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Relative Resistance to Breaking of Pinus taeda L. and Pinus palustris

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RELATIVE RESISTANCE TO BREAKING OF PINUS TAEDA L. AND PINUS PALUSTRIS

A Thesis

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When I started at LSU in 2013, I had little research experience to rely on. The allure of trying to simulate a hurricane with powerful machinery brought me here, and because of that I've learned much about the challenges of creating a unique study and seeing it through to completion. In my case, I grappled with soggy field conditions, physically demanding data collection, 'high-tech' equipment, and applying engineering physics to forestry. In the end, I'm happy to say I feel much better prepared to bridge theory and practice and work independently over a long time frame.

My advisor, Dr. Tom Dean, has been a voice of expertise, reason, support, and in all, a true forestry Jedi. Without him no phase of this project would have been possible. Dr. Richard Keim also helped by challenging me and enriching my ideas. Shannon Kidombo, my office mate and friend, took turns with me ratcheting trees down and was truly my teammate in the field. Shannon, Joseph Nehlig, and Don Bluhm together were the best field team I could have asked for. Also I want to thank Ashley Taylor for drawing much better pictures than I could have, and Spencer Rimes for editing them. Finally, thanks to everyone who came to visit me in Baton Rouge and to all the friends I've been lucky enough to make here. It's been a great experience that I will never forget.

Most importantly, thanks to my family and to God.

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ABSTRACT

Patterns from hurricane damage give an indication that longleaf pine is more windfirm than loblolly pine. Tree windfirmess has been attributed to many factors including species and material properties like wood strength and stiffness. Because longleaf pine wood is stronger and stiffer than loblolly pine wood, this study used static winching methodology to see if these properties account for differences in windfirmness by measuring bending force required to break stems (M_{MAX}). Stress-strain diagrams were constructed for pulled trees to explore how they behave under increasing loads. Based on these diagrams, it appears that living trees can act as linear elastic materials as they experience increasing static lateral stress. As expected, longleaf pine stems were stiffer than loblolly pine wood *in situ* based on Young's moduli (MOE) derived from these diagrams. Tree basal area was the best predictor of M_{MAX} for both species, however, species had no effect on the maximum bending moment required to break tree stems of a given diameter for these trees under these conditions. Estimated values of MOR did not significantly differ by species, nor did the relationships between MOE and MOR. Initial estimates without rigorous testing suggest that perhaps observed differences in wind damage between loblolly and longleaf pine after hurricanes may be due to greater wind drag through loblolly pine crowns. Future studies could look to crown characteristics to continue to understand the difference in windfirmness between these two species.

INTRODUCTION

In the aftermath of Hurricane Katrina, a large category 3 hurricane that hit the United States Gulf Coast in August 2005, longleaf pine (*Pinus palustris*) suffered significantly less mortality and damage than loblolly pine (*Pinus taeda* L.) (Johnsen 2009). This, coupled with similar observations following Hurricanes Hugo (Gresham et al. 1991), Erin (Duryea 1997), and Rita (Harcombe 2009), has led to a general consensus that longleaf pine is more resistant to wind damage than loblolly pine. Loblolly pine is economically significant to the region, as it is the commercial standard for the southern timber industry, occupying the majority of sites on forested land that are managed intensively on the Coastal Plain (Stanturf 2007). Of the more than $5 billion and estimated 19 billion board feet of timber lost due to Hurricane Katrina (Shiekh 2005), the majority was due to wide spread damage to loblolly pine (Johnsen et al. 2009), which is the primary commercial species in the southern United States. Hurricanes like Katrina are likely to become more prevalent. Emanuel (2013) predicts a 40% increase in hurricanes of category 3 and higher by the year 2100 due to thermodynamic effects brought about by increased greenhouse gas concentrations. In the same time period, costs from tropical cyclone damage are projected to double due to climate change (Mendelsohn 2012). Consequently, resistance to wind damage will become an increasingly important criterion in the long-term risk of planting loblolly in areas originally covered by longleaf pine. Longleaf pine stands once covered as many as 90 million acres in the southern United States, of which less than 3 percent remain due largely to converting these areas to loblolly pine (Gilliam 1999). As a result, there are both economic and ecological arguments for foresters to better understand the apparent interspecies differences in windfirmness between longleaf pine and loblolly pine.

The factors that contribute to tree windfirmness have been studied extensively. Duryea and Kampf (2007) surveyed tree damage after 10 hurricanes in the southeastern United States and concluded that tree species, health, age, and structure, as well as site characteristics such as soil composition, soil compaction, and water table depth influence wind damage on trees. Interspecies differences in windfirmness have been attributed to a variety of morphological factors such as tree geometry, root architecture, and wood strength (Everham and Brokaw 1996). Many studies have linked wood properties, including strength and wood density, to wind damage vulnerability (Curtis 1943, Weaver 1989, Hook et al. 1991). Putz et al. (1983) found that Panamanian tree species with low density wood suffered higher mortality rates, 75% of which broke at or above ground level rather than uprooting. Webb (1989) found that wind induced tree mortality in mixed *Pinus-Acer* and *Pinus-Abies* stands in Minnesota, USA was strongly related to species wood strength.

The most common methodology for testing the relationship between tree windfirmness and species wood properties is known as the static winching method. Static winching studies have been utilized for over 50 years to measure the static forces required to break stems or uproot trees *in situ* (Fraser 1962, Peterson and Claasen 2013). Tree resistance to breakage or uprooting is evaluated in these studies by estimating the maximum bending moment at the base of the tree (M_{MAX}) that is the sum of the horizontal and vertical moments caused by wind and gravity based forces, respectively. When M_{MAX} exceeds the maximum resistive forces of tree stems or roots, they break or overturn, respectively. Across the two *Pinus* species in this study, breakage appears to be the more common mode of failure. For example, when tallying the damage Hurricane Katrina inflicted on the trees of the Henderson experimental forest in

Gulf Port, Mississippi, Johnsen (2009) found that longleaf pine were equally likely to break or uproot, while loblolly stems broke 75% of the time and uprooted 25% of the time.

Many regressions have been fit to predict M_{MAX} with the most common predictors being diameter, tree height, stem mass and volume, root depth and width, and soil type (Peltola 2006). Specifically, above ground dimensions have shown strong positive correlations with M_{MAX}, including stem mass (Fraser and Gardiner 1967), root height (Smith et al. 1987), DBH (Papesch et al. 1997), and stem volume (Peltola et al. 2000). Despite the differences in the various applications of the static winching method across studies, there is a general agreement that the method adequately predicts stem or root failure due to intense, sustained winds (Achim 2005, Peltola 2006, Peterson and Claasen 2013). Cooper-Ellis et al. (1999) used the static winching method on nearly 900 trees to create an experimental hurricane, and found that the type of damage and mortality were strongly related to tree species. In this respect, the tendency for stem failures due to hurricane force winds is similar to species vulnerability as determined from static winching analysis (Gresham et al. 1991, Duryea 1997, and Johnsen 2009). Static winching is also repeatable and relatively simple to apply. Wind tunnel studies have also been used to investigate the effects of static loads on trees and are useful in the development of mechanistic models to predict windthrow, but these studies are limited by scale due to obvious size limitations (Peltola 2006).

Wood physical properties may play a role in tree stability, and they differ between loblolly and longleaf pine. The increased specific gravity (0.54 vs. 0.47), strength (modulus of rupture 59,000 kPa vs.50,000 kPa) and stiffness (Young’s modulus 11,000 MPa vs. 9,700 MPa) of green longleaf wood compared to green loblolly wood (Forest Products Laboratory 2010) are consistent with observations that longleaf pine resists stem failure due to high winds better than loblolly pine. If the differences in mechanical properties account for observed differences in wind damage to longleaf and loblolly, then the slope between stem displacement and stress within the linear portion of a stress-strain diagram will be steeper for longleaf pine than for loblolly pine. Also, if differences in modulus of rupture measured on small boards on a 3-point bending machine translate into greater resistance to breakage due to high winds, the maximum turning moment measured when stems break will be higher for longleaf pine than for loblolly pine.

This study focused on the maximum bending moments required to break stems and did not take into account resistance to overturning for two main reasons. Of the two modes of failure that commonly occur in trees due to wind, stem breakage appears to be more common than uprooting across loblolly and longleaf pine. Johnson (2009) found that in the aftermath of Hurricane Katrina, longleaf pine were equally likely to break or uproot while loblolly stems broke 75% of the time, while Putz and Sharitz (1991) noted that of 100 loblolly pine exposed to Hurricane Hugo in South Carolina, 28 broke and 21 uprooted. Also, differences in wood properties like strength and stiffness could account for how much force the stems could withstand, and the static winching method provided a way to measure stem breakage directly. Other factors which have been correlated with tree windfirmness such as tree spacing (Peterson 2013) , soil type (Moore 2000), and root architecture (Coutts 1983) were not analyzed in this study because the mode of failure for all trees in this study was stem breakage rather than overturning/uprooting. The static winching method has previously been applied to loblolly pine trees. Fredericksen et al. (1993) used the static winching method in determining the force required to break loblolly pine stems and found strong positive correlations between M_{MAX} and stem mass in loblolly pine trees, as well as a general reduction in tree flexibility with increased tree size. To my knowledge, no static winching studies have been performed on longleaf pine.

METHODS

I. Site Description

The study was conducted at H. G. Lee Memorial Forest (LMF) located in southeastern Louisiana in Washington Parish, 20 km east of Bogalusa near the town of Pine, Louisiana (Figure 1). In 2005 the Forest was in the path of Hurricane Katrina, sustaining damage to over 500 acres of timber. The soil on the study site is composed predominantly of Smithdale, Ruston, and Savannah fine sandy loams on shallow hills typical of Coastal Plain topography. Average annual rainfall is 1615 mm and average daily temperature is 19.2°C (USDA 1997).

Trees were selected from plantations that were planted in 1991 and thinned in 2013. The understory had been burned every 2-3 years since 2003, most recently in the fall of 2013.

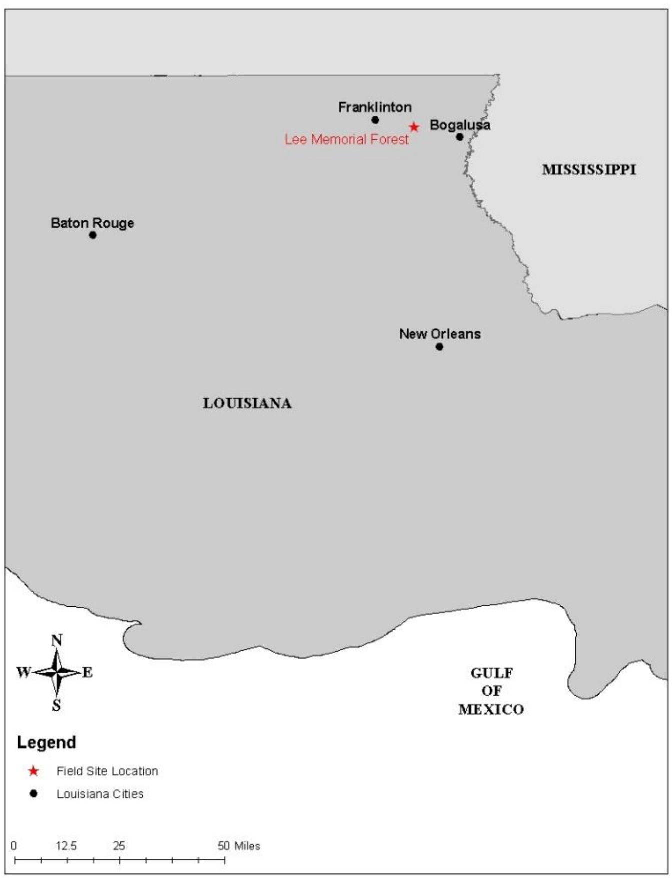

Figure 1: The location of the field site, H.G. Lee Memorial Forest, in Southeastern Louisiana

II. Tree Selection

Trees were selected from within 23 year-old, even-aged pine stands. In all, 22 loblolly pine trees and 18 longleaf pine trees were measured. The sample trees ranged from 14.3-20.3 m height and 9.3-29.7 cm diameter at 3 meter height. This diameter measurement was used rather than DBH to be sure that stump flare was not a factor (Table 1). Sampled trees had to meet several criteria. Anchor trees had to be close enough to sample trees to be within the range of the pulling apparatus (Figure 2). Preferred anchor trees were larger than the corresponding sample tree. Also, the sample tree needed to be free of obstructions such as neighboring crowns as it was pulled over. Lastly, both pulled and anchor trees needed to be straight and free of defects.

Table 1: Summary of sample trees included in study analysis.

Species	n	Diameter at 3 m height (cm)	Height to top (m)	Height to live crown (m)
P. palustris	15	9.3-29.7	14.3-19.2	5.6-10.7
P. taeda	18	10.5-26.1	12.8-20.3	7..9-11.6

III. Winching Procedure

Tree strength and bending properties were measured with a static winching technique as described by Peterson and Claasen (2013) and Samarakoon (2013). Prior to pulling, trees were marked and measured for diameter at 0, 1, 2, and 3 meter heights. Trees were pulled with a 2-m long nylon collar strap attached as close as possible to the base of the crown using Swedish climbing ladders. Clevis hitches (64 mm) were used to link the collar strap to one or more 10-m nylon pulling straps, depending on the distance to the anchor tree. The distal end of the nylon pulling straps was attached to a steel cable hand winch (Masdaam Powr Pull 1800 kg capacity), which was linked to one side of a digital dynamometer load cell (ED junior 3500 kg).

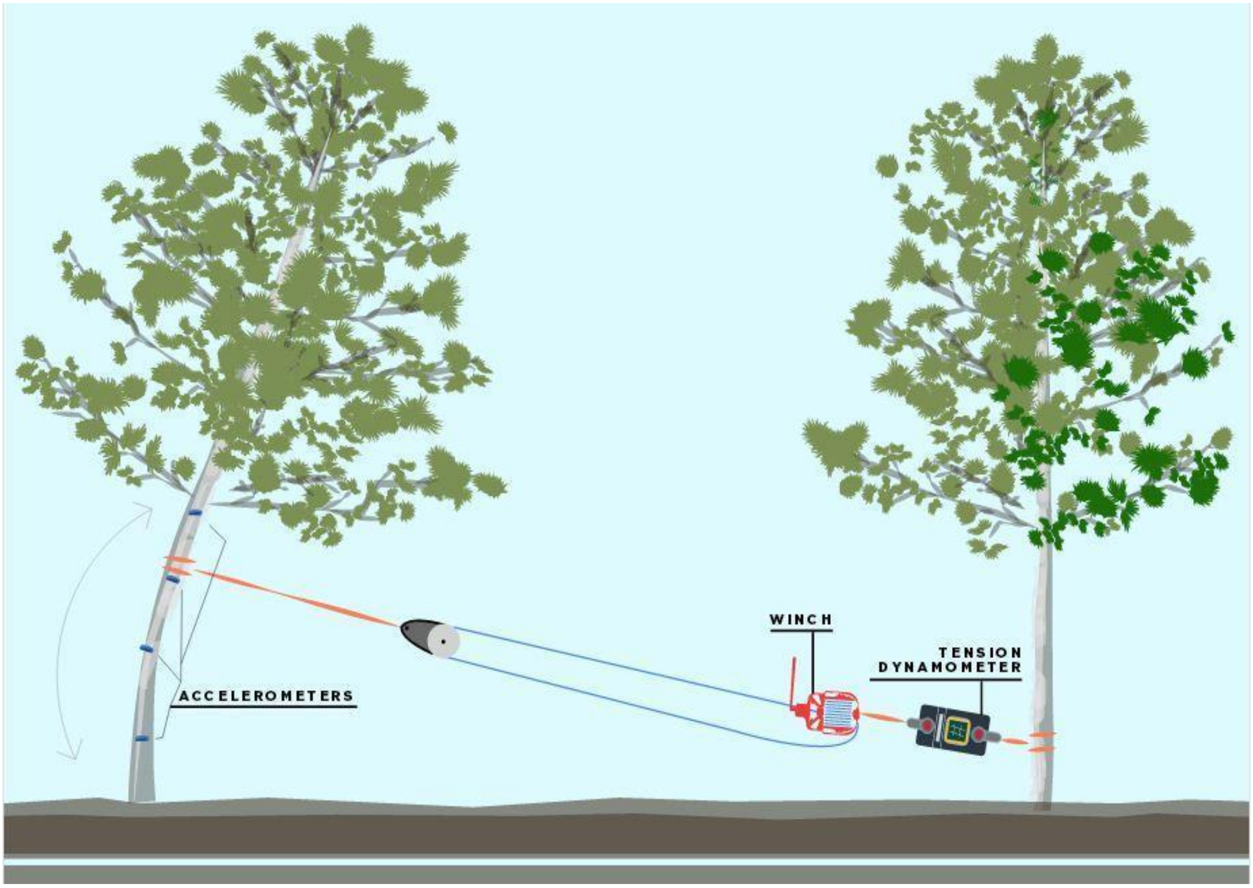

Figure 2: Schematic of static winching test apparatus. The technique in this study differed from previous studies in that it included multiple accelerometers along the tree stem and a pulley that doubled the pulling power of the winch.

The other side of the load cell was then connected to the base of the anchor tree with a second 2-m collar strap. For trees with DBH between 18 and 20 cm, the cable was doubled around a steel pulley connected to the pulling strap, doubling the mechanical advantage of the pulling apparatus. The largest 6 trees (>20 cm DBH) in the study were pulled with a bulldozer (John Deere 450c) similarly to the study by Peterson and Claasen (2013).

Tri-axial accelerometer units (GCDC model A3) were used as tilt sensors to measure displacement from vertical at various height intervals along the stem perpendicular to the pulling direction. The accelerometers were calibrated by securing them along a straight board, then recording multiple angular departures from vertical as measured with a digital level. Sensor output was proportionate to angular deflection, so horizontal displacement of the sensors was easily calculated with basic trigonometry. Sensors were attached to tree stems with 7.6-cm drywall screws. One accelerometer was always located immediately below where the collar strap was attached to the stem, and as many as 6 additional units were placed equidistant below the top unit. The inclusion of additional accelerometers provided better estimates of the offset from vertical (deformation) that corresponds with the height at the point of failure on the stem.

IV. Stress-Strain Diagrams

Stress-strain diagrams were constructed with the data measured during static winching tests. These figures simply display stress caused by the mechanical force acting on a beam as a function of strain, the distance or displacement the beam moves when force is applied. The linear portions of these diagrams represent the elastic zone of the material; the slope of this line is the material's modulus of elasticity (MOE). When sufficient force is applied to equal the elastic limit, the beam will be permanently deformed by the stress, causing a departure from linearity in the stress-strain diagram (Figure 3). If trees in static winching experiments obey Hooke's law (and therefore are linear elastic materials), their stress strain diagrams should have the appropriate shape as described by Osgood (1932).In this study, stress (Ϭ) was calculated using the equation for normal stresses in beams; $\sigma = \frac{Mc}{I}$ (Nash 1972), where *M* is the bending moment, *c* is the distance from the neutral axis, and *I* is the second moment of area for a circle, $I = \frac{\pi}{4}r^2$. Strain (Є) was represented by the horizontal displacement from vertical of the breaking point of the stem at the moment of failure, estimated from the distance traveled by the accelerometers when the stem broke.

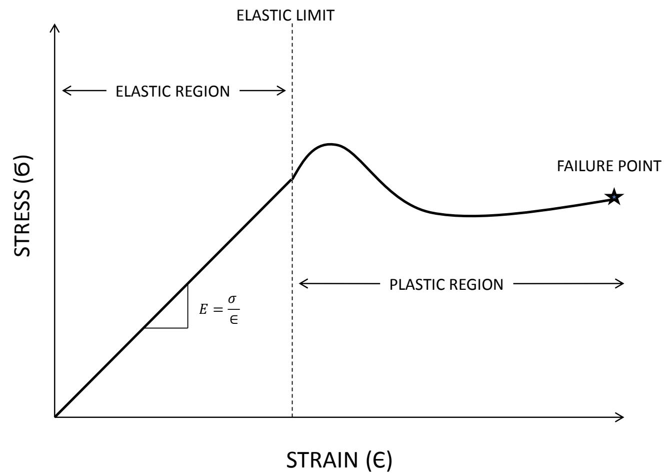

Figure 3: A typical stress strain diagram. The slope of the linear portion of the diagram within the elastic region is defined as the elastic modulus (Young's modulus) of the material.

In order for stress-strain diagrams for winched trees, the data from the accelerometers had to be temporally aligned and the tension dynamometer had to be recorded at the same time. The accelerometers had an internal clock and recorded the data with a time stamp. The dynamometer data were recorded manually periodically with the aid of an external timer. The time stamped accelerometer data had to align with the dynamometer data in order to correctly plot the stress-strain diagrams. This only occurred for 6 loblolly pine trees and 5 longleaf pine trees. The elastic limit for each diagram was established by finding the point that created deviation in the residuals of the linear regression. The data points comprising the linear portions of the diagrams were grouped by species, and Young's modulus of elasticity was estimated from the slope of linear regression.

V. Calculations of M_{MAX}

During pulling tests, the anchor trees were assumed to be stationary and stretching of the pull straps and cable was assumed to be negligible. The maximum critical turning moment (M_{MAX}) is the sum of the horizontal moment due to force acting due to winching and the vertical moment due to gravity acting on the mass of the leaning stem (Peltola 2006). Using force data from the dynamometer and angular data from the accelerometers M_{MAX} was calculated via the following equation from Samarakoon (2013):

$$M_{max} = (FL \cdot \sin\theta) + (WH \cdot \cos\theta)$$

where M_{max} is the maximum turning moment at the base of the trunk (kN m), *F* is the horizontal component of the force applied via the pulling apparatus (kN), *L* is the vertical distance from the failure point to the collar strap attachment point (m), ϑ is the angle from the failure point on the stem to horizontal at the time of maximum load (degrees), and *W* is the gravitational force acting on the tree mass (kN). The failure point is the height of the midpoint of the failure zone, the stem segment that contained the fracture when the stem broke. The location of the failure zone along the stem might differ from experimental results under natural wind stress, specifically because wind acts on the centroid of the crown rather than at the height of the pulling apparatus. This difference was assumed to be negligible.

The distance H is half the total tree height (Figure 4). The product $(FL \cdot \sin\theta)$represents the horizontal component of the total moment and $(WH \cdot \cos\theta)$ represents the vertical, or gravitational, component of the total moment. Tree stems were assumed to be rigidly anchored so that they did not move horizontally at the base during pulling tests. Tree mass was measured for longleaf pine by cutting felled trees into 1 meter sections and weighing them in the field.

Loblolly tree mass was calculated using basic tree dimensions with existing equations (Baldwin 1987).

When trees break along the stem, the maximum bending moment (M_{MAX}) is equal to the maximum resistive moment of the stem (M_{STEM}), so the following equation was used to derive the modulus of rupture (MOR) using the maximum moment and *d*, the diameter at the failure point: $MOR = \frac{M_{MAX}}{d^3} \cdot \frac{32}{\pi}$

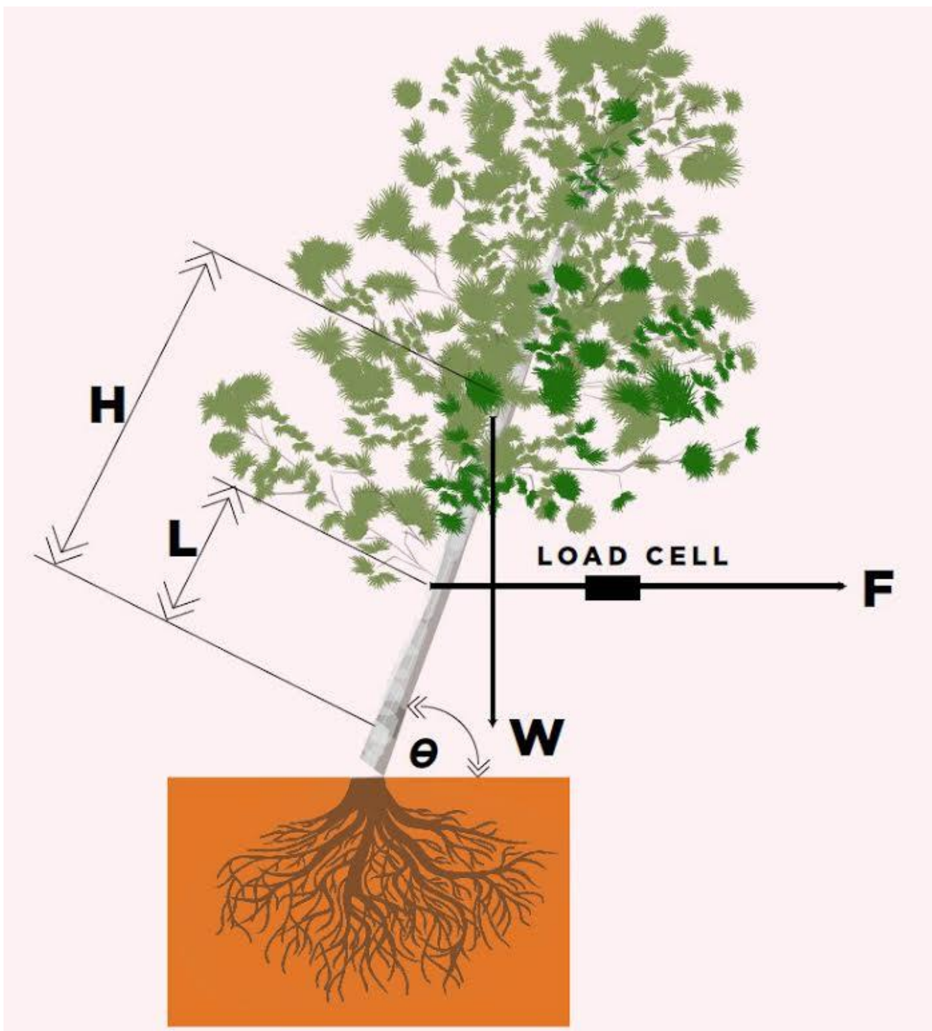

Figure 4: Schematic view of tree pulling experiment showing components used to calculate M_{max}. The component F is the horizontal component of applied force, L is the vertical distance between the failure point and the collar strap, W is the gravitational force acting on the tree mass, θ is the angle of the failure point from horizontal at failure, and H is half the total tree height.

RESULTS AND DISCUSSION

In all, 8 trees were excluded from data analysis. Of these, 3 loblolly pine were excluded because they overturned instead of breaking. These occurred after heavy rains, and the overturning could be due to the soil being inundated with water. Samarakoon (2013) showed that saturated soil reduces overturning moments in trees. An additional 2 loblolly pine and 3 longleaf pine trees were excluded due to data collection error. The error was usually due to slippage of the collar strap up the pulling tree, except for one case where the accelerometers did not provide adequate angular data to calculate M_{MAX}. The slippage likely occurred as a result of extensive bending without breakage in small trees (<15 cm DBH). This high elasticity of juvenile wood may contribute to small trees' ability to avoid wind damage, as reported by Peterson and Classen (2013).

I. Modulus of Elasticity

Stress vs. strain diagrams could be drawn for 6 loblolly pine trees and 5 longleaf pine trees (Figure 5). The elastic range of the tree stems was clearly evident in diagrams and corresponds to the range of data where stress increased proportionately to strain (Figure 6). The composite value of modulus of elasticity of these stems is equal to the slope of fitted lines through the linear portion of stress vs. strain curves. Based on ordinary linear regression with species included as an indicator variable, the slope of the fitted lines through the linear portions of the data were significantly steeper for longleaf pine than loblolly pine (dfe=86. Pr>F=0.001) Values for the slopes of these regressions, the moduli of elasticity, were 10969 MPa and 16315 MPa for loblolly pine and longleaf pine, respectively. That longleaf pine demonstrated a higher MOE than longleaf pine is consistent with data provided by three-point bending tests on green

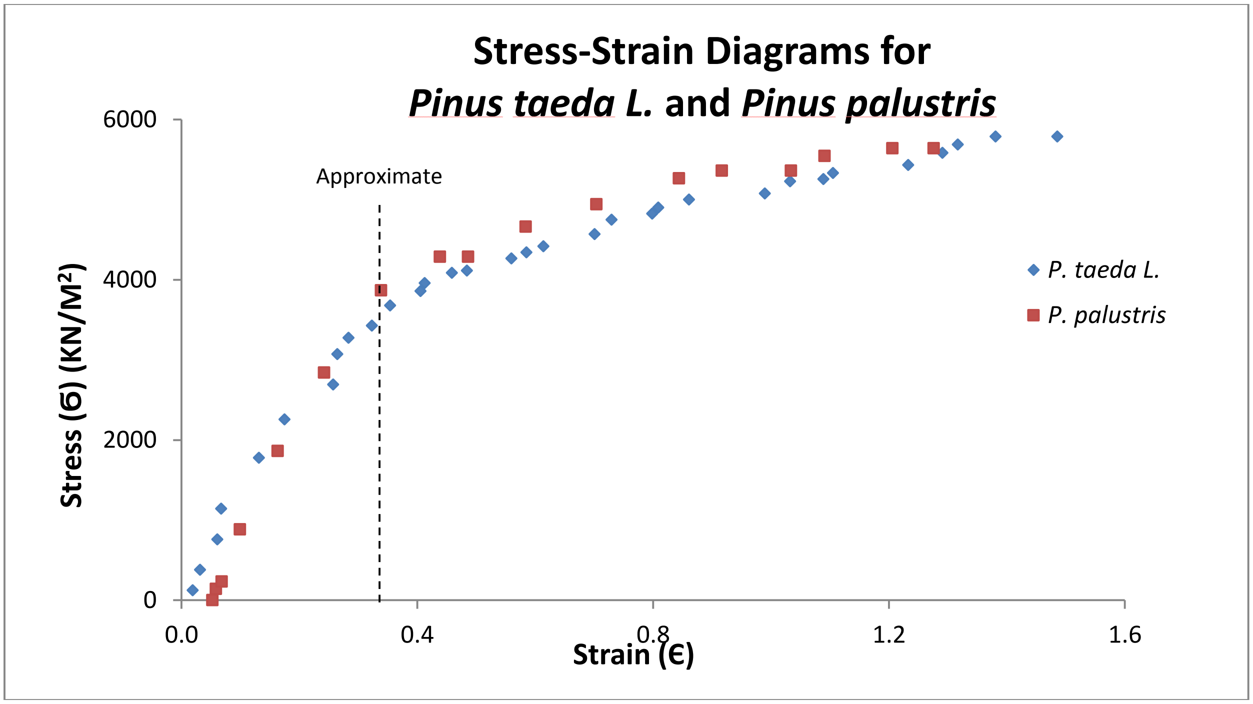

Figure 5: Examples of stress-strain diagrams for one loblolly pine tree and one longleaf pine tree constructed using data from static winching. The elastic (Young's) modulus was estimated for each tree by taking the slope of the linear portion of its diagram, which corresponds with the points to the left of the elastic limit.

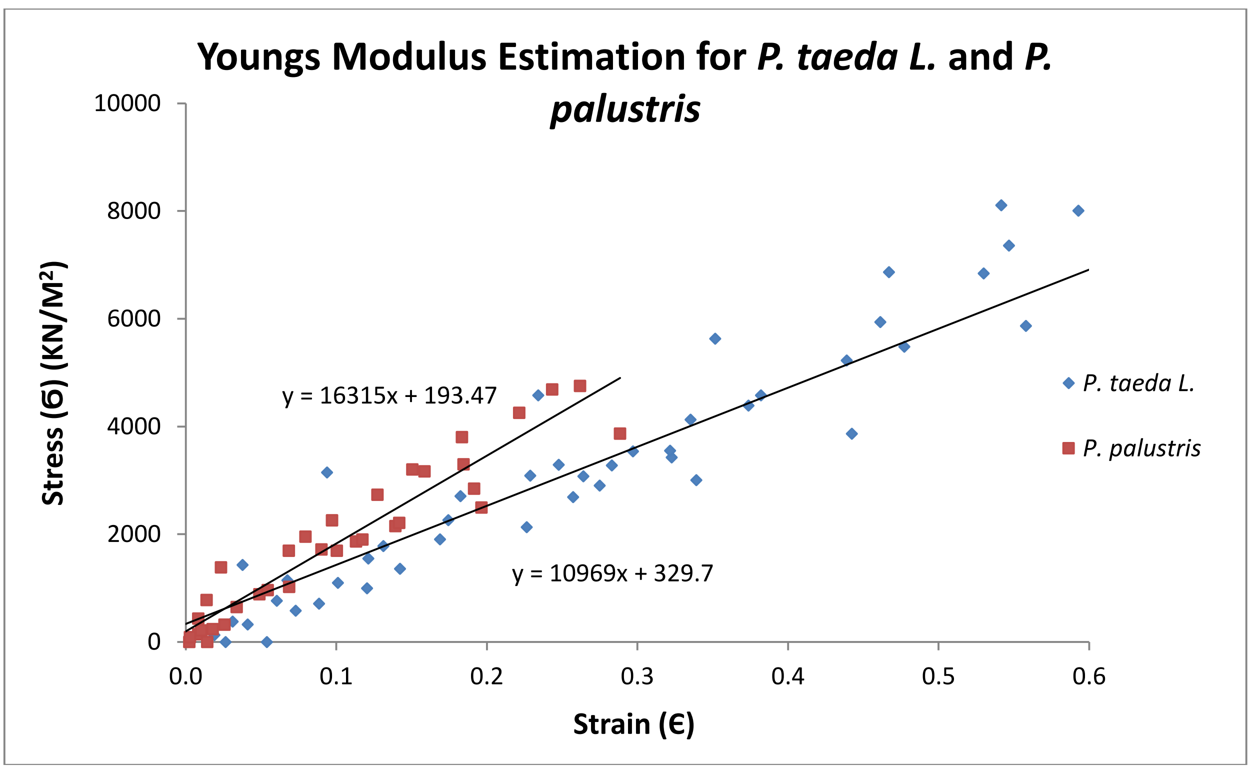

Figure 6: Linear portions of stress strain diagrams for 6 loblolly pine and 5 longleaf pine trees used to estimate Young's modulus (MOE), the slope of the regression line.

boards cut from whole trees, as published by the USDA Forest Service Wood Products Lab (Ross 2011). However, values obtained for both species *in situ* overestimated the *ex situ* values by 13% in the case of Loblolly (10969 vs 9700 kN/m^2, respectively) and 48% in the case of longleaf (16315 vs 11000 kN/m^2, respectively). This disparity is consistent with the findings of Putz et al. 1983, who looked at 16 species of windblown trees in Panama and did not find that wood (material) flexibility derived from laboratory tests was significantly correlated to tree (structural) flexibility. In other words, laboratory calculations come from three-point bending tests carried out on cut boards that are only a subset of the composite living tree stem. This study, on the other hand, tested the composite material as a whole. As a result, there is a discrepancy in the elastic properties of stem-like boards and an entire tree stem. Nevertheless, results support the initial hypothesis of the study: linear portions of stress vs. strain diagrams for longleaf pine stems had a higher slope than those for loblolly pine stems, indicating that longleaf pine trees bend less than loblolly pine trees under the same force. The major assumption for this hypothesis was that the stems behave as linear elastic materials based on the shape of the stress strain diagrams (Osgood 1932). Though there are some constraints, including soil conditions and tree form, there is an indication that whole trees behave as linearly elastic materials in accordance with Hooke's law. This is important because it confirms the validity of static winching experiments as a way to measure and compare the flexural stiffness properties of living trees.

II. Maximum Critical Bending Moment

Because stem size, specifically the second moment of area, is proportional to the maximum resistive force that a stem can exert according to the equation for modulus of rupture, stems with higher MOR can withstand greater force then equal sized stems with lower MOR. As a result, the relationship between maximum critical turning moment and stem size was compared across loblolly pine and longleaf pine trees for the size ranges covered in this study. Individual species exhibited strong positive correlations between various size measures and M_{MAX}, with the best predictor of M_{MAX} being the tree basal area for both longleaf pine (R^2=0.97) and loblolly pine (R^2=0.97). Other size metrics also yielded strong positive correlations when regressed on M_{MAX} (Table 2).This finding was consistent the summary of findings in the work of Peltola (2006) who noted that strong effects have been shown between stem mass, tree height, diameter, and stem volume on M_{MAX}. There was no detectable difference in the relation between M_{MAX} and tree basal area due to species (dfe=29, Pr>F=0.586) (Table 3), however, indicating that for either loblolly pine or longleaf pine, similarly sized trees experience similar M_{MAX} at failure (Figure 7).

Table 2: Ordinary least squares statistics from regressing M_{MAX} on various tree dimensions for loblolly pine and longleaf pine with the model $M_{MAX} = b_0 + b_1 x$

x	n	b_0	b_1	R^2
loblolly pine stem diameter @ 3 m (d) (cm)	18	-47.42	4.96	0.96
longleaf pine stem diameter @ 3m (d) (cm)	15	-62.12	5.59	0.92
loblolly pine stem basal area	18	-3.95	0.13	0.97
longleaf pine stem basal area	15	-9.86	0.14	0.97
loblolly tree height (h) (m)	18	-72.84	6.11	0.32
longleaf tree height (h) (m)	15	-223.94	15.33	0.40
loblolly BA*h	18	1.57	0.006	0.95
longleaf BA*h	15	-5.74	0.007	0.96

Table 3: Statistics for ordered linear regression for the model: $M_{MAX} = (b_0 + (b_1 \cdot i_i)) + ((b_2 + (b_3 \cdot i_e)) \cdot BA + \epsilon$ where *i* =0 for loblolly pine and *i* =1 for longleaf pine (n=33) b_0 = intercept, b_1 = effect of species on intercept, b_2 = slope, and b_3 = effect of species on slope

Parameter	Estimate	Standard Error	P>t
b_0	-3.95	2.52	0.129
b_1	-5.92	3.58	0.110
b_2	0.134	0.008	<0.000
b_3	0.005	0.01	0.586

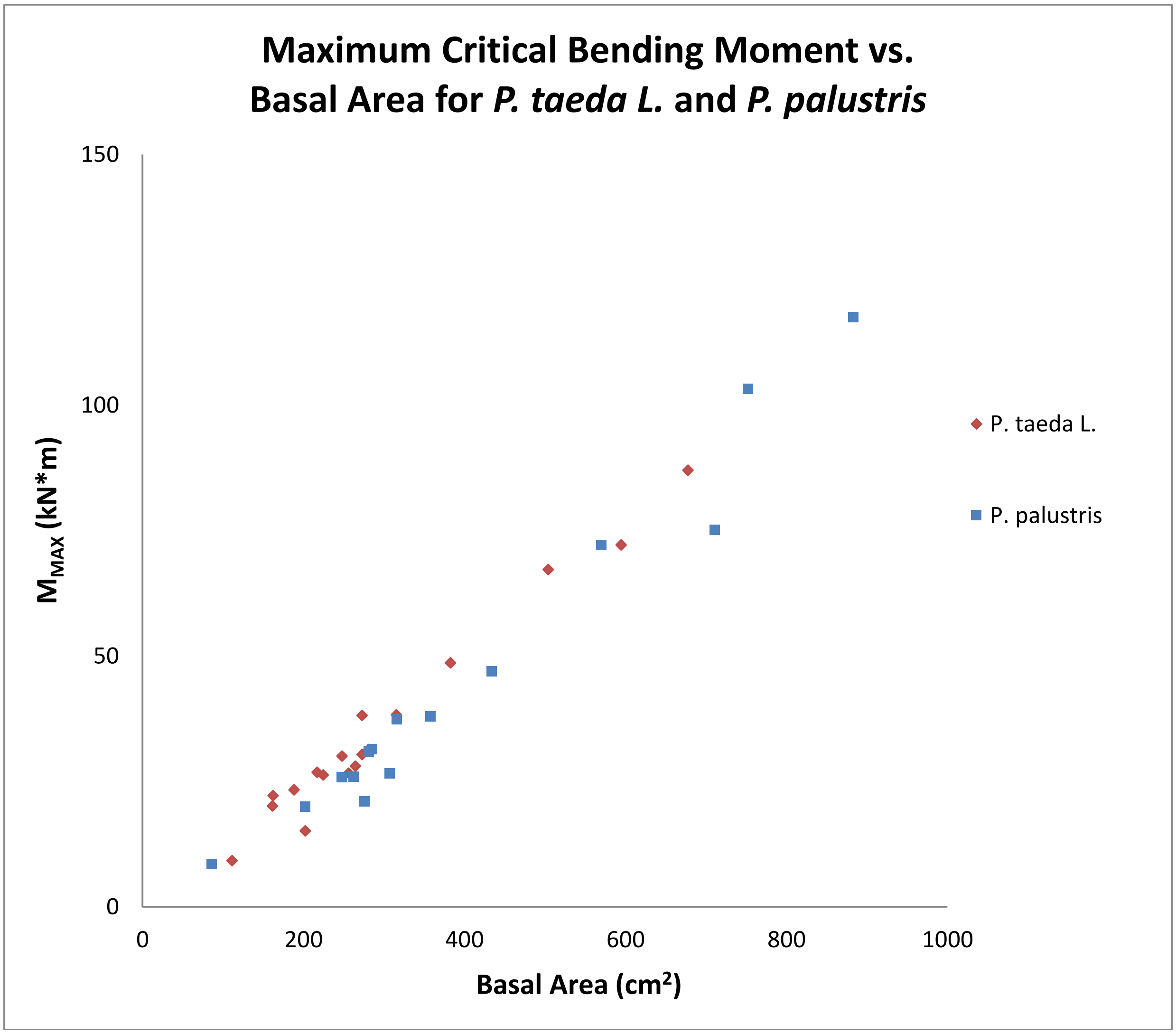

Figure 7: Maximum resistive bending moments vs. cross -sectional stem area at 3 m height for 33 *Pinus* trees at H.G. Lee Memorial Forest.

III. Modulus of Rupture

Despite differences in elastic moduli between species, differences in moduli of rupture (MOR) were not detected. Unpaired Student's t-test failed to reject the hypothesis that the MOR of longleaf pine is different than the MOR of loblolly pine (df= 31, Pr>F= 0.865). Some MOR values for the trees could not be definitively calculated because the failure zone of the stems extended as far as 2 meters in length. Consequently, the diameter of the stem at the point of failure could not be measured directly and had to be estimated using diameter measurements taken at one meter increments along the stem prior to pulling. Stem taper within these zones was minimal, however, allowing good approximation of the diameter of the stems at the midpoint of the failure zone. Furthermore, the estimated values of MOR determined for the trees are usable because they compare well with values for green wood published by the Forest Products Laboratory: The calculated MOR for loblolly pine was 4.9% higher than the handbook value (52.45 vs. 50.0 MPa, respectively) and the calculated MOR for longleaf pine was 7.3% lower than the handbook value (54.7 vs. 59.0 MPa, respectively) (Forest Products Laboratory 2010). Although the values for MOR did not significantly differ by species, the relatively close estimations of MOR in both species using static winching data suggest that engineering material values of the mechanical strength of green loblolly and longleaf pine hold true in whole trees as well as cut boards.

That species differences in stem MOE could be detected between loblolly pine and longleaf pine and not be detected in stem MOR somewhat contradicts the prevailing wisdom that wood with higher values of MOE is stronger than wood with lower values of MOE. Machine-stress ratings of lumber are based on this correlation (Hoyle 1968). While plots of stem-based values of MOR plotted against stem based values of MOR showed some relationship, the data intermingled such that no species effect could be detected on MOR with MOE included as a covariate (dfe=8 Pr>F=0.75) (Figure 8). Because the species did not exhibit a marked difference in resistance to breakage in this static winching test, the hypothesis that the relative increased wind resistance of longleaf pine compared to loblolly pine can be attributed to increased material strength and stiffness was not well supported for these trees, under these conditions. This experiment proved unable to detect a statistical difference in the force required to break similarly sized loblolly pine and longleaf pine tree stems, nor in the material strength of the species' stems by virtue of MOR calculations. But, although the MOR of a material is the most logical indicator of its ability to withstand lateral stress, other material properties such as density are related to torsional (twisting) stress resistance and elastic buckling, the collapse of a tree trunk under its own weight (Putz 1983, Larjavaara and Landau 2010).

If in fact the strength of longleaf and loblolly pine stems do not account for differences in windthrow vulnerability that have been observed, perhaps the force exerted on the stem from wind drag in the crown is greater for loblolly pine than for longleaf pine. Casual observation suggests that loblolly pine has greater branching ratios and a denser crown than longleaf pine suggesting that at equal wind speeds, loblolly pine stems would experience more applied force than similarly sized longleaf pine stems. One measure of crown density is leaf area density (LAD), i.e., foliage area per unit of crown volume. Smith and Long (1992) used a simple estimate of LAD in their analysis of the crown structure on stand growth. They estimated LAD simply as the total leaf area of the crown divided by the crown length. For this study, total leaf area per tree was estimated from DBH, height, and crown length using published equations from Baldwin and Saucier (1983) and Roberts et al. (2005) for longleaf pine and loblolly pine, respectively. Dividing total leaf area by crown length yielded estimates of leaf area density (Figure 9). Simple linear regression indicated a significant species effect on the relationship between LAD and stem diameter such that loblolly pine trees had a greater LAD for a given diameter (dfe=30, Pr>F=0.001). This suggests that for trees of a given size, loblolly crowns are denser than longleaf crowns and, as a result, would create more drag when exposed to wind.

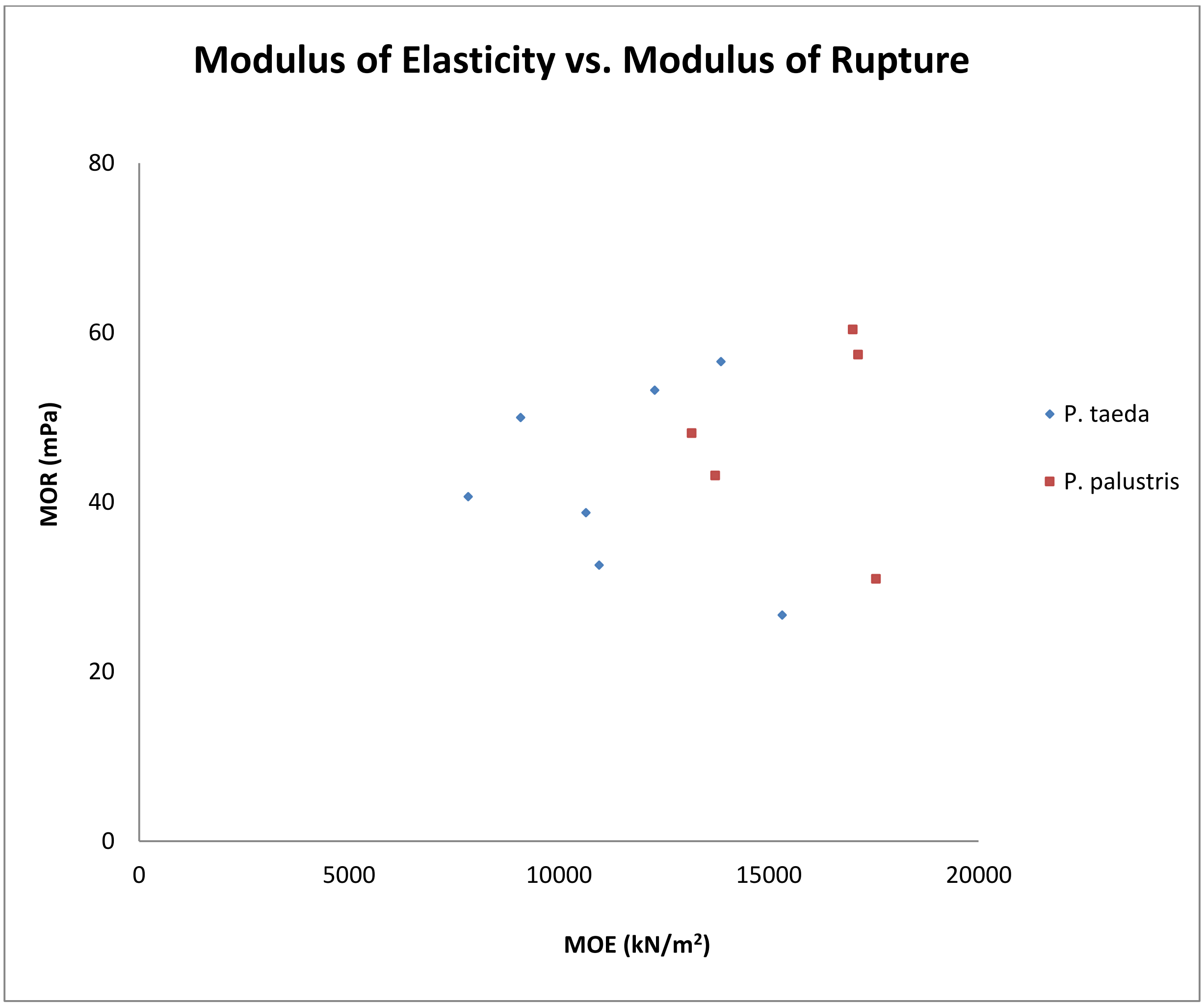

Figure 8: Modulus of elasticity estimations based on stress strain diagrams as a predictor of modulus of rupture for 7 loblolly pine and 5 longleaf pine trees. Linear regression did not detect an effect on the relationship between the stiffness and strength of tree stems (n= 12 Pr>F= 0.68).

Another possible explanation could be, as Mitchell (2013) noted, the loss of foliage and branch shedding reduces drag and the potential for stem breakage and uprooting. This adaptive strategy to storm exposure could also be to blame for increased wind resistance in longleaf pine. As a result, there is a possibility for future researchers to examine the resistance to breakage in longleaf and loblolly branches as opposed to stems, or to quantify the degree to which these trees are able to shed foliage in response to strong winds.

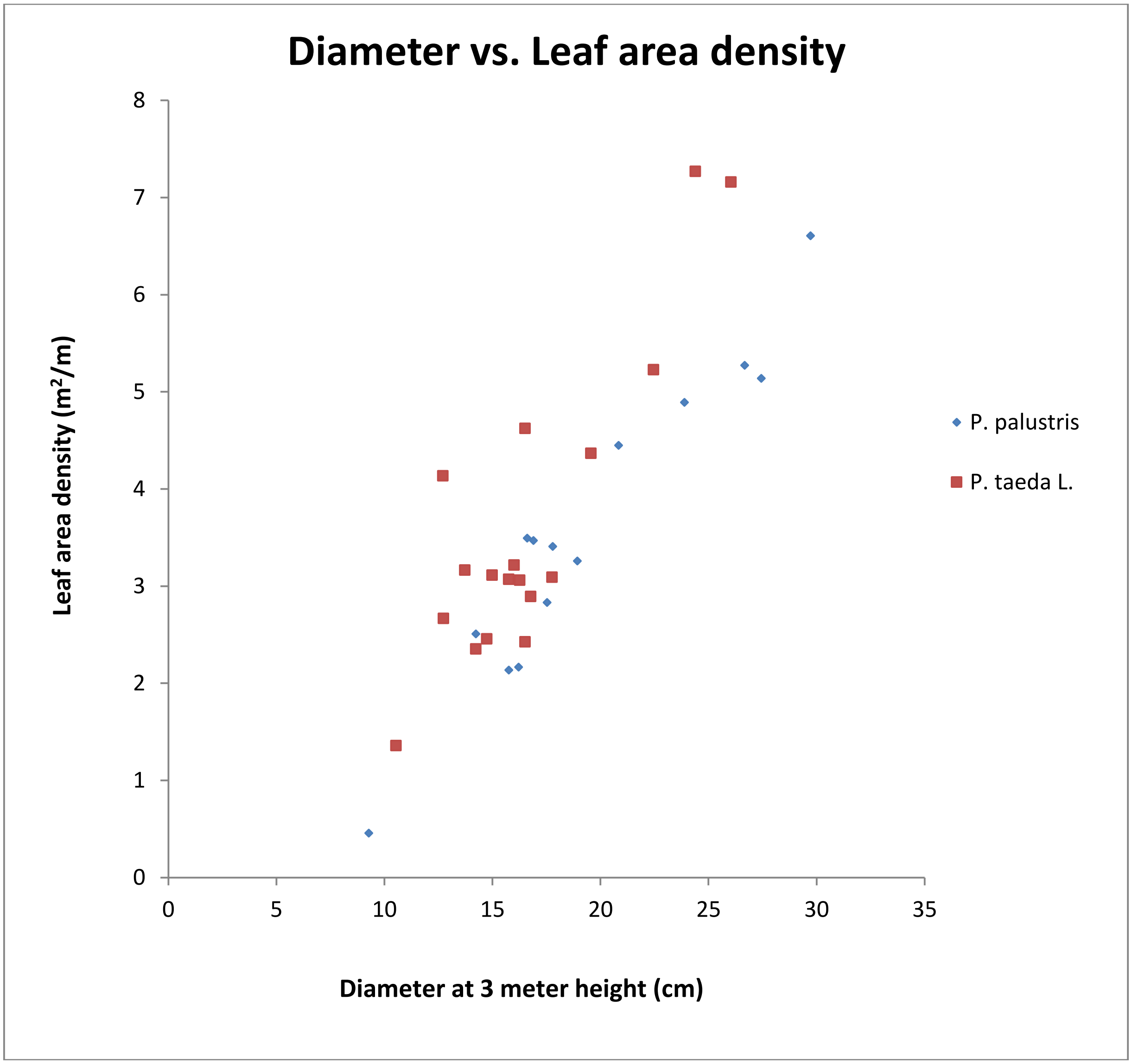

Figure 9: Diameter vs. leaf area density relationships for longleaf pine and loblolly pine trees. Leaf area density was calculated by dividing the total leaf area of the tree (m^2) by the length of the crown (m).

SUMMARY

Patterns from hurricane damage give an indication that longleaf pine is more windfirm than loblolly pine. Tree windfirmess has been attributed to many factors including species and material properties like wood strength and stiffness. Because longleaf pine wood is stronger and stiffer than loblolly pine wood, this study used static winching methodology to see if these properties account for differences in windfirmness by measuring bending force required to break stems (M_{MAX}). Stress-strain diagrams were constructed for pulled trees to explore how they behave under increasing loads. Based on these diagrams, it appears that living trees can act as linear elastic materials as they experience increasing static lateral stress. As expected, longleaf pine stems were stiffer than loblolly pine wood *in situ* based on Young's moduli (MOE) derived from these diagrams. Tree basal area was the best predictor of M_{MAX} for both species, however, species had no effect on the maximum bending moment required to break tree stems of a given diameter for these trees under these conditions. Estimated values of MOR did not significantly differ by species, nor did the relationships between MOE and MOR. Initial estimates without rigorous testing suggest that perhaps observed differences in wind damage between loblolly and longleaf pine after hurricanes may be due to greater wind drag through loblolly pine crowns. Future studies could look to crown characteristics to continue to understand the difference in windfirmness between these two species.

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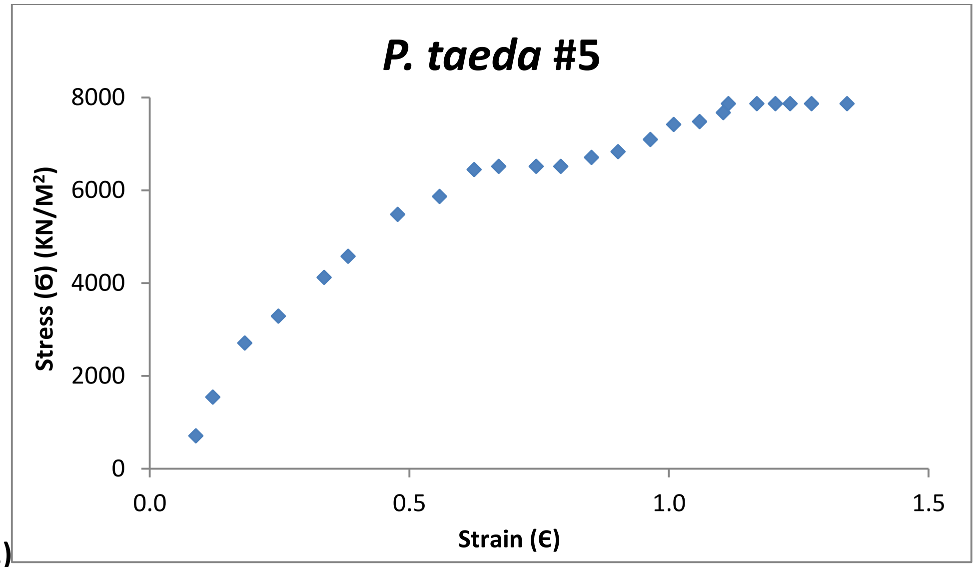
APPENDIX A- INDIVIDUAL STRESS-STRAIN DIAGRAMS



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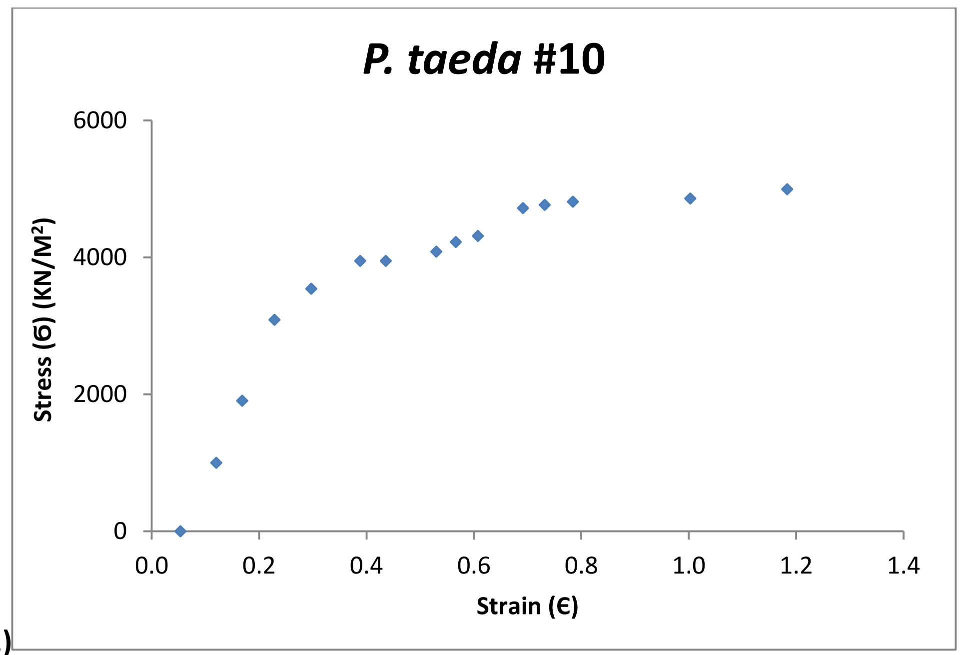
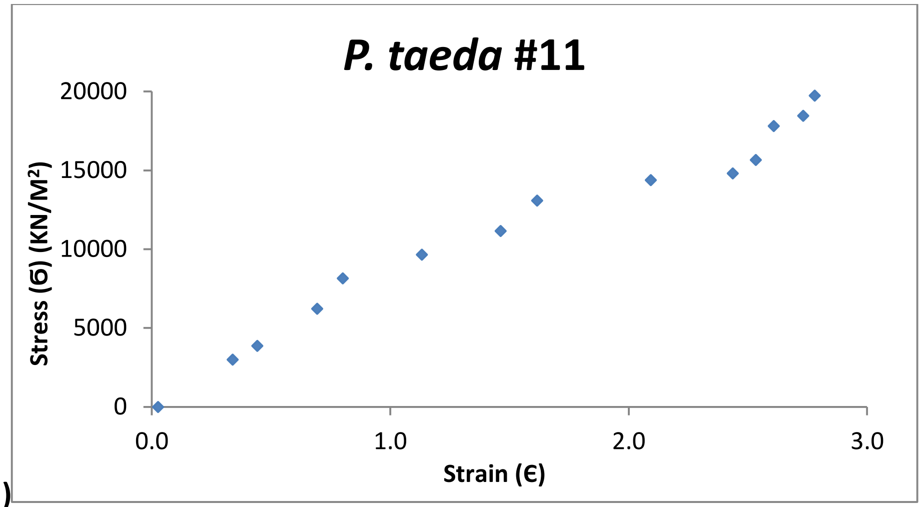


B.)

Figure 10 A-K: Individual stress strain diagrams for 6 loblolly pine and 5 longleaf pine trees constructed from data collected during static winching experiments. The data from the linear portion of these diagrams, known as the elastic zone, was used to estimate Young's modulus in situ for both species.

(Figure 10 continued)



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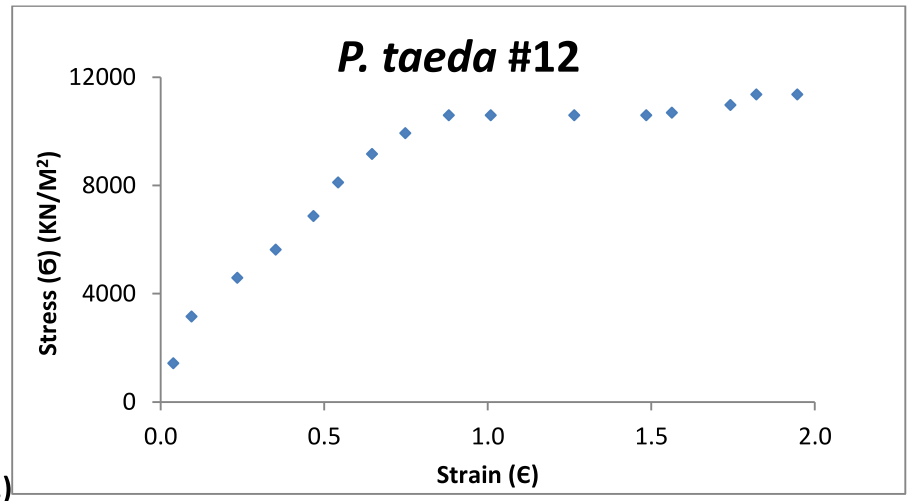

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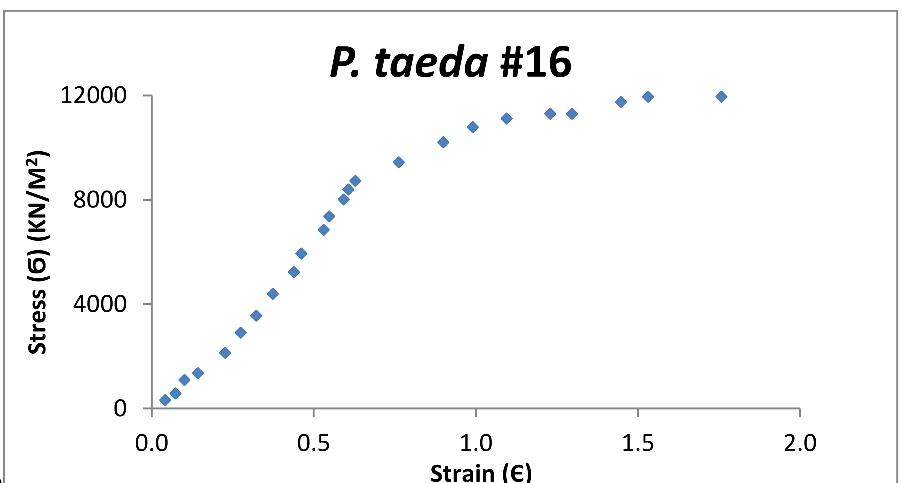

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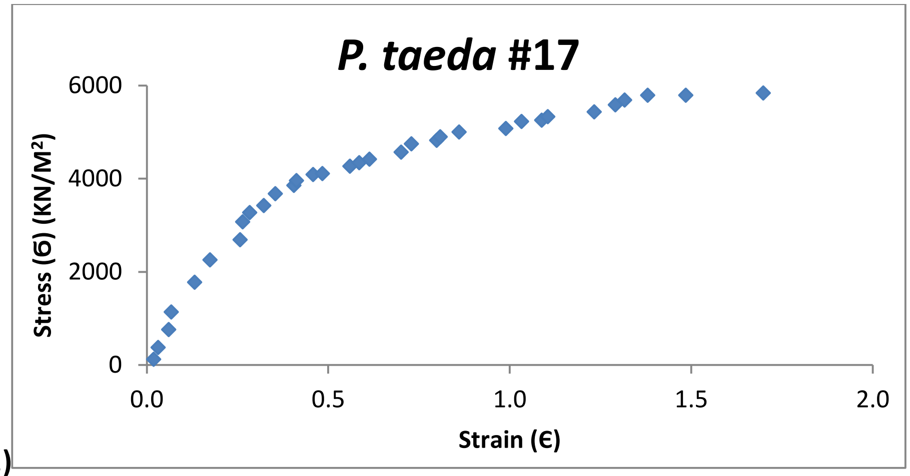

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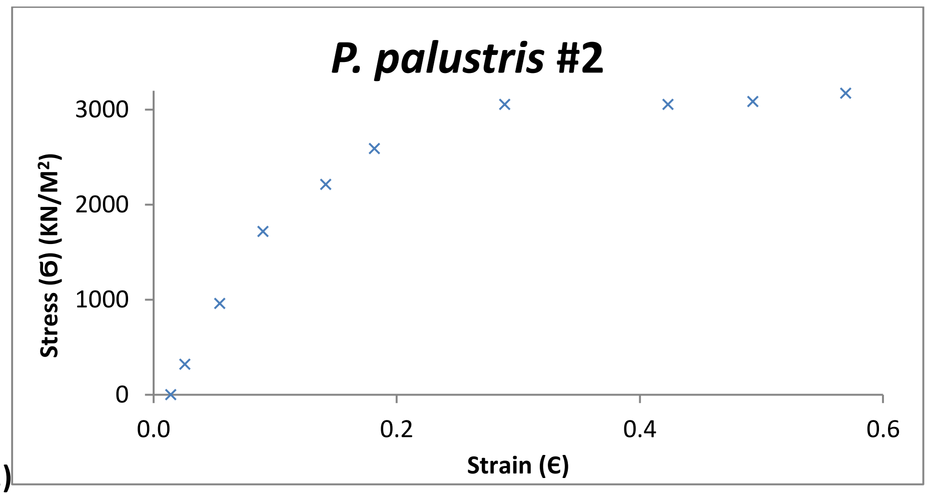

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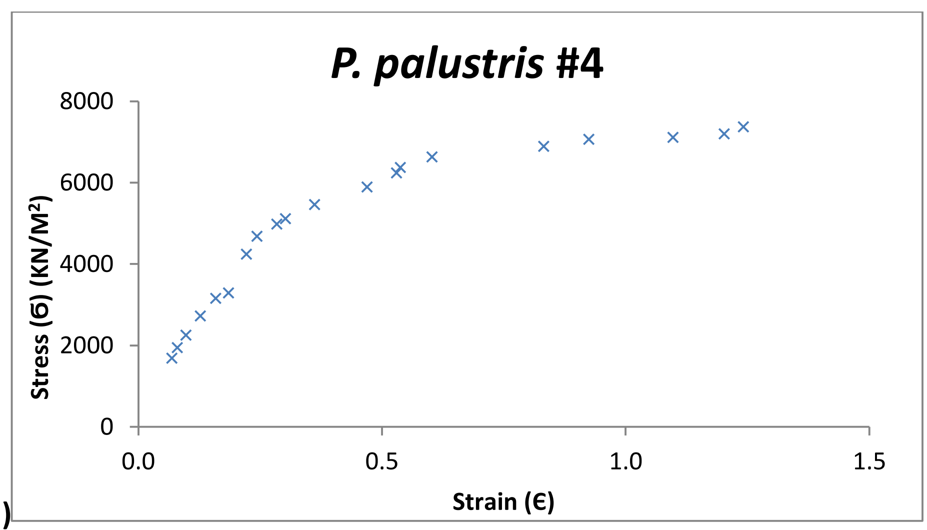

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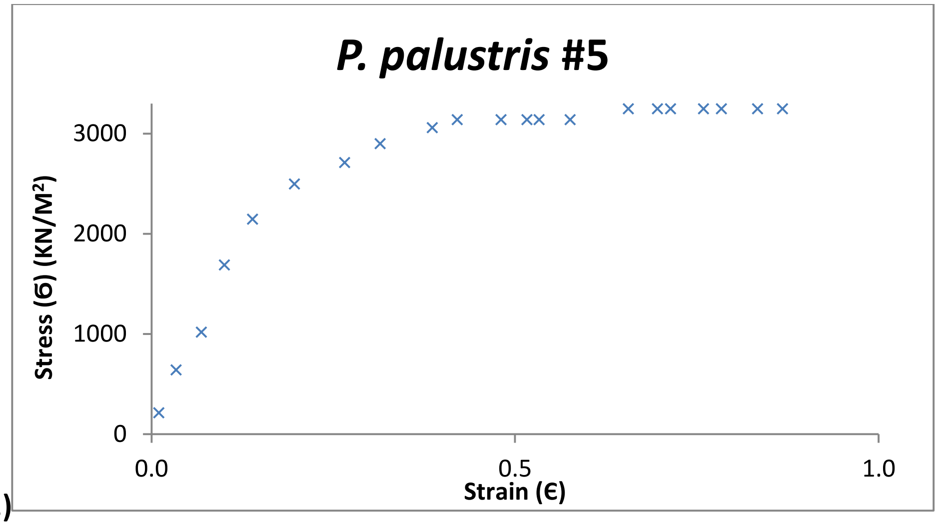

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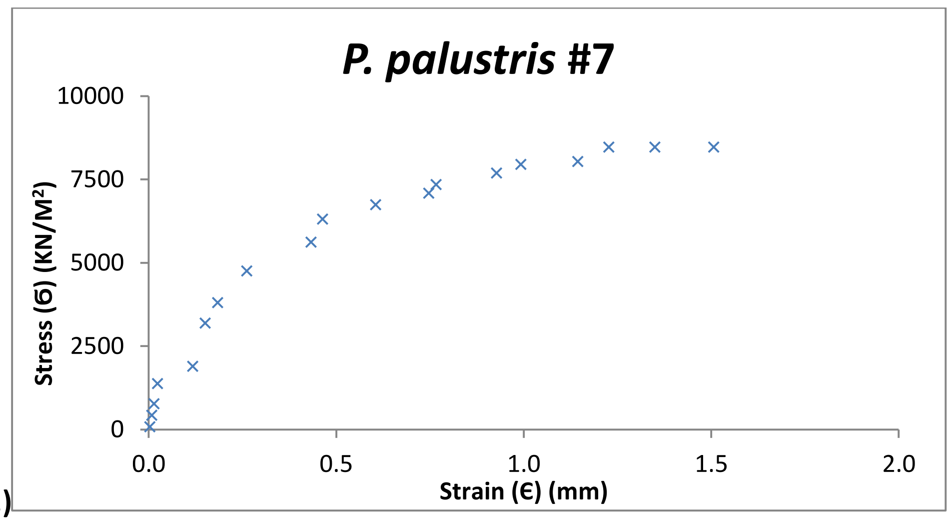
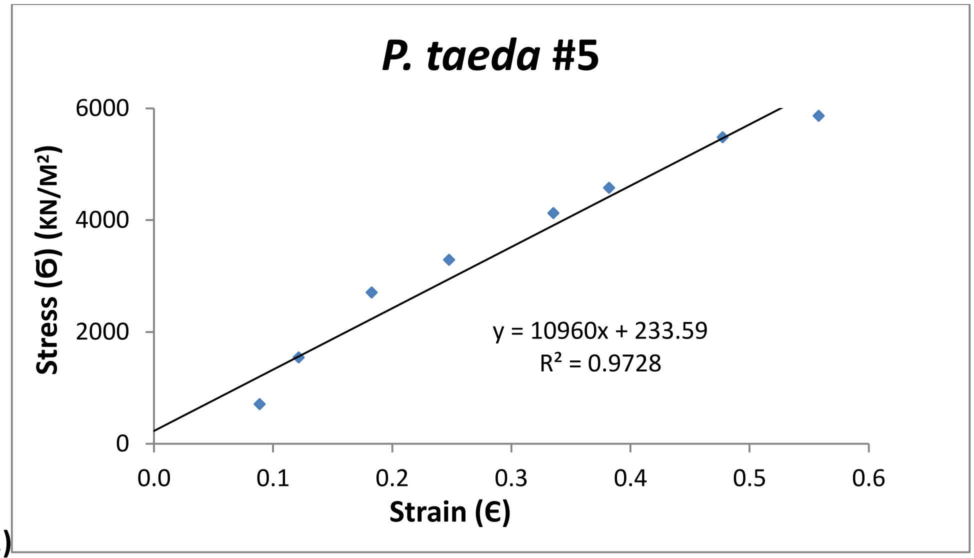


K.)

APPENDIX B- INDIVIDUAL ELASTIC MODULUS ESTIMATIONS



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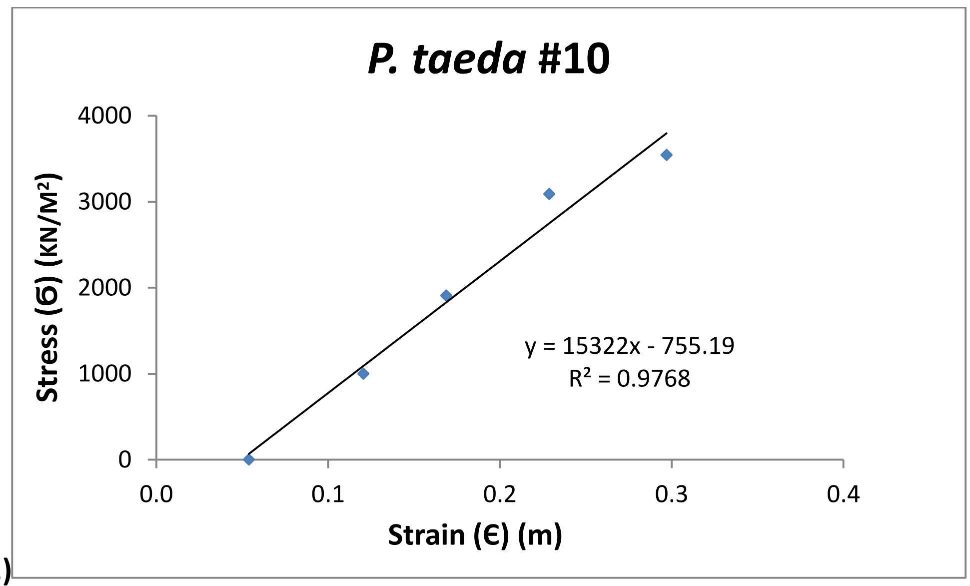

B.)

Figure 11 A-K: Individual linear elastic portions of stress strain diagrams for 6 loblolly pine and 5 longleaf pine trees constructed from static winching data. The slope of the regression line is defined as Young's elastic modulus.

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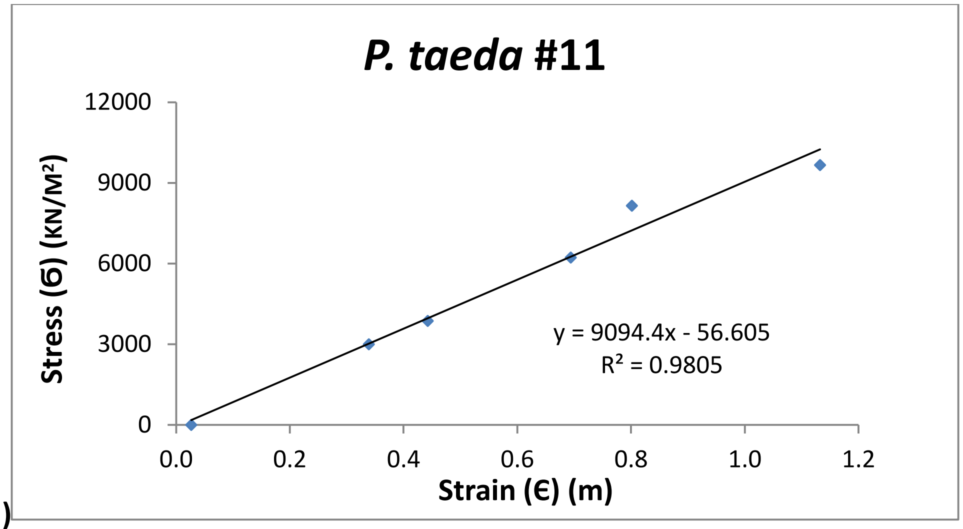

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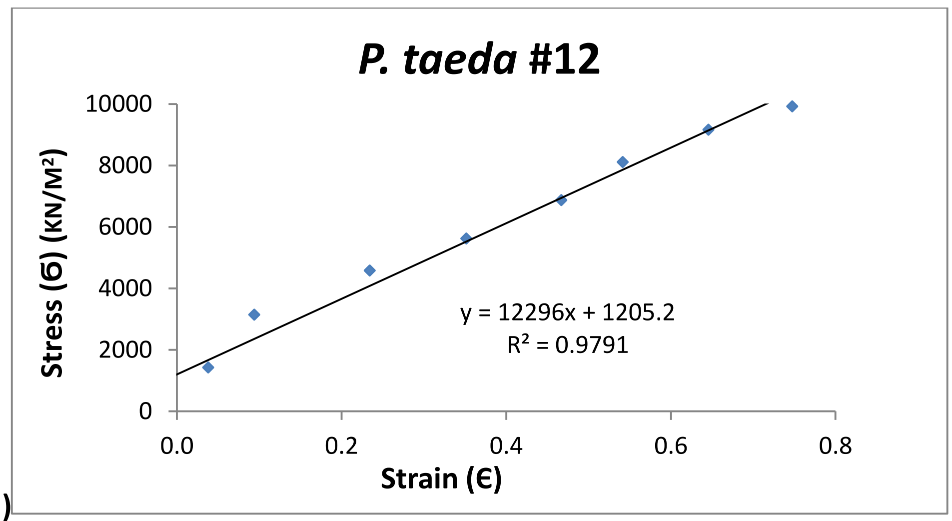

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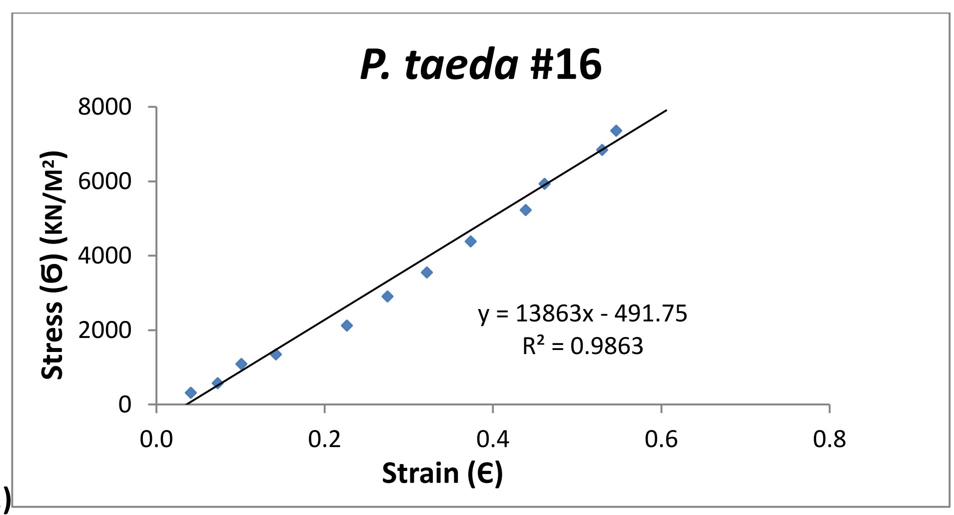

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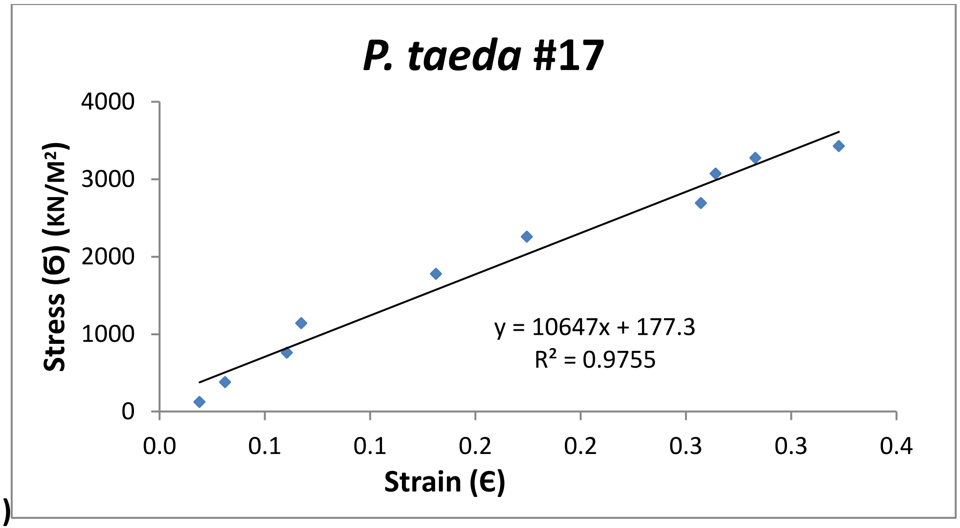

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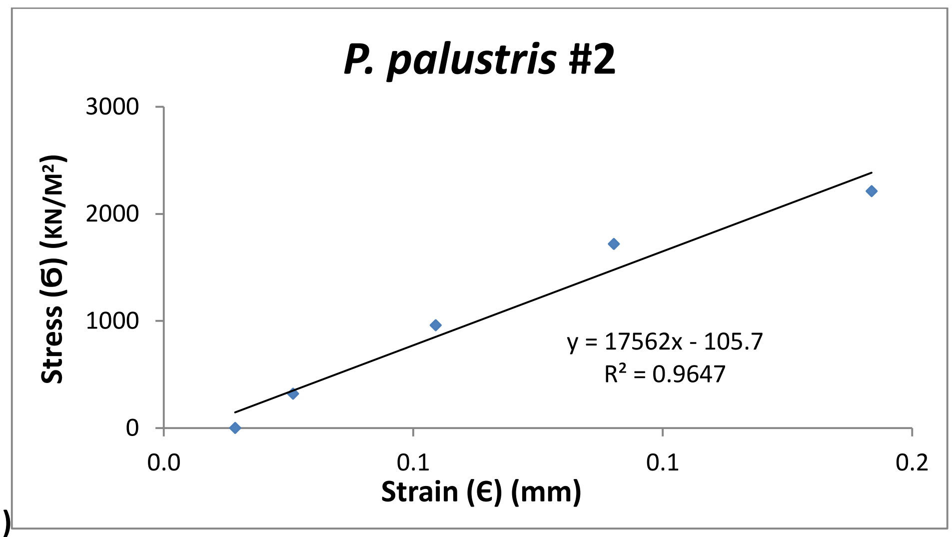

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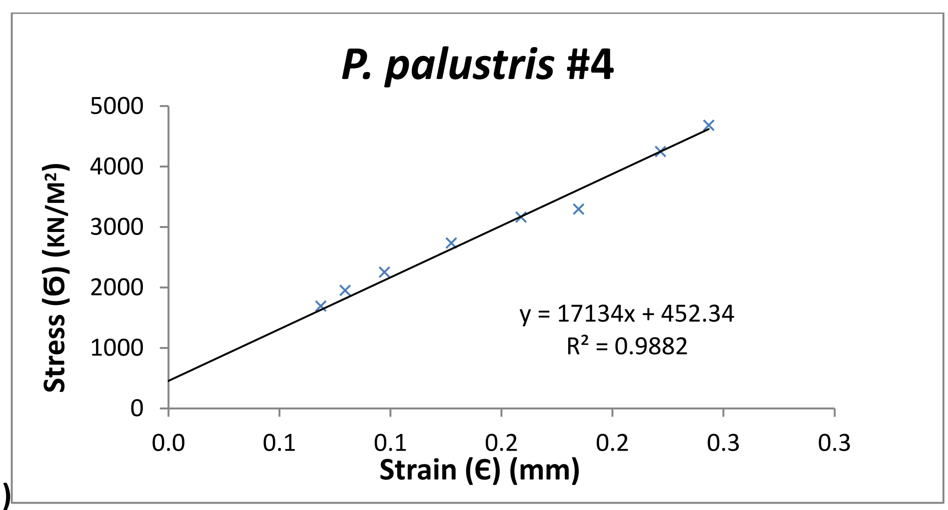

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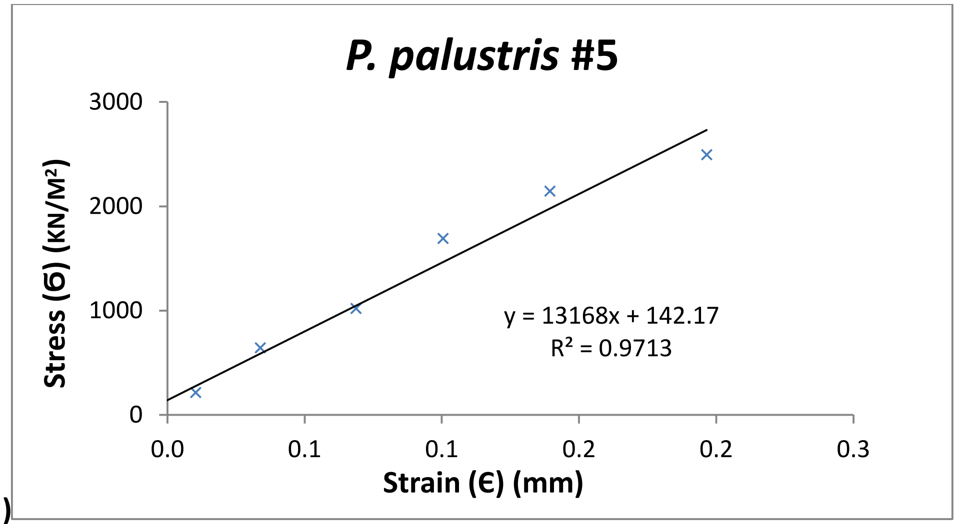

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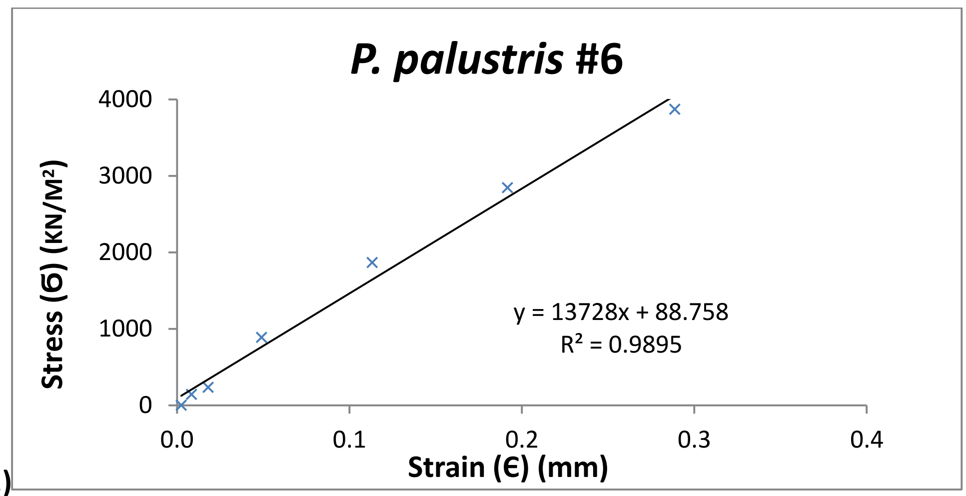

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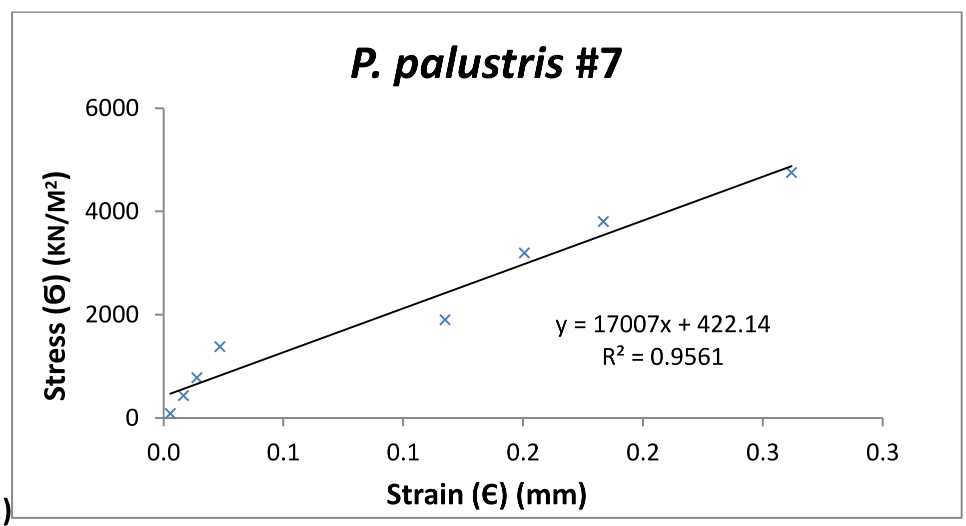

K.)

VITA

Cory Glenn Garms, a native of Amarillo, Texas, received his bachelor of science in Environmental Science at the University of Texas at San Antonio in 2012. His curiosity about unfamiliar ecosystems and love for the outdoors led him to enter the graduate school of Renewable Natural Resources at Louisiana State University in 2013. He is a candidate to receive his master's degree in August 2016, and will begin work on a doctorate in forest engineering at Oregon State University's aerial information systems lab in the fall.