded, there is hardly any demand for blue-stain lumber in the region, therefore, it is typically converted into chips.

Upon the arrival at OSU, the material was stored outdoors in the original tight units without any spacers between pieces and protected from rain and water exposure (July-November 2019). All pieces were visually inspected for the presence of selected grade-defining features that were easily identifiable by an untrained operator. Table 2 presents a summary of the inspection. Wane was the most frequent grade-defining feature, appearing in 54% of the specimens, followed by saw skips (29%), and dead knots (25%). The size, position and grouping of these features have not been marked.

Specific gravity and MOE of the material were determined using Metriguard E-computer Model 340 dynamic tester (Raute Metriguard 2011). The MOE calculation is based on the first mode natural frequency of the simply supported lumber (Ross 1994), where transverse vibration was induced by gently tapping the lumber at the center and data were recorded by a load cell integrated in one of the supports (Fig 1). The proprietary firmware also takes the distance between supports and cross section dimensions (assuming a perfect prismatic shape) as input data, but the documentation does not explain whether the values are actually converted to static MOE values (Raute Metriguard 2011).

MC was measured using a resistance moisture meter (Delmhorst, model RDM3) on every 10th lumber pulled from the unit in sequence, one layer at a time. Since the MC in the layers of units stored for 5 mo in sheltered outdoor condition is not expected to vary much from one piece to another, the measured MC was assigned to the next nine unmeasured pieces in the same layer. Specific gravity and modulus of elasticity of the individual lumber pieces were adjusted to the reference MC of 12% used in NDS tables based on those measured and assigned local MC values. At the time of test, the overall average MC of all pieces was 12.9% ± 0.3%.

Each specimen was marked with an ID, and the data related to grade-defining features along with MOE and specific gravity were recorded, so that the lumber could be traced in the prototype CLT production stage for future analysis. MOE design values for the sample groups were calculated following the ASTM D2915 standard procedure (ASTM International 2017), which covers "evaluation of allowable properties of specified populations of stress-graded structural lumber." As per ASTM D2915 section 5.4, the sample mean MOE is considered as the design value for serviceability.

Table 2. Frequency of pieces with selected grade-defining features (810 specimens).

	No. of pieces by grade			
Defect	No. 1	No. 2	No. 3	Ungraded
Wane	—	40%	73%	52%
Saw skips	—	24%	37%	27%
Dead knot	—	26%	24%	27%
Resin pocket	—	9%	8%	8%
Bow	—	9%	7%	5%
Blue stain	—	2%	6%	22%
Twist	—	10%	3%	4%
Crook	—	3%	6%	1%
Hole	—	0%	4%	2%
Total no. pieces	Not significant	388	271	132

RESULTS

The MOE distribution of all four groups (grade Nos 1-3 and the ungraded sample) is presented as boxplots in Fig 2. The gray clouds demonstrate the distribution of data points in each sample. The mean MOE values for grade Nos. 2, 3, and ungraded lumber were remarkably similar to each other (6.47, 6.54, and 6.42 GPa, respectively). Grade No. 1 showed a significantly higher average MOE than the other groups (7.11 GPa), but still lower than the NDS value for No. 1 in WW (7.58 GPa, marked as the top horizontal line in Fig 2). Visually comparing the data clouds and the boxplots, the MOE distributions of grade Nos

Figure 1. MOE and specific gravity measurement using Metriguard E-computer Model 340 dynamic tester.

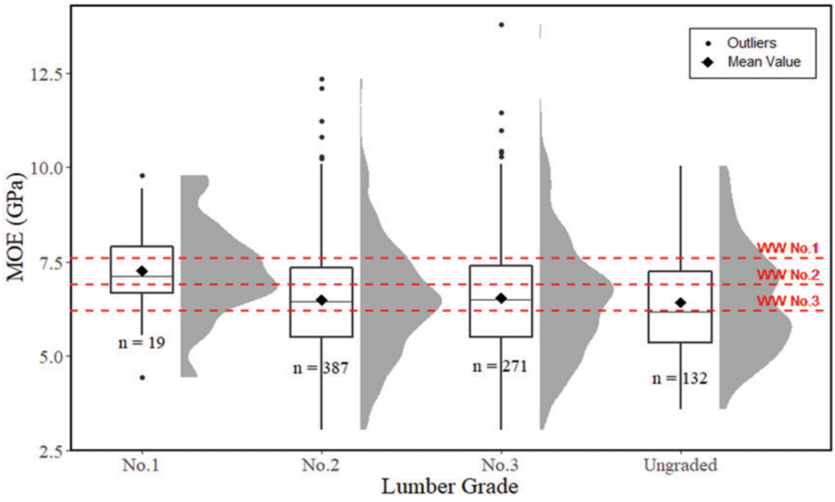

Figure 2. MOE distributions and derived design values for restoration harvested Pacific *Pinus ponderosa* compared with the design values published for Western Woods species.

2, 3, and ungraded lumber were also very similar to one another (<2% difference in average values).

While the mean MOE values of grade Nos. 1 and 2 fall below the respective NDS design values for WW (7.58 and 6.90 GPa, respectively, marked as horizontal lines in Fig 2) all mean MOE values were higher than WW grade No. 3. This means that, if the data are pooled together, the mean MOE value for the pooled group would be higher than WW grade No. 3 as well. The effect of grade No. 1, constituting just 2% of the population on the overall average MOE was negligible. Figure 3 represents the cumulative distribution of MOE for the pooled group. Based on the mean and standard deviation values, a normal distribution line was fitted to the data and a good visual match can be appreciated in the graph. The average MOE of the material for all grading groups pooled together is 6.50 GPa, which is lower than WW No. 2 but higher than WW No. 3.

Table 3 summarizes the specific gravity and MOE design value of PP individual grade groups obtained in this study compared with WW species and previous studies. Mean specific gravity of all individual grade groups of restoration program PP were similar. Following NDS format, average specific gravity of all groups combined were calculated as 0.38 ± 0.04 at the MC of 12%, which was higher than 0.36 assigned to WW species in NDS supplement handbook, and higher than the values reported for PP harvested from Northern Idaho (Erikson et al 2000). Grade Nos. 1 and 2 restoration program PP had lower MOE compared with similar grades for WW and in-grade data. However, grade No. 3 PP had higher MOE compared with grade No. 3 WW.

DISCUSSION

The fact that grade Nos. 1 and 2 restoration harvested PP lumber had lower MOE compared with the same grades for lumber harvested from commercial stands is likely a result of the presence of higher proportion of juvenile wood in the restoration program material compared with lumber generated in commercial harvesting. As mentioned in the introduction, the presence of juvenile wood reduces the mechanical properties of lumber. However, it is not easy to detect a transition line between juvenile and mature wood on a macroscale (Moore and Cown 2017); hence the proportion of juvenile wood in individual pieces of lumber cannot be easily determined by bulk visual clues (such as those used in visual grading).

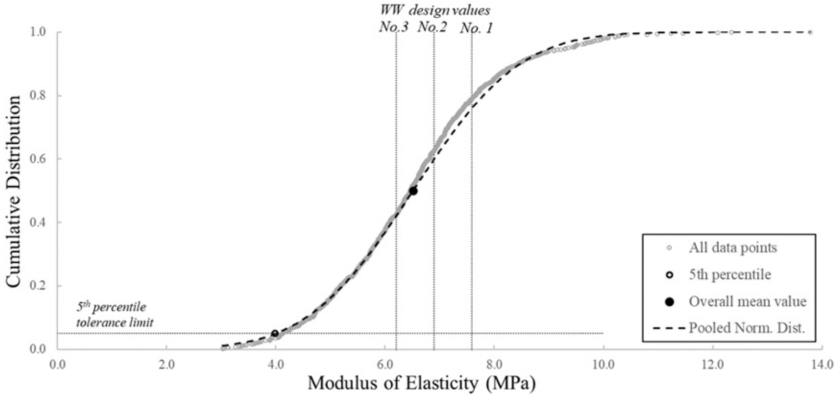

Figure 3. Pooled MOE data values for restoration harvested Pacific *Pinus ponderosa* compared with the design values published for Western Woods species.

Currently, the presence of juvenile wood is not considered a grading criterion for structural lumber.

According to in-grade data (Green and Evans 1987) commercially harvested PP has the second lowest mechanical properties among WW species, followed only by Sugar pine (*Pinus lambertiana*). All grades of restoration harvested PP lumber evaluated in this study had higher mean MOE values compared with the NDS design value for WW species grade No. 3. The material was needed for production of prototype CLT specimens and could not be subjected to destructive tests to determine strength-related properties. The exact correlation between MOE and other properties of restoration program Pacific PP could not be determined in this study and must be assumed unknown. Determination of this correlation should be a subject of a future study.

If for practical purposes it can be assumed that other properties of the lumber are directly correlated with MOE, we might also assume that the other design properties of restoration harvested PP should exceed the corresponding NDS WW No. 3 design values as well. With this assumption, the design values of WW grade No. 3 could be considered conservative approximations of design values for Southern Oregon and Northern California restoration harvested PP lumber, until exact correlations are determined.

Given the close similarities of the MOE distributions in visual grade Nos. 2 and 3 with the ungraded lumber and a marginal representation of

Table 3. Summary of specific gravity and average MOE of restoration harvested Pacific *Pinus ponderosa* (PP) lumber adjusted to 12% MC and the comparison with previous studies and commercially harvested PP.

	Location		SG	No. 1	No. 2	No. 3	Other	Pooled data
This study	SOR and NCA	MOE (GPa)	0.38	7.11	6.47	6.54	6.42[a]	6.50
		STD	(0.04)	(1.01)	(1.56)	(1.61)	(1.54)	(1.54)
Erikson et al (2000)	NID	MOE (GPa)	0.36	6.48	5.90	5.81	NA[b]	6.06[c]
		STD	—	(1.35)	(1.28)	(1.50)	—	—
Green and Evans (1987)	Mixed	MOE (GPa)	—	—	7.05	—	—	—
		STD	—	—	(1.34)	—	—	—
WW NDS	Mixed	MOE (GPa)	0.36	7.58	6.89	6.20	—	—

SOR, southern Oregon; NCA, northern California; NID, northern Idaho (N, ID); mixed, commercially harvested lumber acquired from various US mills with unknown specific locations.

[a] Ungraded.

[b] MOE values for economy not measured.

[c] Pooled data do not include economy.

No. 1, there is a potential of pooling all grades of restoration harvested PP lumber as one class of material. This might reduce complexities in the production lines of engineered wood panels utilizing lumber from restoration thinning.

One limitation of this study is that the MOE were measured by a dynamic tester machine. The manufacturer's description of the output provided by proprietary firmware does not specify any correction factors used to determine the static MOE from the dynamic modulus. In this study, it has been assumed that the output produces unadjusted dynamic MOE values, which typically overestimates the static MOE. Previous studies using the same device reported a linear correlation ($R^2 \approx 0.85$) between dynamic and static MOE measurements (Wang et al 2008; França et al 2018). The difference between these values for PP dimension lumber obtained from small diameter trees in North Idaho was approximately 4% (Erikson et al 2000). Applying similar adjustments to the dynamic MOE measured in this study does not reduce the characteristic MOE values of any group below WW grade No. 3, therefore the conclusions remain valid.

Although it is shown that the mechanical characteristics related to design values cannot be effectively differentiated by visually grading of the restoration harvested PP, by principle, grading cannot be avoided because standards for engineered wood products, such as CLT, does not permit utilization of ungraded lumber. If MSR grading is considered as an alternative for visual grading, it should be noted that the mean MOE of the restoration program PP lumber pooled in one group does not meet the MOE qualifications of any currently established standard MSR grade. One solution that can be investigated in future studies is to define a new MSR grade specifically for restoration program PP. This is also beneficial since presence of juvenile wood is not considered in the current visual grading standards, therefore performing MOE measurements is a more accurate mean for determination of the properties of restoration program lumber.

Lastly, although grade-defining features such as wane, bow, and twist do not influence mechanical properties of the restoration harvested material, excessive presence of such defects can be unfavorable for the use in engineered wood products. For instance, significant wanes that cannot be removed by surfacing the lumber cause gaps between lamellas of CLT which can accelerate moisture penetration when exposed to precipitation during open construction periods (Schmidt et al 2019) and reduce acoustic and fire performance. Substantial twist in large number of laminations may be hard to overcome in pressing CLT layups. Therefore, it is suggested to apply visual limiting criteria to the restoration harvested material accordingly.

CONCLUSIONS

MOE distribution determined on a sample of visually graded PP lumber harvested from restoration programs in Southern Oregon and northern California was compared with design values for corresponding grades determined in previous studies and with published values for commercially harvested PP as reflected in the NDS WW species group.

Characteristic MOE values of visual grade Nos. 1 and 2 of PP from restoration programs considered in this study were lower than respective design values for NDS WW group. However, the mean MOE values of all groups considered individually as well as pooled together were higher than NDS WW grade No. 3. MOE distributions for all groups, except for the visual grade No. 1, were remarkably similar, showing negligible differences in the mean values.

The design values published for WW grade No. 3 in NDS supplement handbook were suggested as provisional conservative representation of the restoration program Pacific PP lumber, until proper correlations between MOE and the other design values for the material are experimentally determined.

ACKNOWLEDGMENTS

This research is supported by the United States Department of Agriculture Wood Innovation Grants Program 2017—(17-DG-11062765-742) and 2018—(18-DG-11062765-738). The material used in the study was donated by Collins Co. (Lakeview). Special thanks to Dr. Rakesh Gupta and Lucas Walter.

REFERENCES

ANSI/APA (2019) ANSI/APA PRG 320:2019 standard for performance-rated cross-laminated timber. APA—The Engineered Wood Association, Tacoma, WA.

ASTM International (2017) ASTM D2915 standard practice for sampling and data-analysis for structural wood and wood-based products. American Society for Testing and Materials, West Conshohocken, PA.

Bhandari S, Jahedi S, Riggio M, Muszynski L, Luo Z, Polastri A (2020) CLT modular low-rise buildings: A prototype for deployable structures using low grade timber *in* World Conference on Timber Engineering (WCTE), Santiago, Chile.

Callaham RZ (2013) *Pinus ponderosa*: A taxonomic review with five subspecies in the United States. U.S. Department of Agriculture, Forest Service, Pacific Southwest Research Station Research Paper PSW-RP-264, Albany, CA. 52 pp.

Entsminger ED, Brashaw BK, Seale RD, Ross RJ (2020) Machine grading of lumber—Practical concerns for lumber producers. General Technical Report FPL-GTR-279. U.S. Department of Agriculture, Forest Service, Forest Products Laboratory, Madison, WI. 66 pp.

Erikson RG, Gorman TM, Green DW, Graham D (2000) Mechanical grading of lumber sawn from small-diameter lodgepole pine, ponderosa pine, and grand fir trees from northern Idaho. Forest Prod J 50(7/8):59-65.

FPL (2010) Wood handbook: Wood as an engineering material. General Technical Report FPL-GTR-190. U.S. Department of Agriculture, Forest Service, Forest Products Laboratory, Madison, WI. 508 pp.

França FJN, Seale RD, Ross RJ, Shmulsky R, França TSA (2018) Using transverse vibration nondestructive testing techniques to estimate stiffness and strength of Southern pine lumber. U.S. Department of Agriculture, Forest Service, Forest Products Laboratory Research Paper FPL-RP-695, Madison, WI. 8 pp.

Green D, Kretschmann D (1991) Lumber property relationships for engineering design standards. Wood Fiber Sci 23(3):436-456.

Green DW, Evans JW (1987) Mechanical properties of visually graded lumber: A summary. Vol. 1. U.S. Department of Agriculture, Forest Service, Forest Products Laboratory, Madison, WI.

Hernandez R, Green DW, Kretschmann DE, Verrill SP (2005) Improved utilization of small-diameter ponderosa pine in glulam timber. U.S. Department of Agriculture, Forest Service, Forest Products Laboratory Research Paper FPL-RP-625, Madison, WI. 36 pp.

Kretschmann D, Bendtsen B (1992) Ultimate tensile stress and modulus of elasticity of fast-grown plantation loblolly pine lumber. Wood Fiber Sci 24(2):189-203.

Larkin B (2017) Effective bonding parameters for hybrid cross-laminated timber (CLT). MS thesis, Oregon State University, Corvallis, OR. 184 pp.

Lawrence B (2017a) Utilization of low-value lumber from small-diameter logs harvested in Pacific Northwest Forest Restoration Programs in hybrid cross laminated timber (CLT) core layers: A market response. MS thesis, Oregon State University, Corvallis, OR. 114 pp.

Lawrence C (2017b) Utilization of low-value lumber from small-diameter timber harvested in Pacific Northwest Forest Restoration Programs in hybrid cross laminated timber (CLT) core layers: Technical feasibility. MS thesis, Oregon State University, Corvallis, OR. 166 pp.

Moore JR, Cown DJ (2017) Corewood (juvenile wood) and its impact on wood utilisation. Curr For Rep 2(3): 107-118.

Powell DC (2013) Silvicultural activities: Description and terminology. White Paper F14-SO-WP-Silv-34. USDA Forest Service. Pendleton, OR.

Raute Metriguard (2011) Metriguard Model 340 E-computer user manual. Pullman, WA. https://www.raute.com/ (12 November 2021).

Ross RJ (1994) Nondestructive testing for assessing wood members in structures: A review. General Technical Report FPL-GTR-70. U.S. Department of Agriculture, Forest Service, Forest Products Laboratory, Madison, WI. 40 pp.

Schmidt EL, Riggio M, Barbosa AR, Mugabo I (2019) Environmental response of a CLT floor panel: Lessons for moisture management and monitoring of mass timber buildings. Build Environ 148:609-622.

Shinneman DJ, Means RE, Potter KM, Hipkins VD (2016) Exploring climate niches of ponderosa pine (*Pinus ponderosa* Douglas ex Lawson) haplotypes in the western United States: Implications for evolutionary history and conservation. PLoS One 11(3):e0151811.

Smith G (2021) Personal communication. Collins Co., Lakeview, OR.

Timber Age (2018) Working with ponderosa. https://www.timberage.com/ (12 October 2021).

Vaughan D, Auty D, Dahlen J, Sánchez Meador AJ, Mackes KH (2021) Modelling variation in wood stiffness of *Pinus ponderosa* using static bending and acoustic measurements. Forestry 94(2):232-243.

Wang SY, Chen JH, Tsai MJ, Lin CJ, Yang TH (2008) Grading of softwood lumber using non-destructive techniques. J Mater Process Technol 208:149-158.

WWPA (2017) Western lumber grading rules. Western Wood Products Association, Portland, OR.