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Heartwood Taper in Northern Red Oak (*Quercus rubra* L.)

John P. Brown

Forest Service Northern Research Station Research Paper NRS-32 March 2019

Abstract

To better understand how the practice of long–term tree retention affects value, northern red oak (*Quercus rubra* L.) trees from the Menominee Indian Reservation in Wisconsin were harvested and examined for patterns of heartwood development in relation to several tree characteristics. A total of 69 mature northern red oak trees from three dbh size classes, small (34-47 cm, 20 trees), medium (48-60 cm, 20 trees), and large (≥ 61 cm, 29 trees), were logged and optimally bucked. Cross-sectional disks were then removed from the tops of the stumps and each log and were analyzed for patterns of change in heartwood radius. Four factors were found to have a statistically significant effect on heartwood radius: age of the tree, size class, height, and inside bark radius. The inside bark radius was the strongest predictor of heartwood radius. A 1 cm increase in inside bark radius led to approximately a 0.95 cm increase in heartwood radius. Increasing height had a small negative effect, with heartwood radius decreasing approximately 0.05 cm for each meter above ground. Age of the tree had a small positive effect of 0.0016 cm per year and was only significant in one expert model considered. These results provide consumers of oak logs and forest managers insight to the interior heartwood pattern and can lead to improved value assessments for northern red oak logs.

The Author

JOHN P. BROWN is a research forester with the USDA Forest Service, Northern Research Station, Princeton, WV, jpbrown@fs.fed.us.

Cover Photo

Photo showing a cross-section of a red oak log. Photo by Janice Wiedenbeck, USDA Forest Service.

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Manuscript received for publication 26 June 2018

Published by

U.S. FOREST SERVICE
11 CAMPUS BLVD SUITE 200
NEWTOWN SQUARE PA 19073

March 2019

INTRODUCTION

Northern red oak (*Quercus rubra* L.) is an important commercial species in the hardwood timber industry. Lower quality lumber is used for pallets and railroad ties, but with increasing quality, it is suitable for flooring, furniture and cabinets, molding, and veneer. Many factors are influential in determining the value of hardwood logs (Rast and others 1973), with defects being an important consideration in the assessment of log grade (Carpenter and others 1989). Size also plays a role in determining log grades (Hanks and others 1980).

Sapwood is found immediately inside the bark (phloem) and external to the heartwood portion of the xylem (wood) in a tree's cross-section. Sapwood is the metabolically active portion of the wood in a living tree. In many, but not all species, the sapwood can be visually distinguished from the heartwood by a color change. In those species that show a color difference between heartwood and sapwood, the transition zone or boundary region may be less desirable for certain products than either 100 percent heartwood or sapwood portions. Sapwood is removed in the manufacture of veneer for several hardwood species (Wiedenbeck and others 2004) but typically is not for red oak.

In red oak, as in most species, the extractive chemicals contained in the heartwood are more resistant to decay organisms than those in the sapwood (Hawley et al. 1924). Thus, for certain end uses, the sapwood of red oak may be less desirable than the heartwood. An important difference between the heartwood and sapwood of red oak that is noteworthy is the risk of heartwood containing "wetwood," a condition caused by anaerobic bacteria that leads to significant lumber drying defects (Ward and Pong 1980).

While the heartwood formation process is not completely understood, it is the death of parenchyma cells and the deposition of extractives that lead to changes (Bamber and Fukazawa 1985). Nelson (1976) examined sapwood width in black walnut and black cherry, finding it was weakly correlated with tree age in walnut and uncorrelated in cherry. In addition, it was found in that study that sapwood thickness was narrower for both walnut and cherry at the top of the first butt log versus the ground level. Yang and Hazenberg (1991a) found that a positive linear relationship exists between tree age and heartwood width (radius) in quaking aspen (*Populus tremuloides* Michx.). The same relationship was found in jack pine (*Pinus banksiana* Lamb.) (Yang and Hazenberg 1991b). A curvilinear relationship between sapwood thickness and height was also shown for jack pine and tamarack (*Larix laricina* (Du Roi) K. Koch) (Yang and others 1985). Taylor and others (2002) note that in general, heartwood tapers from the ground up and increases with tree age with respect to certain species. In red oak, sapwood thickness is often observed as a thin ring surrounding the heartwood in mature trees. However, the proportion of heartwood has not been previously investigated. Quantifying the proportion of heartwood is important to determining potential yields of higher valued wood. The goal of this study is to determine if allometric relationships exist between heartwood, tree diameter, and height and also to determine whether tree age influences the proportion of heartwood in northern red oak trees, which may prove useful to loggers, log buyers, and inventory foresters.

METHODS

Site Description

The study area is located on the Menominee Indian Reservation, Menominee County, Wisconsin. The reservation has a mean annual temperature of 6.8 °C, with January the coldest month (-9.7 °C) and July the warmest (21.2 °C). Mean annual precipitation is 796 mm, about 70 percent of which is evenly distributed throughout the spring and summer, with precipitation diminishing into the fall and through the winter. July is the wettest month (99 mm) and February the driest (23 mm).

Experimental Design

The study was an opportunity to work concurrently with another study that investigated how the economic value of individual northern red oaks vary by tree characteristics (Dwyer and Dey 2007). A total of 69 trees were selected from three nominal dbh classes (DBHClass): small (34-47 cm, 20 trees), medium (48-60 cm, 20 trees) and large (≥ 61 cm, 29 trees), and dbh was recorded for each tree (DBH). All trees selected were in the dominant and codominant crown classes and were in vigor class 1 as defined by Menominee foresters (Dwyer and Dey 2007). Sample trees were selected from four sites among three habitat types: Acer-Fagus/Viburnum, Acer-Quercus/Viburnum, and Acer-Tsuga/Maianthemum (Kotar and Burger 1989). This forest habitat classification system is an assessment of forest site productivity that is based on associations of understory plants and is an indicator of the best forest cover types suited to that habitat. Northern red oak is a component species of the best forest cover types on the three habitat types selected. On the Menominee tribal forest, northern red oak is managed using both even-aged and uneven aged stands, with silvicultural systems selected based on the forest habitat classification system.

The trees were felled in February 2001 by Menominee logging crews with chainsaws leaving low stumps (< 30 cm). Optimally designed bucking guidelines were used by Menominee logging crews to buck the logs to length (Dwyer and Dey 2007). This resulted in a total of 356 logs with a mean log length of 3.4 m. The shortest log was 2.5 m and the longest 5.1 m. Cross-sectional disks were cut from the stumps and from the top of every log from each tree. Log lengths and lengths of buckouts were recorded to the tenth of a foot and used to compute the height above stump in meters (HT) for the disks. Disks were numbered sequentially from the stump up to the highest disk. A total of 425 disks were cut and transported to the Forestry Sciences Laboratory at Princeton, West Virginia.

The amount and proportion of heartwood and sapwood were evaluated using the following procedures. Each disk was assigned a random angle ranging from 0-359 degrees in increments of 1 degree. A 20-cm-diameter circular protractor was placed with its center point at the pith of each disk. The random angle was then referenced on the protractor and a mark was made there and at angles 90, 180, and 270 degrees relative to it. Perpendicular lines were drawn across the disks through the two diameters defined by these marks. Linear measurements of each diameter in centimeters were taken at the bark-cambium boundary, sapwood-heartwood boundary, pith, heartwood-sapwood boundary, and cambium-bark boundary. The distance from the bark-cambium boundary to the pith is the radius inside bark (RIB) and the distance from the heartwood-sapwood boundary to the pith is the heartwood radius (HR). Ring counts were also recorded for each diameter at the same points.

Fourteen butt disks did not receive ring counts due to missing pith caused by decay (10 trees), caused by damage, or having been lost in the field or in transport. The trees that these disks came from, however, had upper intact disks. Tree age was estimated for these trees using the northern red oak site index (SI) table for Michigan (Carmean and others 1989) according to the following method. Tree age (AgeTree) was obtained from intact butt disks. Tree ages were pooled according to the four sites the trees were collected from. For each upper disk of these trees, the disk ring count was subtracted from AgeTree. This value was the age of the tree for height up to that disk and together with the disk height formed a height age pair. Height age pairs from disks where trees were older than 20 years were pooled by site, with 338 disks having actual ages. The suitable parameter values of the SI equation (Eq. 1) for northern red oak (Carmean and others 1989: 63) were used to calculated SI for each available disk.

$$SI = 0.1692HT^{1.2648}\left(1-e^{-0.0110\,Age}\right)^{-3.4334HT^{-0.3557}} \qquad (1)$$

Values for multiple disks were averaged by tree—there were one to six disks per tree—and then the SI for all trees on each site were averaged to determine SI for that site. Next, the height equation and the parameters for height (HT) from Carmean and others (1989) were used to determine estimated tree age (AgeEst).

$$HT = 6.1785SI^{0.6619}\left(1-e^{-0.0241\,Age}\right)^{25.0185SI^{-0.7400}} \qquad (2)$$

Here, Age represents the age of the tree when it grew to the height of the removed disk, which is the difference of AgeEst and disk-ring count. Eq. 2 was applied to each disk from trees that were missing tree age. The reasoning here is that with a known SI for each site, the height age pairs of each disk should fall on the SI curve for that site. This nonlinear equation (Eq. 2) was solved for AgeEst (the unknown value) using the root function of Proc NLIN in SAS® software Version 9.4 (SAS Institute Inc. 2012) with equations grouped by disks from the same tree. This allowed predicted ages to be imputed for trees missing age data. In two cases, inconsistent ages were obtained where AgeEst was smaller than the ring count of the first disk up from the stump. Here, the average height growth for the first disks of all aged trees within the same habitat type were used to estimate the number of years it took the non-aged trees to reach the height of their first disk. This number of years was added to the ring count of the first disk for that tree to determine AgeEst. Because all trees were in the dominant and codominant crown classes, and such trees are normally selected for SI, there is no reason to suspect bias in this method.

Data Analysis

The four radial measurements for all disks of each tree constitute repeated measures for that tree. Heartwood radius was therefore modeled as a linear mixed model, with each tree as the subject and radius nested within disks as the repeated effect. AgeTree, DBH, DBHClass, HT, and RIB were considered as fixed effect factors and SITE was considered as a random effect.

$$y = X\beta + Z\gamma + \varepsilon \qquad (3)$$

where

y is a vector where each element is the i^{th} HR from the j^{th} disk from the k^{th} tree, with *i, j,* and *k* indices.

X is a matrix consisting of values for AgeTree, DBH, DBHClass, HT, and RIB.

β is the vector of the unknown fixed effects parameters.

Z is the known design matrix based on the selected covariance structure.

γ is the vector of the unknown random effects parameters.

ε is the unobserved vector of random errors.

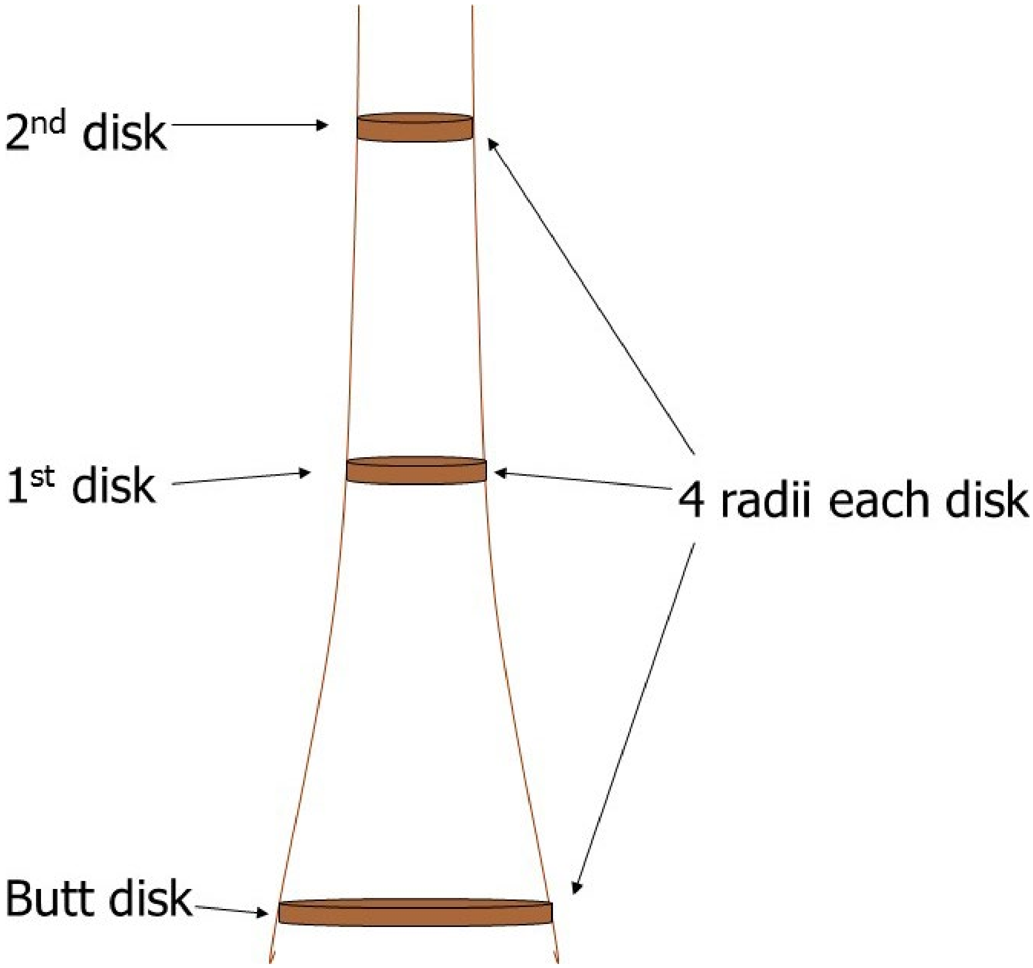

Figure 1.—Example of the first two logs that demonstrates the arrangement of the repeated measures.

Initial analysis was conducted to determine a suitable covariance structure for the repeated effects. Consideration was given to possible covariance types that aligned with the relationship between the physical measurements. Disks were taken at irregularly spaced intervals of HT, while heart radius was measured four times on each disk (Fig. 1). The covariance types selected to test were compound symmetry (CS), compound symmetry grouped by disk for each tree, heterogeneous compound symmetry (CSH), Toeplitz (TOEP), banded Toeplitz (TOEP(q)), Toeplitz grouped by disk for each tree, unstructured (UN), and variance components (VC). The compound symmetry covariance structure in its general form has a constant covariance on the diagonal and a common correlation among any two differing observations. The Toeplitz covariance structure maintains a constant covariance on the diagonal of the covariance matrix. The off-diagonal correlations between measurements within a subject (here the tree) can vary for differing pairs of observations. The CSH structure lessens the overall correlation between observations by a power function of the correlation. Banding on the Toeplitz structure zeroes out the covariance between observations if they exceed the band selected. Here multiples of four for the band size were selected as there are four radii measured on each disk. Grouping covariance structures by disk limits calculation of the covariance to observations for that disk rather than by each tree.

The model with the least Aikake information criterion (corrected) (AICc) value for the full model of HR=f(AgeTree, DBH, DBHclass, HT, RIB) was selected for further consideration (Littell and others 1996). Models were analyzed with these covariance structures using Proc Mixed in SAS® software Version 9.4 (SAS Institute Inc. 2012).

Preliminary modeling indicated that assumptions of normality and homoscedasticity were violated. Normal probability plots showed nonconformance to a normal distribution and residuals plotted against the predicted values and other independent variables exhibited heteroscedasticity (megaphone shaped residual patterns). This was remedied through the use of weighted least squares with the weight function determined to be a function of RIB.

Model selection proceeded using a set of three candidate models. A base model was formed that included RIB, HT, and the interaction term HT*RIB. Each of the three following terms was added as an additional term to the base to form the three candidates: AgeTree, DBH, and DBHclass. The three terms were considered in separate models to avoid multicollinearity as AgeTree and DBH were correlated ($\rho = 0.76$) and DBHclass is an ordinal variable categorized from DBH.

Model 1- $HR = \beta_{0,1} + \beta_{1,1}\,AgeTree + \beta_{2,1}\,HT + \beta_{3,1}\,RIB + \beta_{4,1}\,HT*RIB$ (4)

Model 2- $HR = \beta_{0,2} + \beta_{1,2}\,DBH + \beta_{2,2}\,HT + \beta_{3,2}\,RIB + \beta_{4,2}\,HT*RIB$ (5)

Model 3- $HR = \beta_{0,3} + \beta_{1,3}\,DBHclass + \beta_{2,3}\,HT + \beta_{3,3}\,RIB + \beta_{4,3}\,HT*RIB$ (6)

Model selection proceeded using a backward selection process with statistical significance level α set to 0.05.

RESULTS

The Toeplitz covariance structure, grouped by disk, had the lowest AICc value and was used in subsequent model development (Table 1). The AICc value for compound symmetry, grouped by disk, was a close second at 1,898.

The interaction term HT*RIB was not significant for Model 1, $p = 0.2691$. For Model 2, both the interaction term HT*RIB and DBHclass were not significant, $p = 0.1521$ and $p = 0.4413$ respectively. For Model 3, the interaction term HT*RIB was again not significant, $p = 0.6965$, as was DBHclass, $p = 0.1948$. This produced just two models with significant predictors (Table 2), as the final form of Models 2 and 3 (Model 2/3) were identical. Considering Model 1, RIB has a positive effect on HR. A 1 cm increase in RIB increases HR by 0.9509 to 0.9621 cm (95 percent confidence limits). AgeTree also has a positive effect on HT; an increase of 1 year shows an increase of just 0.0016 to 0.0044 cm in HR or 0.016 to 0.044 cm every 10 years (95 percent confidence limits). HT has a negative effect on HR where a 1 m increase in HT decreases HR by 0.0464 to 0.0519 cm. The coefficients for Model 2/3 are nearly the same as for Model 1. A 1 cm increase in RIB increases HR by 0.9581 to 0.9628 cm (95 percent confidence limits) and a 1 m increase in HT decreases HR by 0.0435 to 0.0488 cm.

Table 1.—Values for the Aikake information criterion corrected (AICc) of the full model [HR=f(AgeTree, DBH, DBHclass, HT, RIB)] with differing covariance structures for the covariance of the repeated measures

Covariance structure	AICc
Compound symmetry	2,516.8
Compound symmetry (grouped by disk)	1,898.0
Heterogenous Compound symmetry	2,433.5
Toeplitz	*
Banded Toeplitz (4 bands)	2,490.2
Banded Toeplitz (8 bands)	2,425.4
Toeplitz (grouped by disk)	1,896.7
Unstructured	*
Variance components	2,794.6

*Final Hessian not positive definite

Table 2.—Solutions for the parameters of the final backward selected linear mixed models, Models 1-3, with 95 percent confidence intervals

	Effect	Lower 95 percent C.L.	Estimate	Upper 95 percent C.L.	Std. error	p
Model 1	Intercept	-0.3623	-0.2275	-0.0927	0.0685	0.001
	AgeTree	0.0016	0.0030	0.0044	0.0007	< 0.0001
	RIB	0.9509	0.9565	0.9621	0.0028	< 0.0001
	HT	-0.0519	-0.0464	-0.0408	0.0028	< 0.0001
Model 2/3	Intercept	-0.3623	-0.0548	-0.0927	0.0564	0.3326
	RIB	0.9581	0.9628	0.9675	0.0024	< 0.0001
	HT	-0.0488	-0.0435	-0.0381	0.0027	< 0.0001

DISCUSSION

Both final models include RIB and HT, with coefficients that are effectively the same. Consideration of the size of each significant effect demonstrates that the most influential factor for determining heartwood radius (HR) is radius inside bark (RIB). The tallest height measured for any disc was just over 25 m. For even this highest disk, 25 m in height decreases the HR by approximately 1 cm. The oldest disk was 182 years old and was the second disk of a tree missing its stump disk, with AgeEst = 193 years. Assuming 200 years for ease of calculation, the contribution to HR from that age is only 0.32 cm. With RIB ranging up to 78.3 cm and RIB increasing 0.95-0.97 cm per cm of RIB, it is clear that RIB has the most influence on HR.

Cochard and Tyree (1990) reported that conductive sapwood in northern red oak is comprised predominantly by the two outermost growth layers. Taylor and others (2002) notes that heartwood volumes are cumulative. Once heartwood formation starts, sapwood cells die and become part of the heartwood, while new sapwood forms the outer growth rings. Consider also that each increase of 1 centimeter in radius inside bark leads to an increase of at least 0.95 cm in heartwood radius. In effect, heartwood radius nearly parallels the tree surface due to the strong influence radius inside bark has on heartwood radius, as the negative effect of HT is small. The standard error for the parameter on radius inside bark is small compared to the parameter. This indicates little variability in the estimate for radius inside bark, which translates to uniformity of shape for heartwood in cross-section. Wiedenbeck and others (2004) found that veneer log northern red oak commanded a premium when the heartwood was centered, so establishing that radius inside bark and its standard error is a good predictor of heartwood radius provides a useful tool for assessing log value, as the buyer will know that the heartwood is effectively running parallel to the RIB with little variation.

It is often the case that dbh and age are correlated measures for many tree species. For these sample trees, the correlation between tree age and dbh was 0.72. In addition, the full model also contained the class variable DBHClass, which is a categorization of the continuous variable DBH. Results of the three candidate models showed that there was a slight age effect as opposed to a size effect on heartwood. Therefore, there was a positive effect on heartwood formation resulting from trees being left to grow to older ages.

The Toeplitz grouped by disk covariance structure was identified as best. Because the disks were sampled from log ends, the distance between disks was much greater than the distance between radii on a disk. Both the best covariance structure and the second-best covariance structures were grouped by disk, the Toeplitz and compound symmetry structures respectively. This is evidence that there is close correlation between observations on a disk but that the observations between disks are less correlated. The better performance of the Toeplitz structure over compound symmetry may result from eccentricity of the bole from a circular form circumferentially.

CONCLUSIONS

The close alignment of heartwood radius to total wood radius inside bark provides buyers of northern red oak logs assurance that what is showing on the face of the log in respect to heartwood radius will be consistent relative to log radius throughout the length of the log. This provides certainty for estimating yields of heartwood where it is important to product outputs. Some of the uncertainty for loggers bidding on standing trees may be alleviated as well. These results also demonstrate that there is a positive effect for heartwood radius due to age and increased inside bark radius for northern red oak trees. This provides forest managers support for retaining trees for longer periods of time, such as in deferment cutting and variable retention systems. Further study is necessary, however, to determine whether these relationships hold for lower grade trees and other regions.

ACKNOWLEDGMENTS

Thanks go to Menominee Tribal Enterprises forestry staff for permitting tree sampling and conducting logging of tree samples and to John Dwyer and Daniel Dey for coordinating study plans. Special thanks to Michael Wiemann for initial study implementation and to Neal Bennett and Deborah Butler for help with data measurements.

LITERATURE CITED

Bamber, R.K.; Fukazawa, K. 1985. **Sapwood and heartwood: a review.** Forestry Abstracts. 46(9): 567-580.

Carmean, W.H.; Hahn, J.T.; Jacobs, R.D. 1989. **Site index curves for forest tree species in the eastern United States.** Gen. Tech. Rep. NC-128. St. Paul, MN: U.S. Department of Agriculture, Forest Service, North Central Forest Experiment Station. 142 p.

Carpenter, R.D.; Sonderman, D.L.; Rast, E.D.; Jones, M.J. 1989. **Defects in hardwood timber.** Agricultural Handbook 678. Washington, DE: U.S. Department of Agriculture, Forest Service, Northeastern Forest Experiment Station. 88 p.

Cochard, H.; Tyree, M.T. 1990. **Xylem dysfunction in Quercus: vessel sizes, tyloses, cavitation, and seasonal changes in embolism.** Tree Physiology. 6(4):393-407. https://doi.org/10.1093/treephys/6.4.393.

Dwyer, J.P.; Dey, D.C. 2007. **Product recovery from tree grade 1 northern red oak on Menominee tribal lands.** In: Buckly, D.S.; Clatterbuck, W.K., eds. Proceedings, 15th central hardwood forest. e-Gen. Tech. Rep. SRS-101. Asheville, NC: U.S. Department of Agriculture, Forest Service, Southern Research Station: 478-484.

Hanks, L.F.; Gammon, G.L.; Brisbin, R.L.; Rast, E.D. 1980. **Hardwood log grades and lumber grade yields for factory lumber logs.** Res. Pap. NE-468. Upper Darby, PA: U.S. Department of Agriculture, Forest Service, Northeastern Forest Experiment Station. 92 p.

Hawley, L.F.; Fleck, L.C.; Richards, C.A. 1924. **The relation between durability and chemical composition in wood.** Ind. Eng. Chem. 16(7): 699-700.

Kotar, J.; Burger, T.L. 1989. **Forest habitat type classification for the Menominee Indian Reservation.** Madison, WI: University of Wisconsin, Department of Forestry. 90.

Littell, R.C.; Milliken, G.A.; Stroup, W.W.; Wolfinger, R.D. 1996. **SAS System for mixed models.** Cary, NC: SAS Institute Inc. 633.

Nelson, N.D. 1976. **Gross influences of heartwood formation in black walnut and black cherry.** FPL-268. Madison, WI: U.S. Department of Agriculture, Forest Service, Forest Products Laboratory. 11 p.

Rast, E.D.; Sonderman, D.L.; Gammon, G.L. 1973. **A guide to hardwood log grading.** Gen. Tech. Rep. NE-1. Broomall, PA: U.S. Department of Agriculture, Forest Service, Northeastern Forest Experiment Station. 31 p.

SAS Institute Inc. 2012. **SAS Version 9.4.** Cary, NC.

Taylor, A.M.; Gartner, B.L.; Morrell, J.J. 2002. **Heartwood formation and natural durability--a review.** Wood and Fiber Science. 34(4):587-611.

Ward, J.C.; Pong, W.Y. 1980. **Wetwood in trees: a timber resource problem.** Gen. Tech. Rep. PNW-112. Portland, OR: U.S. Department of Agriculture, Forest Service, Pacific Northwest Experiment Station. 56 p.

Wiedenbeck, J.K.; Wiemann, M.; Alderman, D.; et al. 2004. **Defining hardwood veneer log quality attributes.** Gen. Tech. Rep. NE-313. Newtown Square, PA: U.S. Department of Agriculture, Forest Service, Northeastern Research Station. 9 p.

Yang, K.C.; Hazenberg, G. 1991a. **Relationship between tree age and sapwood/hardwood width in *Populus tremuloides* Michx.** Wood and Fiber Science. 23(2): 247-252.

Yang, K.C.; Hazenberg, G. 1991b. **Sapwood and heartwood width relationship to tree age in *Pinus banksiana*.** Canadian Journal of Forest Research. 21(4): 521-525. https://doi.org/10.1139/x91-071.

Yang, K.C.; Hazenberg, G.; Bradfield, G.E.; Maze, J.R. 1985. **Vertical variation of sapwood thickness in *Pinus banksiana* Lamb. and *Larix laricina* (Du Roi) K. Koch.** Canadian Journal of Forest Research. 15(5): 822-828. https://doi.org/10.1139/x85-133.

Brown, John P. 2019. **Heartwood taper in northern red oak (*Quercus rubra* L.).** Res. Pap. NRS-32. Newtown Square, PA: U.S. Department of Agriculture, Forest Service, Northern Research Station. 9 p. https://doi.org/10.2737/NRS-RP-32.

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KEY WORDS: heartwood, taper, northern red oak, linear mixed models

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