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Non-Destructive Measurement of the Modulus of Elasticity of Wood Using Acoustical Stress Waves

Gregory Dahle, Aaron Carpenter, and David DeVallance

Abstract. Many biomechanical models include modulus of elasticity (*E*) but it is not always available in the literature. It would be useful to directly measure *E* for species, and one of the standard techniques for doing so is to utilize a universal testing machine (UTM). While laboratory testing can determine static flexural modulus of elasticity using a UTM, it requires destructive sampling and therefore is only useful after a tree or limb has been removed. Acoustic testing can be used to estimate the dynamic modulus of elasticity (*DMOE*) of wood, by measuring the speed of sound through a sample of wood without the need to remove any wood samples. This research investigated if acoustic testing can be used to accurately estimate the modulus of elasticity of green wood. Stump sprouts arising after a shelterwood harvest were cut and left at room temperature (21.1°C, warm) or conditioned to -6.7°C (frozen). The modulus of elasticity was measured using a stress-wave timer (*DMOE*) and a UTM (E_S). The *DMOE* was higher in the frozen samples, but temperature did not affect E_S. While the stress-wave timer used in the study found a slightly higher *E* than a UTM, a simple prediction equation was determined for converting the results. Researchers believe tools such as this can be successfully utilized by the arboriculture industry to rapidly assess the modulus of elasticity of standing trees in the field.

Key Words. Acoustic Testing; Biomechanics; Dynamic Modulus of Elasticity; Green Wood; Northern Red Oak; *Quercus rubra* L.; Stress Wave; Temperature.

Many biomechanical models include modulus of elasticity (*E*), such as the static similarity model (allometric) (McMahon 1975; Niklas and Spatz 2004; Dahle and Grabosky 2010a) and pull tests for tree stability (Wessolly and Erb 1998; Bruechert et al. 2000; Brudi and Van Wassenaer 2001). Researchers have noted that *E* is modified as trees age (Pruyn et al. 2000; Plomion et al. 2001; Thibaut et al. 2001; Groom et al. 2002; Woodcock and Shier 2002; Woodrum et al. 2003; Kern et al. 2005; Read and Stokes 2006; Dahle and Grabosky 2010b), and this change may be tied to overall stability or shifts in the role of branch and stems as they mature (Dahle and Grabosky 2010b). The ability to assess *E* in the field would benefit the researcher in assessing or modeling tree stability.

Many times investigators use published data in catalogs for *E* (Spatz and Pfisterer 2013), such as from the Forest Products Laboratory Wood Handbook (Kretschmann 2010), Jessome (1977), or Lavers (1983). While published data are useful, variation can be high between individual species (Niklas 1992; Spatz and Bruechert 2000; Plomion et al. 2001; Read and Stokes 2006; Dahle and Grabosky 2010b; Kretschmann 2010) and is often limited to important timber species (Dahle and Grabosky 2009; Kretschmann 2010). The diversity of trees in the urban forest is typically high and includes many exotic species or species whose material properties have not been fully tested or are not readily available.

Given the within-species variability of wood, directly measuring *E* for living trees would be a useful tool, even though values may be available in the literature. While laboratory testing can determine static flexural modulus of elasticity (E_S), often using a universal testing machine (UTM), it requires destructive sampling and therefore is only useful after a tree or limb has been removed. Acoustic testing, or stress-wave testing, can be used to estimate the flexural modulus of elasticity (E_S) of wood by measuring the speed of sound through a sample of wood

(Grabianowski et al. 2006; Downes and Drew 2008; Kretschmann 2010) without the need for destructive sampling. Research has led to the understanding that acoustic stress-wave velocity is an accurate predictor of the dynamic modulus of elasticity (*DMOE*) of wood that is derived from standing trees (Lindström et al. 2002; Grabianowski et al. 2006; Auty and Achim 2008; Gao et al. 2013; Chen et al. 2015). Yet much of this work has not directly tested the *DMOE* against E_S. Stress-wave relationships between sawn logs and lumber have shown that the modulus of elasticity of the log correlates well to the average modulus of elasticity of the lumber (Ross et al. 1997).

Gao et al. (2012; 2013) found that wood temperature had a significant effect on how acoustic sound travels through clear wood in standing trees. As the temperature of wood reaches freezing, velocity of sound waves increase as temperature decreases (Gao et al. 2012; Gao et al. 2013). The speed of sound slowly decreases as branch wood warms above freezing (Bächle and Walker 2006; Kretschmann 2010). Although branches tend to include small imperfections, such as knots, the one-way flight path of the stress-wave timer will circumvent these areas reasonably well (Chauhan and Walker 2006).

Acoustic stress wave technology has been used in fields for nondestructive materials resonance testing as an indicator of material properties (Vary and Lark 1978; Vary and Bowles 1979; Henneke and Stinchcomb 1986; Halabe et al. 1997; DeVallance et al. 2011). In standing trees, advanced stress wave technology is used to measure decay that cannot be seen from the outside (Gilbert and Smiley 2004; Wang and Allison 2008; Wang et. al 2009; Johnstone et al. 2010a; Johnstone et al. 2010b). Along with providing a good estimation of the amount of internal decay, this technology can be used to estimate the testing of flexural modulus of living trees, but comes with a large cost associated with the equipment and a lengthy setup due to the number of probes. Stress-wave timers, such as the Fakopp® microsecond stress wave propagation timer used in this study, allow for simplistic acoustical testing of living trees and prevent the need for destructive sampling.

A UTM is a direct measure of materials elasticity (ASTM 2005), yet this requires destructive testing and takes a significant amount of time. The ability to use a portable acoustical stress-wave system can allow a rapid estimation of flexural modulus of elasticity without the need for destructive sampling. This research was designed to determine if the acoustic technology can be an applied when measuring *E* in standing trees, thus allowing the use of a rapid, non-destructive method of obtaining *E* that can be used in prediction stability in urban trees.

MATERIALS AND METHODS

Northern red oak (*Quercus rubra* L.) stump sprouts arising after a three-stage shelterwood harvest were collected in February 2013 and September 2014. The samples were growing in a 29.95 ha site within the Research Forest of West Virginia University (Monongalia County, West Virginia, U.S.). One hundred and twenty sprouts were harvested with only one sprout per stump cut. Sprout diameter ranged from 2.7 to 4.6 cm, and all sprouts were cut to a length of 55.9 cm beginning at the proximal end of the sprout. The sprouts were randomly separated into two groups: sixty were placed at room temperature (warm), estimated at 21.1°C, and sixty at -6.7 °C (frozen), for five days in a CSZ-H/AC environmental unit (model ZPH-32-2-2-H/AC, Cincinnati Sub-Zero, Cincinnati, Ohio, U.S.). Two of the frozen samples were subsequently discarded during processing due to damage.

Dynamic Modulus of Elasticity

The *DMOE* was evaluated using a Fakopp Microsecond Timer (frequency 23 kHz, Fakopp Enterprises, Agfalva, Hungary) by determining the time it takes for a stress wave, generated by a hammer tap on an spike transducer (Figure 1), to travel from one end of the sample to the other end. This was replicated five times per sample for each group following a protocol that assumed that measuring each sample with three hits at the same location would be sufficient in assessing different stands (Carter et al. 2005a; Carter et al. 2005b). Longitudinal *DMOE* was calculated as Equation 1:

[1] $$DMOE = c^2 \times \rho$$ (DeVallance et al. 2011)

where *DMOE* = dynamic longitudinal modulus of elasticity in gigapascals $\left(\frac{n}{m^2}\right) x10^9$
c = stress-wave velocity (cm/second)
ρ = density $\left(\frac{mass\ (g)}{980\ \mathrm{cm}/s^2 * \mathrm{volume}\ cm^3}\right)$

Figure 1. Measuring dynamic modulus of elasticity (*DMOE*) with the Fakopp stress-wave microsecond timer.

Flexural Modulus of Elasticity

Directly after *DMOE* testing, the samples were subjected to a three-point bending test, with a span of 44.45 cm using a UTM (model MTS 810, Instron®, Norwood, Massachusetts, U.S.) (Figure 2) at a rate of 0.16 cm per minute. The span/depth ratio was selected in accordance to a 14:1 cm length to diameter ratio as recommended by the ASTM D 198-05 (ASTM 2005) to minimize shear. The slope of the force versus deformation regression was determined for each sample from the load press output, and flexural modulus of elasticity was calculated as Equation 2:

[2] $$E_S = \frac{(4 \times * slope * \times (length^3))}{48 * \times \pi * \times (radius^4)} \quad \text{(ASTM 2005)}$$

where E_S = flexural modulus of elasticity in gigapascals $\left(\frac{N}{m^2}\right) x10^9$

Length = the overall test span of the sample (m)

Radius = the average radius of the overall sample taken at three points: large-end radius, middle radius, and small-end radius (m)

Slope = slope of the linear region taken from the force (n) versus deflection (m) curve

After testing modulus of elasticity, a disc (approximately 2 cm) was cut from each stump sprout and weighed, then oven dried for three days at 50°C in an Isotemp™ 500 Series oven (Fisher Scientific Co. LLC, Pittsburgh, Pennsylvania, U.S.) to determine the dry weight. The weight of each sample was measured on Day Two and Day Three and no difference were found. A subsequent evaluation of drying samples at 103°C found only minor (<5%) differences in moisture content compared to 50°C. Moisture content (MC) was calculated as Equation 3:

[3] $$MC = \frac{wet\ weight - dry\ weight}{dry\ weight} * 100$$

Statistical analysis used t-tests, paired t-tests, and regression analysis conducted in SAS 9.4 using $\alpha = 0.05$. Statistical parameter data and residuals were tested and determined to be normal.

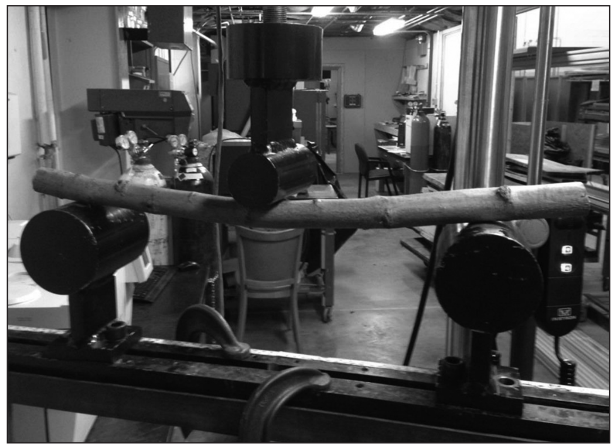

Figure 2. Measuring flexural modulus of elasticity (E_S) with the universal load press.

RESULTS & DISCUSSION

The ability to determine the material properties of green wood in a standing tree can aid the arboricultural practitioner and researcher in predicting the stability of a tree or branch. Knowing *E* is important and useful during tree pull tests to assess stability (Wessolly and Erb 1998; Bruechert et al. 2000; Brudi and Van Wassenaer 2001). A long branch, such as a fast-growing water sprout with a disproportional amount of flexible juvenile wood, may bend too much under loading, leading to failure. In addition to ontogenetic shifts in *E*, there may be shifts due to reaction wood (Kane and Ryan 2003), which may influence the categorization of the likelihood of failure during tree risk assessments.

A UTM is a direct measure of materials elasticity (ASTM 2005), yet this requires destructive testing and takes a significant amount of time. The ability to use a portable acoustical stress-wave system can allow a rapid estimation of flexure modulus of elasticity without the need for destructive sampling. The *DMOE* for frozen samples was significantly higher than the warm samples ($P < 0.0001$, N = 118, Table 1), but this was not the case for the load press where no difference was found between the temperatures ($P = 0.0757$, N = 118, Table 1). Mean diameter was not found to vary ($P = 0.6623$, N = 118) between the warm (3.5 ± 0.05 cm) and frozen (3.4 ± 0.04 cm) samples.

When comparing *E* obtained from the UTM, the stress-wave timer system was higher than the load press, whether temperatures were warm ($P < 0.0001$, N = 58, Table 2), frozen ($P < 0.0001$, N = 60), or grouped ($P < 0.0001$, N = 118). These findings are consistent with other research that indicates when wood temperature is below freezing, there is a continual increase of acoustic velocity (Gao et al. 2012). This phenomenon can be observed in other naturally occurring materials such as rocks and aluminum (Timur 1977; Fukuhara and Yamauchi 1993). Moisture content was not found to differ between the warm (55.1% ± 0.9 SE) and cold (53.6% ±1.0 SE) samples ($P = 0.2169$ N = 118). The MC was lower than reported by the Forest Products Laboratory Wood Handbook at 69% (Glass and Zelinka 2010), yet in the literature there is little difference in material properties when MC is greater than 50% (Lavers 1983; Kretschmann 2010; Spatz and Pfisterer 2013).

To measure velocity in the fiber direction, in this study, the pins were placed in the cross section of the samples, rather than radially through the bark. However, the results are expected to be the same when testing radially through the bark, as comparison testing on other tree branch pieces showed little to no difference in stress wave time (less than 1 microsecond) when testing at the ends and radially through the bark with low-angle pin placement. This result is also similar to the manufacturer's results, as they reported that the angle of the fiber and transducer pins is negligible as long as the pins are not placed at an angle of more than 45 degrees when placing the pins radially through the bark (Fakopp, no date). Hence the reason researchers of the current study believe the test is a suitable approximation of this system.

Regression analysis determined that there was a 1:1 relationship between the two measurement systems, but that *DMOE* was higher ($E_S = 1.01 * DMOE - 272.9$, $r^2 = 0.42$, N = 118, Figure 3). While the r^2 for this regression is not overly high, the study authors believe this supports further investigation of stress-wave timers as a potential field tool for arborists. Separate regressions were developed between *DMOE* and E_S (not presented here), yet the slopes between the two treatments (warm and frozen) were not significantly different ($P = 0.4669$). Interestingly, the stress-wave meter had a lower standard error than the destructive testing, which could make this a desirable method for calculating branch rigidity.

No significant differences were found between the diameters (warm = 3.5 ± 0.1 cm, frozen = 3.4 ± 0.1 cm, $P = 0.6623$, N = 118) or age (warm = 3.2 ± 0.06 years, frozen = 3.4 ± 0.07 years, $P = 0.0694$). The size and age of the sample suggests that the wood is juvenile and thus has a lower modulus of elasticity than mature red oak green wood (E = 9300 MPa) reported by the For-

Table 1. Mean flexural modulus of elasticity (*E*) when tested using a universal testing machine or stress-wave timer. *P*-values less than 0.05 represent significant differences using a paired t-test.

Testing machine	E_{warm} (MPa) ± SE	E_{frozen} (MPa) ± SE	N	*P*-value
UTM	1120 ± 40.0	1216 ± 38.9	118	0.0757
Stress wave	1355 ± 20.6	1495 ± 25.5	118	<0.0001

Table 2. Mean flexural modulus of elasticity (*E*) tested at each temperature (warm 21.1°C or frozen -6.7°C) when tested using a stress-wave timer (*DMOE*) or universal testing machine (E_S). *P*-values less than 0.05 represent significant differences using a paired t-test.

Treatment	E_S (MPa) ± SE	*DMOE* (MPa) ± SE	N	*P*-value
Warm	1120 ± 36.9	1355 ± 20.6	60	<0.0001
Frozen	1216 ± 38.8	1495 ± 25.5	58	<0.0001
Grouped	1169 ± 27.1	1426 ± 17.6	118	<0.0001

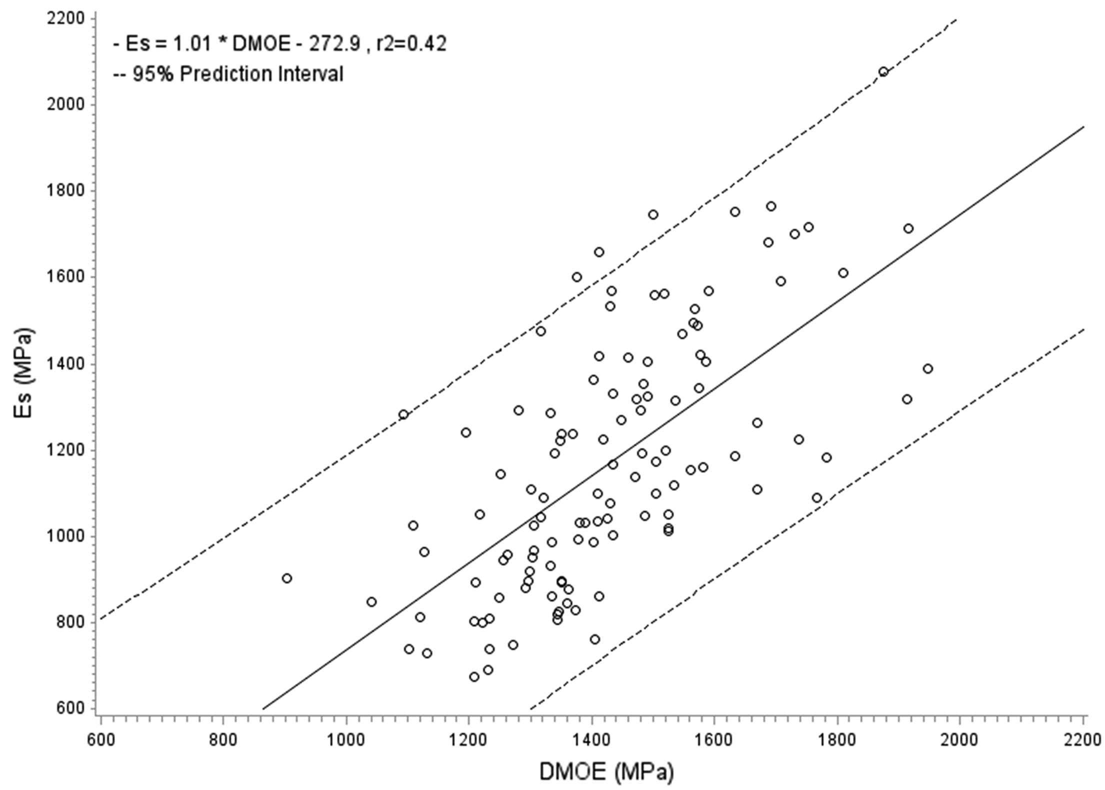

Figure 3. Regression predicting the modulus of elasticity (E_S) from the estimate for dynamic modulus of elasticity (*DMOE*) derived from the Fakopp stress-wave timer.

est Products Laboratory Wood Handbook for E (Kretschmann 2010). Material properties of juvenile wood are lower than in mature wood (Lindström et al. 1998; Thibaut et al. 2001; Groom et al. 2002a; Woodrum et al. 2003; Kern et al. 2005; Read and Stokes 2006; Dahle and Grabosky 2010b). The E in juvenile wood has been reported to be as much as 75%–85% of E in mature wood (Holbrook and Putz 1989; Dahle and Grabosky 2010b), which the current data fall in line with. Additional research should be conducted on more mature wood, and it may be possible to use acoustic systems to determine if juvenile or mature wood is being laid down by the cambium.

In this study, *DMOE* was found to increase in frozen wood, while E_S did not vary with temperature. Overall, *DMOE* was slightly higher than E_S and an equation was developed to predict E_S from *DMOE*. While more research is needed to determine the effect of pin placement and wood temperature, researchers believe that tools, such as a stress-wave meters, can be used to rapidly estimate modulus of elasticity without the need for destructive sampling of standing trees in the field.

CONCLUSIONS

This study demonstrated that a portable acoustic stress-wave system can be used to rapidly estimate *DMOE* in standing trees. While *DMOE* was found to be slightly higher than $E_{S,}$ simple regression can be developed to predict E_S from *DMOE* for a given species of interest.

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Gregory Dahle (corresponding author)
Division of Forestry and Natural Resources
West Virginia University
Morgantown, West Virginia 26505, U.S.
gregory.dahle@mail.wvu.edu

Aaron Carpenter
Division of Forestry and Natural Resources
West Virginia University
Morgantown, West Virginia 26505, U.S.

David DeVallance
Division of Forestry and Natural Resources
West Virginia University
Morgantown, West Virginia 26505, U.S.

Résumé. De nombreux modèles biomécaniques incorporent le module d'élasticité (*E*), mais il n'est pas toujours disponible dans la littérature. Il serait utile de mesurer spécifiquement le *E* des espèces et l'une des techniques courantes pour le faire consiste à utiliser une machine d'essai universelle (MEU). Bien que les tests en laboratoire aident à déterminer la flexion statique du module d'élasticité en utilisant une MEU, l'échantillonnage est destructif et il n'est utile que lorsqu'un arbre ou une branche ont été coupés. Le test acoustique peut être utilisé pour évaluer le module dynamique d'élasticité (*MDE*) du bois en mesurant la vitesse du son à travers un échantillon de bois et ce, sans qu'il soit nécessaire d'extraire cet échantillon de l'arbre vivant. Cette recherche vise à établir si le test acoustique peut être utilisé pour évaluer avec précision le module d'élasticité du bois sain.

Zusammenfassung. Viele biomechanische Modelle schließen einen Modulus von Elastizität (*E*) ein, aber das ist nicht immer in der Literatur vorhanden. Es würde nützlich sein, *E* direkt bei den Arten zu messen und eine der Standarttechniken dafür ist die Verwendung einer Universalen Testmaschine (UTM). Während im Labor unter Einsatz der UTM der statisch flexurale Modulus von Elastizität bestimmt werden kann, erfordert es eine destruktive Probennahme und daher ist es nur sinnvoll, wenn der Baum oder ein Teil davon entfernt wurde. Akustische Testreihen können verwendet werden, um den dynamischen Modulus von Elastizität (*DMOE*) zu schätzen, indem die Geschwindigkeit von Signalen durch eine Holzprobe ohne die Erfordernis zur verletzenden Probennahme gemessen wird. Diese Studie untersucht, ob akustische Tests für eine akkurate Bestimmung des Elastizitätmodulus von grünem Holz verwendet werden können.

Resumen. Muchos modelos biomecánicos incluyen módulo de elasticidad (*E*), pero no siempre están disponibles en la literatura. Sería útil medir directamente *E* para las especies y una de las técnicas estándar para hacerlo es utilizar una máquina de prueba universal (UTM). Mientras que las pruebas de laboratorio pueden determinar el módulo de elasticidad estático utilizando una UTM, se requiere un muestreo destructivo y por lo tanto sólo es útil después de que un árbol o rama se ha eliminado. Se puede utilizar la prueba acústica para estimar el módulo dinámico de elasticidad (*DMOE*) de madera mediante la medición de la velocidad del sonido a través de una muestra de madera sin la necesidad de retirar las muestras de madera. Se investigó si la prueba acústica se puede utilizar para estimar con precisión el módulo de elasticidad de la madera verde.