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I am submitting herewith a thesis written by Tyler Matt Lynn Brannon entitled Examining Methodologies to Assess Abrasion in Tree Crowns. I have examined the final electronic copy of this thesis for form and content and recommend that it be accepted in partial fulfillment of the requirements for the degree of Master of Science, with a major in Forestry.

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Examining Methodologies to Assess Abrasion in Tree Crowns

A thesis presented for the Master of Science Degree

The University of Tennessee, Knoxville

Tyler Matt Lynn Brannon
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DEDICATION

This thesis is dedicated to my grandfather, Matt Witt. Thank you for inspiring, supporting and making possible the opportunities I have had that were not available to you. Your example and work ethic has helped mold me in who I am today.

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ABSTRACT

New methodologies were explored to determine if crown abrasion affects shoot elongation of preformed and sustained growth form species during stand development. Bud growth form differences can influence which species' buds are abraded or broken upon impact with adjoining crowns affecting crown growth. Analysis of branch elongation, apical bud toughness and tree sway were investigated in this study. Branch elongation was measured on crowns where growth was inhibited by crowns of adjacent trees and on crowns where growth is uninhibited. Bud mass was also measured. Bud toughness by species' shoot growth form was evaluated using a pendulum impact tester for the dormant and growing seasons. Crown movement was assessed by using 3-axial accelerometers in outermost points of crowns. Accelerometers logged the movement of branches in the tree crown over a period of time and were evaluated using local wind data during leaf-off and leaf-on. By using both the crown sway acceleration and associated bud toughness and mass data, possible force was calculated to evaluate the influence of crown friction. Branch elongation was greater for most species sampled on the exterior of the stand. Preformed buds are generally tougher in the dormant and growing season than sustained growth buds. Acceleration from wind gusts increased more rapidly as wind speed intensifies in the growing season when leaves are on the trees. Under the conditions of this study, more crown damage can occur with lower wind speeds during leaf-on. Crown friction and abrasion are contributors to crown and stand development patterns in mixed species stands, often allowing species with determinate shoot growth to stratify above trees with indeterminate growth.

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INTRODUCTION

Crown friction/abrasion is the physical loss of terminal branches and buds when adjacent tree crowns overlap. This process occurs during wind sway (Rudnicki et al. 2001). Crown friction could be affecting stand dynamics, crown differentiation, and crown dynamics. Clatterbuck and Hodges (1988) observed stand development in an even-age stand of sweetgum (*Liquidambar styraciflua*) and cherrybark oak (*Quercus pagoda*). Sweetgum quickly captured the site, but by age 20 to 25, oak crowns were able to stratify above the sweetgum. Crowns of surrounding sweetgums now shy away from the crown of the oak, possibly caused by abrasion. Crown abrasion has been studied in coniferous forests (Meng et al. 2006, Rudnicki et al. 2003). Abrasion has also been observed in black mangrove (*Avicennia germinans*) forests in Costa Rica (Putz et al. 1984). Crown abrasion led to reduced yields in overstocked pine plantations due to crown damage (Tarbox and Reed 1924). Mechanical abrasion is hypothesized to be a factor influencing suppression of shoot extensions by neighboring trees (Oliver and Larson 1996). Quantitative data of this phenomenon are limited. The purpose of this study is to examine crown abrasion in hardwoods and the effects on stand dynamics.

Crown Dynamics in the Forest System

Tree crowns are the productive parts of trees that convert sunlight, CO_2 and H_2O into carbohydrates. The energy derived from carbohydrates is used by all other parts of the tree. The amount of crown is dynamically related to the growth of the tree because production of photosynthate dictates shape and size of all other parts of a tree (Holland and Rolfe 1997). Of all the components of a tree, crowns are one of the most easily influenced by environmental conditions.

Crowns can only change in a few specific ways. This includes change through height growth, branch growth, and crown recession. Height growth is the main source of crown change because of the upward growth of the crown. Branch growth expands the crown outwards to utilize empty growing space to maximize photosynthesis. Crown recession refers to death of the lower branches at the base of the crown, decreasing crown length. Recession is a direct result of crown and canopy density and the lack of light, causing the lower branches to die from a net loss of photosynthate production (Sprugel 2002).

When an even-age cohort is initiated from a disturbance, the species that establish are generally rapid growing pioneers or remnants present before the disturbance. Shade intolerant species will out-compete shade tolerant species and dominate the canopy initially due to differences in height growth rates. More shade tolerant species will persist in the understory and grow at a slower rate. A tree in the understory that is growing in the shade of another tree is classified as suppressed. The lack of light reaching the tree causes a reduction of height growth (Oliver and Larson 1996). Not all species depend on full sunlight to continue growing at a normal rate and therefore are tolerant of low light conditions (Kozlowski and Pallardy 1997). If left undisturbed, natural succession will continue and the canopy composition will change as gaps are created from single tree mortality. The eventual result would be vertical stratification as more shade tolerant species grow into gaps of the canopy (Oliver and Larson 1996).

Mechanical Abrasion

Stem break, root break and tree throw are all well-known types of damage from wind disturbance (Mayer 1987). Mechanical abrasion is a more subtle type of wind disturbance that occurs over time. As crowns expand to compete for more space, physical shearing of crowns is inevitable from wind sway. As trees grow taller, their limbs grow longer and sway farther

(Oliver and Larson 1996). Most trees cannot experience a powerful wind event without damage (Mayer 1987).

In both pure and mixed species stands, closely neighboring trees can physically obstruct one another (Meng et al. 2006, Clatterbuck and Hodges 1988). Meng et al. (2006) observed competition in a pure stand of lodgepole pine (*Pinus contorta*) resulted in a loss of crown size from wind sway. After trees in the stand were tethered such that crown abrasion between trees could not occur, crown cover increased significantly. If a tree has more rigid apical or lateral branches, it may be able to damage or break the lateral branches of neighboring trees (Oliver and Larson 1996). Meng et al. (2006) also recorded that in maturing lodgepole pine trees eventually sway at a high enough velocity to produce damaging collisions which resulted in significant reduction in leaf area per branch. Clatterbuck and Hodges (1988) observed in an even-aged stand of sweetgum and cherrybark oak that sweetgum quickly captured the site and were taller than cherrybark oak. After about 20 years, the cherrybark oak crowns were able to stratify above the sweetgum. The crowns of the sweetgums around the cherrybark oaks appeared damaged. The authors hypothesize that crown collisions were an important factor in allowing this stratification. These collisions would have resulted in damage of terminal shoots and buds, which would affect elongation and height expansion (Wierman and Oliver 1979, Aradottir et al. 1997).

Lockhart and others (2006) reported that when cherrybark oak were at or above the height of neighboring sweetgums, the sweetgum branches were often damaged, especially terminal branches. The damaged sweetgums exhibited more lateral growth than those without damaged terminal branches. Damaged sweetgum crowns receded from cherrybark oak crowns. Subsequently, most of the neighboring cherrybark oaks' growth was in height, allowing

cherrybark oaks to stratify above sweetgum. Lockhart and others (2006) suggest that crown abrasion is the process allowing this to occur.

Mechanical abrasion would render some canopy space between trees unusable (Rudnicki et al. 2003). This could restrict the maximum amount of leaf area a tree is allowed to produce and maintain. Reduced leaf area may be an important factor in initiating declines of productivity in pure species stands as they age (Ryan et al. 1997). Leaf area reduction in mixed species stands could be a contributing factor in permitting crown stratification as weaker species' leaf areas are reduced.

Mechanical abrasion may also play an important role in interspecific plant competition. Competition to fill space is a basic interaction between trees crowns in a forest. When trees compete for resources, differences in physiology can give a species a competitive advantage. As space is filled in a forest canopy by a single tree, that tree intercepts more light. As more light is intercepted, the amount of water and nutrients that can be absorbed via evapotransportation is increased, allowing growth to accelerate. The result is a dynamic relationship between crown size and tree growth (Larsen 1994). Adequate resource acquisition will significantly increase the chance of success of a tree reaching the canopy. Once a tree reaches the canopy, more sunlight is available for continued growth.

The extent of impediment caused by wind-induced collisions of branch tips on shoot extension is presently undetermined. Internal (genetic) and external (environmental) factors can influence growth rates of trees. How crown abrasion influences tree, crown and stand development is not known, especially different species.

Primary and Secondary Growth

Woody plant growth results from cellular division proceeded by enlargement and differentiation which forms tissues of the tree. This growth is concentrated in the apical and

lateral meristem. Growth can be characterized by two distinct stages; primary and secondary. Primary growth is the elongation of a bud or root tip. Secondary growth is growth in the cambium which results in diameter growth in stems, branches and roots (Kozlowski and Pallardy 1997).

A bud can be classified as an embryonic shoot. Buds result from the formation of a telescoped shoot with nodes, internodes and small rudimentary leaves, all of which compose the primordia, which are enveloped in bud scales or folded leaves. Buds can be classified by their position, contents, or function. A terminal bud is located at the tip of a meristem. A lateral bud develops in the axis of the leaves (Zimmermann 1964; Zimmermann and Brown 1971; Kozlowski and Pallardy 1997).

Shoot Development

Different growth forms of apical buds could be influencing abrasion in mixed species stands. Oliver and Larson (1996) hypothesized that terminal or lateral branches of one species can be mechanically injured or knocked off by tougher limbs of the same or another species. Some species will grow fast to expand the crown, but they leave shoots vulnerable for abrasion. Other species will have hardier shoots but grow slower and cannot compete. The two shoot development patterns of interest in this study are the preformed (determinate) growth form and the sustained (indeterminate) growth form.

Preformed shoot development refers to a pattern of growth that involves the elongation of preformed leaf primordia after dormancy is broken. All leaf primordia that will expand that growing season are contained in the bud (Kozlowski and Pallardy 1997). Several factors influence the number of leaf primordia found in buds such as genotypes, bud location (Remphrey and Davidson 1994), and climate (Cannell et al. 1976).

Sustained shoot development allows “free growth” to occur throughout the growing season. This involves elongation of a shoot while simultaneously initiating and elongating new stems (Pollard and Logan 1974). Some primordia are formed before shoot elongation from the previous year, but as these primordia extend in the spring, new primordia continue to develop and elongate shortly thereafter. During the growing season, recurrent flushing causes apical shoots to remain green and tender. (Romburger 1963; Kozlowski and Pallardy 1997; Oliver and Larson 1996).

Shoots expanding from terminal buds are classified as terminal shoots. The shoots of some species can also produce abnormal late-season shoot growth (Kozlowski and Pallardy 1997). These shoots develop from recently formed buds that are created during the present growing season for the following year. There are two types of late season shoots. The first are lammas shoots which elongate from terminal buds. The second are proleptic shoots which arise from lateral buds. The outcome from both is a telescoped shoot forming a bud surrounded by leaf stipules which are surrounded by bud scales. These abnormal late-season shoot types can be found individually or in combination (Kozlowski and Pallardy 1997).

Hormone Influence

Hormones are the regulators of growth associated with inherited characteristics. Hormones in plants are organic compounds that are produced in the plant and cause a physiological response. Depending on the type and concentration, they can either promote or regulate growth (Kozlowski and Pallardy 1997, Oliver and Larson 1996). Although hormones are a factor in regulating plant growth, they were not investigated in this study.

Crown Forms

Crown shapes are influenced by both external and internal factors which affect areas of primary growth. External factors include availability of light, nutrients, moisture, wind, and

accessible space for shoot extension. Internally, genetic and physiology factors, especially hormones and growth regulators determine the rate of shoot growth, apical dominance, branching patterns and leaf arrangement. In mixed species stands, crown differentiation occurs and space utilization is maximized (Kozlowski and Pallardy 1997; Lockhart et al. 2006). Species also have specific crown forms, excurrent and decurrent, that may aid in differentiation and crown development (Kozlowski and Pallardy 1997).

Strong apical dominance results in an excurrent crown form. The terminal bud hormonally suppresses the growth of lateral branches. The terminal bud also controls the angle and length of lateral shoots (Oliver and Larson 1996). Excurrent crowns exhibit a pyramid shape with a distinct central stem.

Weak apical dominance causes a decurrent crown form, allowing lateral branches to grow extensively and act as terminals. The central stem is difficult to determine in the crown of this form. The lateral branches grow (elongate) as fast as or faster than the terminal stem. The result is a crown shape that is more round or sweeping (Oliver and Larson 1996). Excurrent and decurrent trees growing simultaneously in a mixed stand would maximize utilized space in the canopy and could result in crown friction (Oswalt 2008).

Wind Factors

Movement of a tree crown depends on the extent of static and dynamic strain created by the wind disturbance. Dynamic strain is dependent on pressure from gusts of wind and the frequency of oscillation in the crown. Oscillation frequency of broad-leaf trees is seasonally dependent as leaf area and moisture content of the tree changes (McMahon and Kronauer 1976). Leaf mass during the growing season can reduce the frequency of oscillation. During the winter (without leaves) the oscillation frequency can be two to three times greater (McMahon and Kronauer 1976). Despite winter oscillations frequencies being higher, a single strong wind gust

in the summer may be more damaging to terminal buds and branches as more energy is transferred during a collision (Dewit and Reid 1992).

OBJECTIVE OF STUDY

The objective of this study is to evaluate and combine different quantitative methods that might be used in confirming and assessing how crown abrasion occurs and how it impacts stand development. The objective is tested by the following hypotheses:

1) Branch growth will be more restricted on interior crowns than exterior crowns.
2) Preformed bud growth will require more energy to break than sustained bud growth.
3) Crown movements will have more acceleration in the growing season than in the dormant season.

In order to test these hypotheses, the following will be evaluated:

1) Conduct branch elongation analysis for evidence of crown abrasion
2) Determine bud toughness with a pendulum impact tester.
3) Measure and compare crown movement during dormant and growing seasons using accelerometers.

METHODS

Introduction

New techniques were investigated to evaluate the process of crown abrasion and potential impacts of crown abrasion on stand development. Three studies examined the process of crown abrasion. For the first study used branch elongation analysis to examine growth patterns of crowded branches under two conditions: one where crowns were interacting with adjacent crowns and the other where crowns were more open grown and not being influenced by adjacent crowns. For the second study, a pendulum impact tester was used to evaluate bud toughness, which is the amount of energy a bud can absorb before fracture. A pendulum impact tester was selected over other testing methods due to its consistency in testing, and its similarities to colliding branches within and between tree crowns. The third study used accelerometers to measure gravitational force of the branches on the crown edge and to 2-dimensionally map energy of branch movement following the work of Rudicki and others (2001). In their study, clinometers were used to measure bole displacement in lodgepole pine.

Branch Elongation and Bud Analysis

Planted stands of Nuttall oak (*Quercus texana*), sweetgum and yellow-poplar (*Liriodendron tulipifera*) were sampled for branch elongation analysis. The Nuttall oak stand was the same stand where the accelerometer data were collected. The yellow-poplar stand was planted in 1991 for progeny testing purposes at the East Tennessee Nursery. The sweetgum stand in the J.W. Starr Memorial Forest of Mississippi State University in Winston County, Mississippi, (33°17' N, 88°52' W, elevation 100.5 meters) was planted with two-year-old seedlings in 1972 (Nelson and Switzer 1992). All three stands were overstocked with crowns of adjacent trees overlapping.

Edge trees with no contact with adjacent crowns during wind sway were selected and five branches were cut for analysis. Five interior tree branches which had constant contact with adjacent crowns during wind sway were also selected. Thus, ten branches of each species (5 interior and 5 exterior branches) were analyzed resulting in a total of 30 branches. Branches were segmented at various intervals and rings were counted using standard stem analysis procedures. For the last 30.5 centimeters at the end of the branch, rings and bud scars were used to determine age.

The amount of branch length added each growth year was determined. Graphs were then created to show growth differences between interior branches and exterior branches. If damage has occurred from crown abrasion, the data, along with physical damage on the branch, should indicate differences between interior and exterior branch elongation.

Mass and moisture content were calculated for the buds of each species that were studied in this research. These data were only collected during the growing season. Buds of American sycamore were not sampled. The apical shoot of American sycamore was continuously elongating during the growing season (sampling period) such that the bud was not apparent or fully-formed. Mean bud mass was calculated for each species using a balance. Once mass was recorded, buds were dried at the standard drying temperature of about 200 degrees Celsius for 24 hours, and dry mass was also recorded for each bud sample. Equation (1) was used to calculate moisture content.

$$\frac{(Wet\ Mass)-(Ovendry\ Mass)}{(Ovendry\ Mass)} * 100 \quad (1)$$

Apical Bud Toughness Tests

Samples of various species were collected from the University of Tennessee Arboretum located in Oak Ridge, Tennessee (84˚34'26.67" W, 35˚14'52.63" N, elevation 224 meters). Although species' growth forms are ambiguous in the literature, southern red oak (*Quercus falcata*), northern red oak (*Quercus rubra*), white oak (*Quercus alba*), Nuttall oak, black walnut (*Juglans nigra*) and mockernut hickory (*Carya tomentosa*) were designated as preformed species. Indeterminate growth species evaluated in this study were yellow-poplar, sweetgum, American sycamore (*Platanus occidentalis*) and red maple (*Acer rubrum*).

Buds were collected from apical tips of branches. To ensure natural moisture conditions in the tissue, all buds were tested within four hours of collection. The testing room temperature was between 21 to 23 degrees Celsius. Dormant season samples were collected in January 2011. Growing season samples were collected in June 2011 after completion of the first leaf flush of determinate growth species (Romberger 1963). No lateral buds were sampled as they were assumed to not be directly affected by crown abrasion.

Apical bud toughness refers to the amount of energy a bud can absorb before fracture (Gere and Timoshenko 1997). Toughness was tested on several species with a Tinius Olsen Model 92T Impact Tester. The impact tester is a pendulum that swings through and strikes the sample (Figure 1). The amount of energy that is absorbed by the sample is given in Joules. Buds were braced with a block of wood to ensure the break occurred at the bud collar (Figure 2). If samples were not braced, the sample could break at any weak point of the twig or stem below the base of the bud.

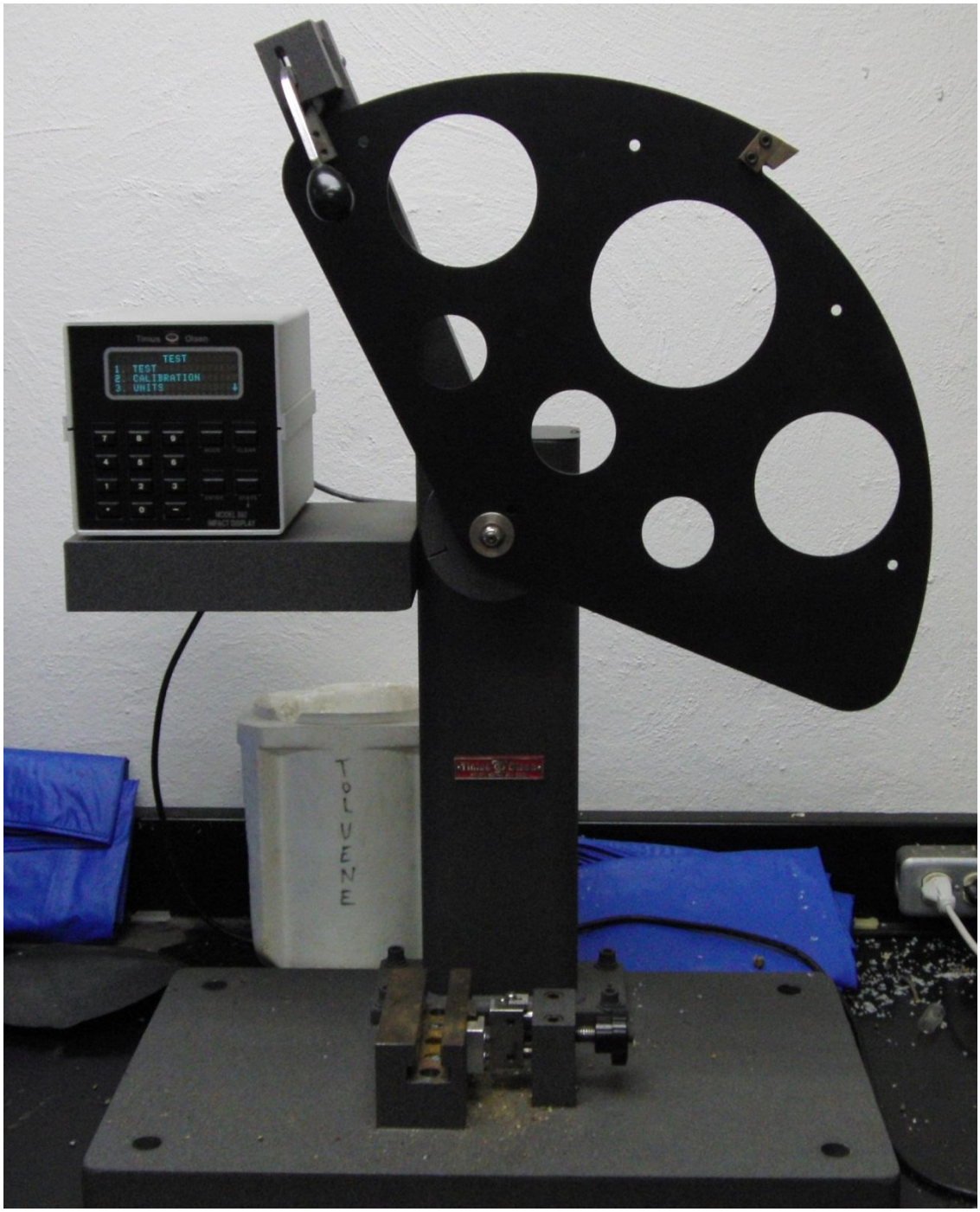

Figure 1: Tinius Olsen Model 92T Impact Tester (pendulum) used for breaking bud samples for the crown abrasion study, Tennessee, 2011.

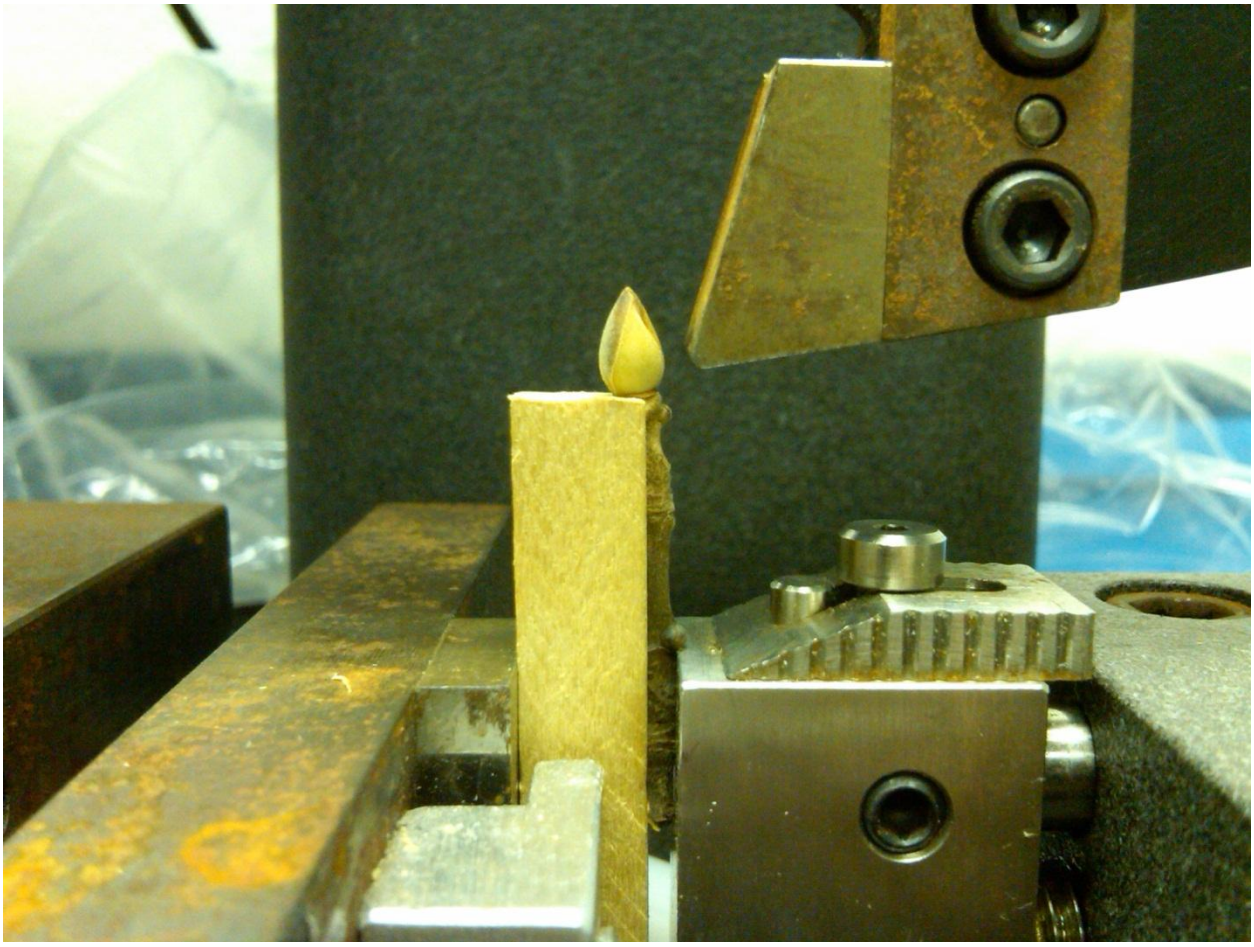

Figure 2: Mockernut hickory bud braced by wood and striking point of pendulum for the crown abrasion study, Tennessee, 2011.

For every bud break, bud collar diameter and the amount of energy required to break that particular sample were recorded. Samples were placed in a wooden brace to direct the break upon impact from the pendulum. All samples were broke with one strike from the impact tester. Although no single bud was symmetrical, bud positioning in the brace had no apparent effect. Most of the oaks had several buds or bud clusters making it impossible to isolate the largest terminal bud for striking by the pendulum. In the case of multiple buds, the largest bud was selected and bud collar diameter was measured. Notes were made if samples had more than one terminal bud broken during the test.

Bud toughness data were analyzed using mixed models analysis of variance in SAS© software version 9.2 (SAS Institute, Cary, NC). A Completely Randomized Design (CRD) analysis was used at an alpha level of 0.05 to test differences between seasonality. Mean comparisons between species' bud collar diameter and bud break energy were evaluated using Tukey's Honestly Statistical Difference (HSD).

Growing season bud break occurred before all species could be collected and analyzed in the dormant season. Thus, dormant buds of black walnut, northern red oak and southern red oak were not available for analysis. Buds from refrigerated seedlings of these species were assessed and analyzed in an attempt to use dormant seedling buds (2010 growing stock) as a substitute for dormant branch buds. However, dormant buds from stored seedlings were judged to be too dissimilar in thickness and not representative of branch buds, especially where the bud attached to the twigs for meaningful comparisons.

Tree Sway Accelerations

The study area is located at the East Tennessee Nursery near Delano, Tennessee (84˚13' 11.76" W, 35˚59' 38.12" N, elevation 267 meters). Data were collected in 2011 in a Nuttall oak tree that was planted in the spring of 1993. The trees in the stand averaged 6.1 meters tall with the live crown beginning at 2.7 meters above the ground, and branches expanding 4.9 meters from the stem. One tree in the southwestern corner was selected to place tri-axis accelerometers because of its exposure to prevailing wind, crown symmetry, and accessibility (Figure 3).

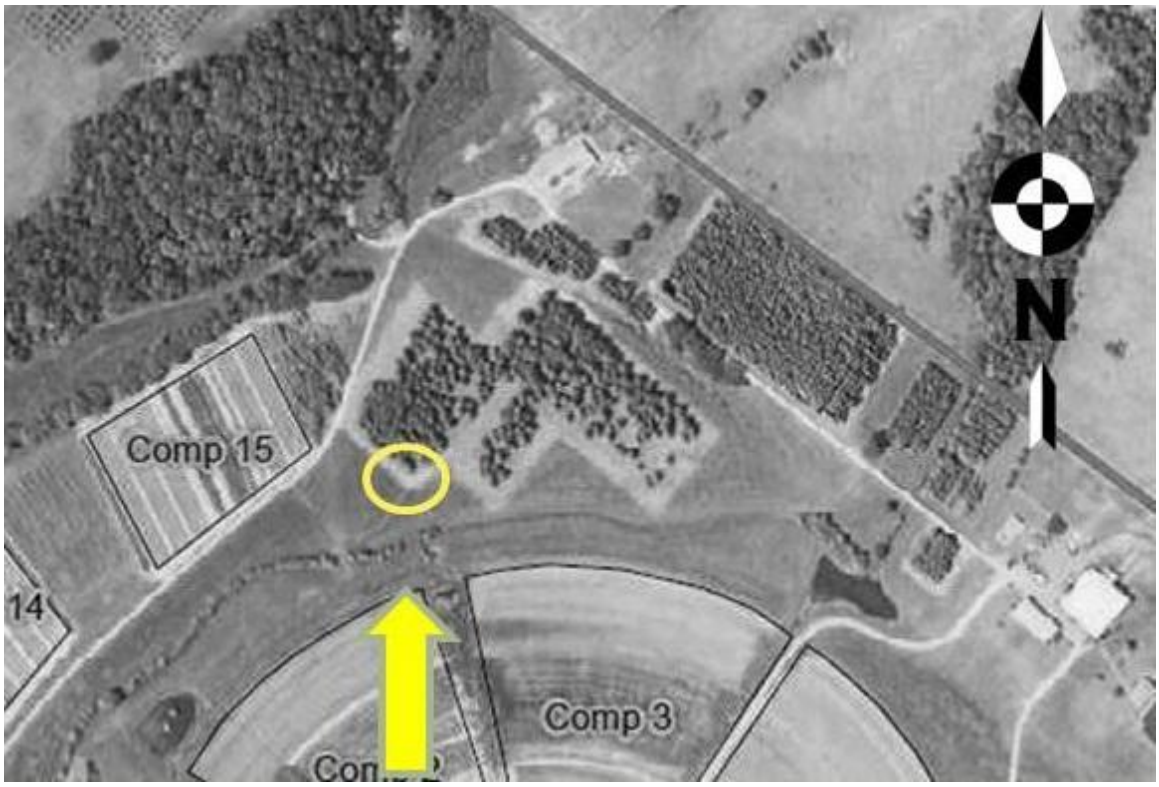

Figure 3: Aerial photograph of study site with yellow arrow denoting prevailing winds for the crown abrasion study, Tennessee, 2011.

The accelerometers were placed about six meters into the crown in each cardinal direction (Figure 4). The four accelerometers were zip tied about 0.6 meters from the end of the branches to ensure that movement was not influenced by the weight of the device. Universal Serial Bus (USB) cords (9.1 meters) connected the accelerometers to the data recorder (laptop computer) at the base of the tree (Figure 4). Only one accelerometer at a time could be accessed through the data recorder, so synchronous data from the four cardinal directions could not be conducted. Data were continuously recorded for a period of time and were synchronized with the wind data. Data from all devices were analyzed together. Accelerometers record gravitational force (G) on each axis (X, Y and Z) and were set to record at +/- 4 G's. The X-axis recorded left-right acceleration, the Y-axis recorded forward-back and the Z-axis recorded up-down (Figure 5). The accelerometers also record at 10 hertz, resulting in data recording 10 times a second.

Data were collected during various windstorm events throughout the dormant season of 2010-2011. Growing season data were collected after full leaf out in June 2011.

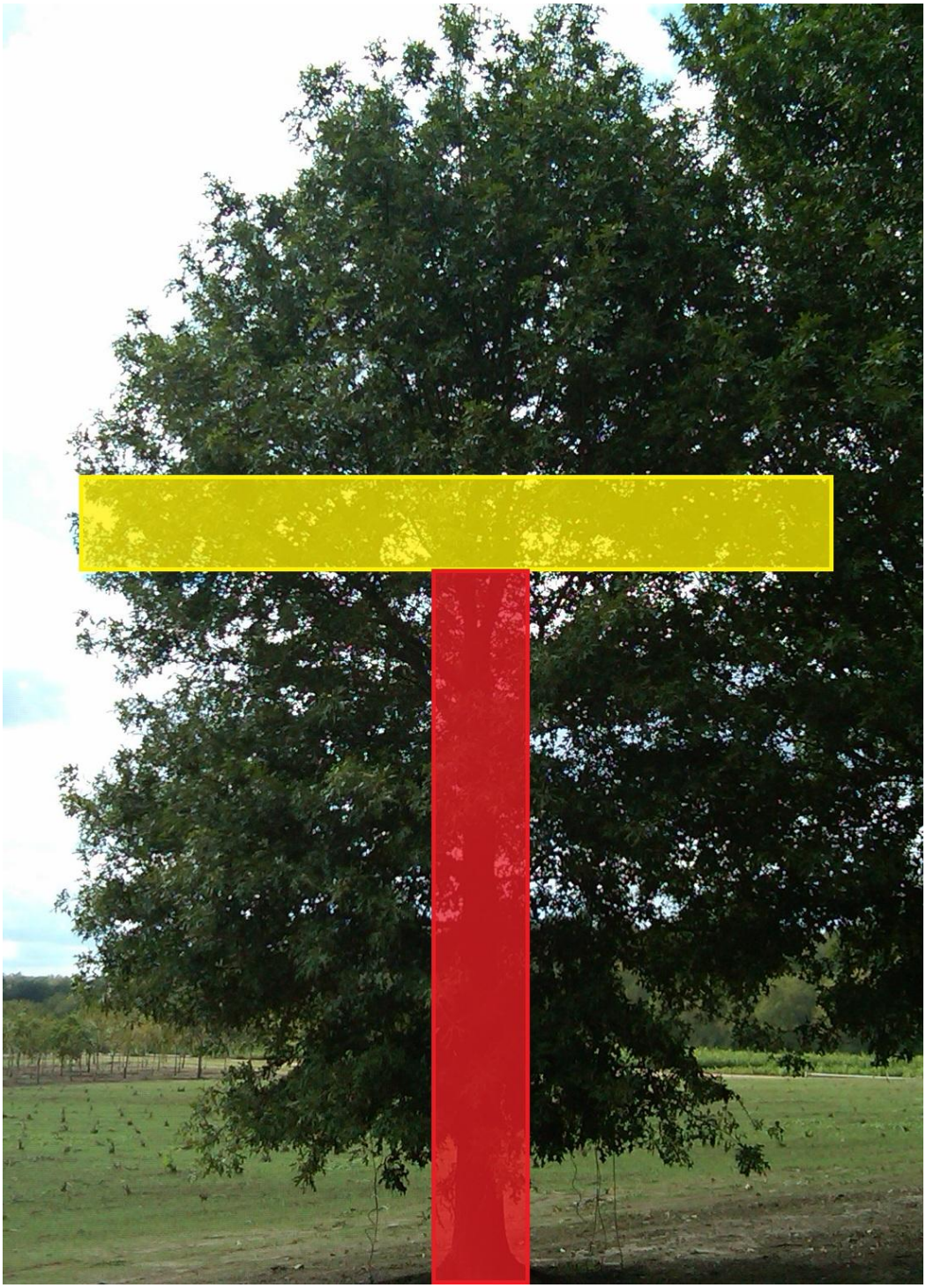

Figure 4: Yellow indicates location of accelerometers for the crown abrasion study, Tennessee, 2011. Red denotes location of USB cords.

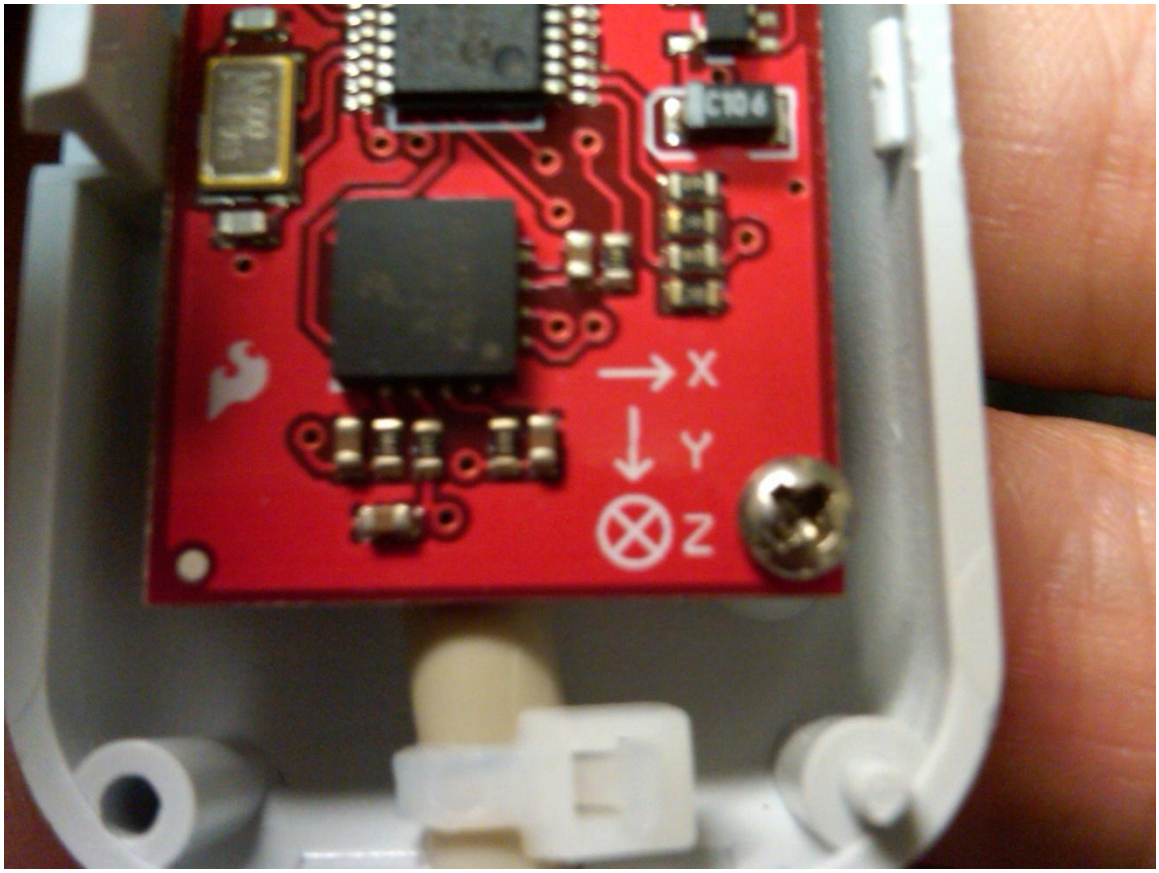

Figure 5: Accelerometer chip showing axes data were recorded on for the crown abrasion study, Tennessee, 2011.

A WindLog™ Wind Data Logger anemometer recorded local wind data near the stand. The anemometer was placed 2.7 meters high and recorded average wind speed and top wind gust. The device was set to record once every minute while accelerometer data were being recorded. All wind data reported were from top gusts and were recorded in kilometers per hour (KPH). Gusts cause the most force in tree movement. Top wind gust speeds were divided into categories: 0 to 8.1, 8.2 to 16.1, 16.2 to 24.1, 24.2 to 32.2, 32.3 to 40.2, 40.3 to 48.3, 48.4 to 56.3 and 56.4 to 64.4 KPH.

The accelerometer data were analyzed using mixed models analysis of variance in SAS© software version 9.2. A Randomized Block Design (RBD) was used at an alpha level of .05 in this analysis with blocking on accelerometers to test seasonality (growing and dormant) differences on acceleration of each axis. A RBD for growing and dormant seasons were evaluated using HSD in each wind speed category. Data were transformed using a rank transformation. Data from the accelerometer were an average every 10 observations. Equation (2) was used to combine all axes into one mean vector that included the effect of gravity for each wind category.

$$Xaxis^2 + Yaxis^2 + Zaxis^2 = (Mean\ Vector)^2 \qquad (2)$$

Separate figures were created to show maximum acceleration for each wind gust category and rate of change between categories. Maximum acceleration was calculated by taking the greatest range of acceleration for each wind speed category and pairing it with wind gust data. A 2-dimensional energy plot was also created for each wind gust category for both seasons. To better understand oscillation differences between dormant and growing season, similar data were graphed as a function of time after they were standardized using equation (3).

$$\frac{(Acceleration\ Observation) - (\text{Acceleration Mean})}{(Acceleration\ Standard\ Deviation)} = Standardized\ Observation \qquad (3)$$

Forces in Newtons (N) were calculated to better understand the possibility of abrasion. Joules recorded from the pendulum impact tester are units of work and cannot be used to calculate the minimal force required for bud failure. The drop height of the pendulum was 61

centimeters and this was used to calculate minimal force by applying equation (4) where F is the force and U is the energy.

$$F = U * 0.6069m \quad (4)$$

Newtons of force possible for each wind category were calculated using the bud mass and branch accelerations from the growing season data for each species. Acceleration for each wind category was from wind gusts and represents maximum acceleration observed. Once maximum force possible was calculated, it could be compared to the minimal force required to cause bud failure to assess breakage. Maximum force possible was calculated using equation (5) where F is force, M is bud mass and A is branch acceleration.

$$F = M * A \quad (5)$$

BRANCH ELONGATION AND BUD ANALYSIS

Results

Mean branch lengths sampled for each species varied. Both interior and exterior mean branch length for Nuttall oak was 309.9 cm, yellow-poplar 302.3 cm and sweetgum 284.5 cm. Although not all samples were analyzed from the tree bole to apical tip, yellow-poplar and sweetgum were observed to have greater branch elongation on limbs that were on the exterior (open side of the tree) than in the interior side where limbs were adjacent to crowns of other trees (Figures 6-9). However, Nuttall oak was an exception and had shorter branch length on the exterior side of the stand as compared to branches on the interior (Figures 10 and 11). On all interior samples, some years of growth were missing. Missing years were more frequent in the sweetgum than other sampled species.

Mockernut hickory had the most bud mass of all the species examined in this study (Table 1). The majority of all other species had a mass between 0.01g to 0.08g. Red maple had the least mass of all species with 0.0049g. Although moisture content varied between species, the species with sustained bud growth from buds generally had higher moisture content (Table 1). The yellow-poplar's leafy green bud had the highest moisture content of 257 percent.

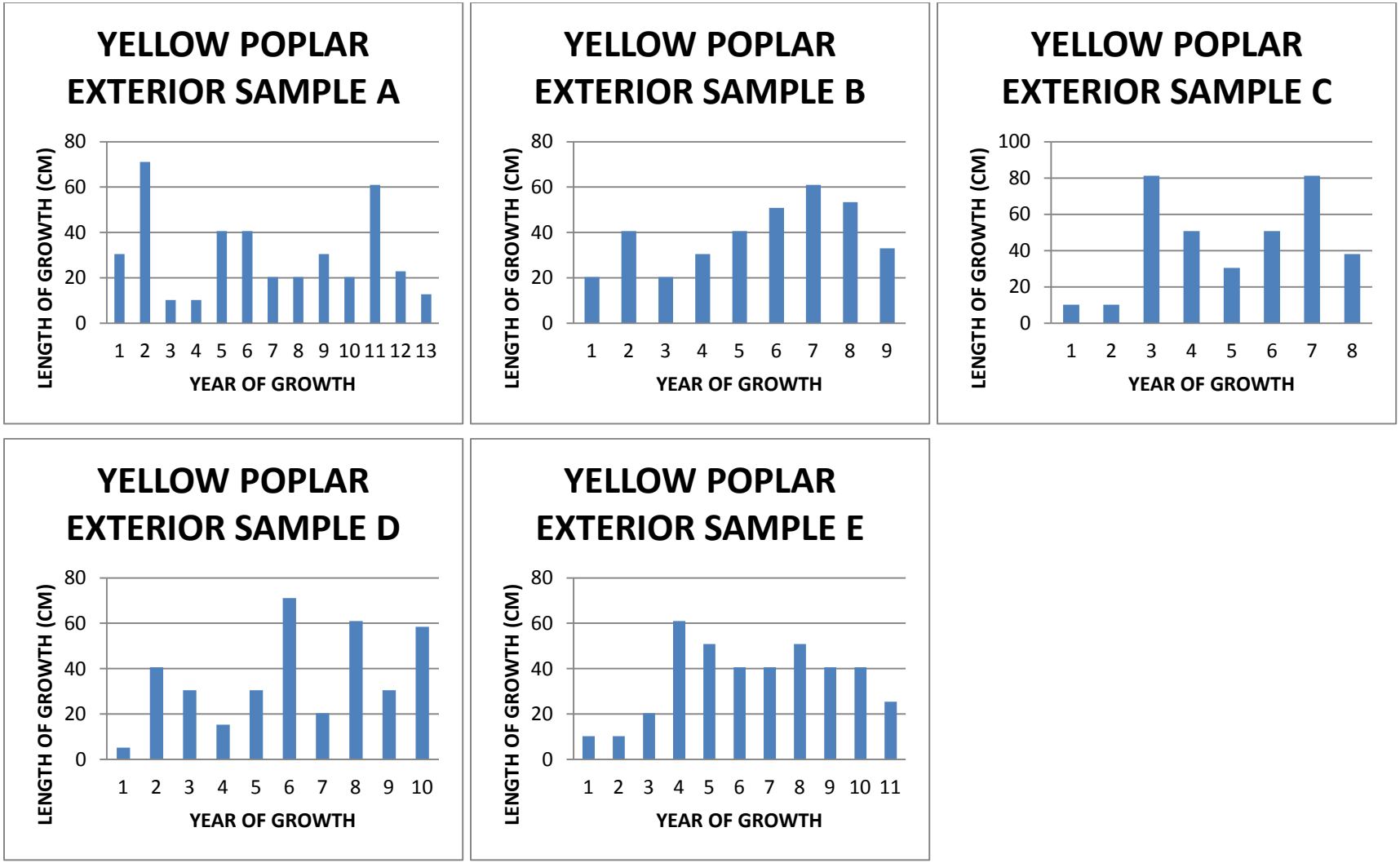

Figure 6: Length of branch growth (cm) found in each year from the base of the stem (one) for the crown abrasion study, Tennessee, 2011. All samples were from yellow-poplar and were located on the exterior of the stand.

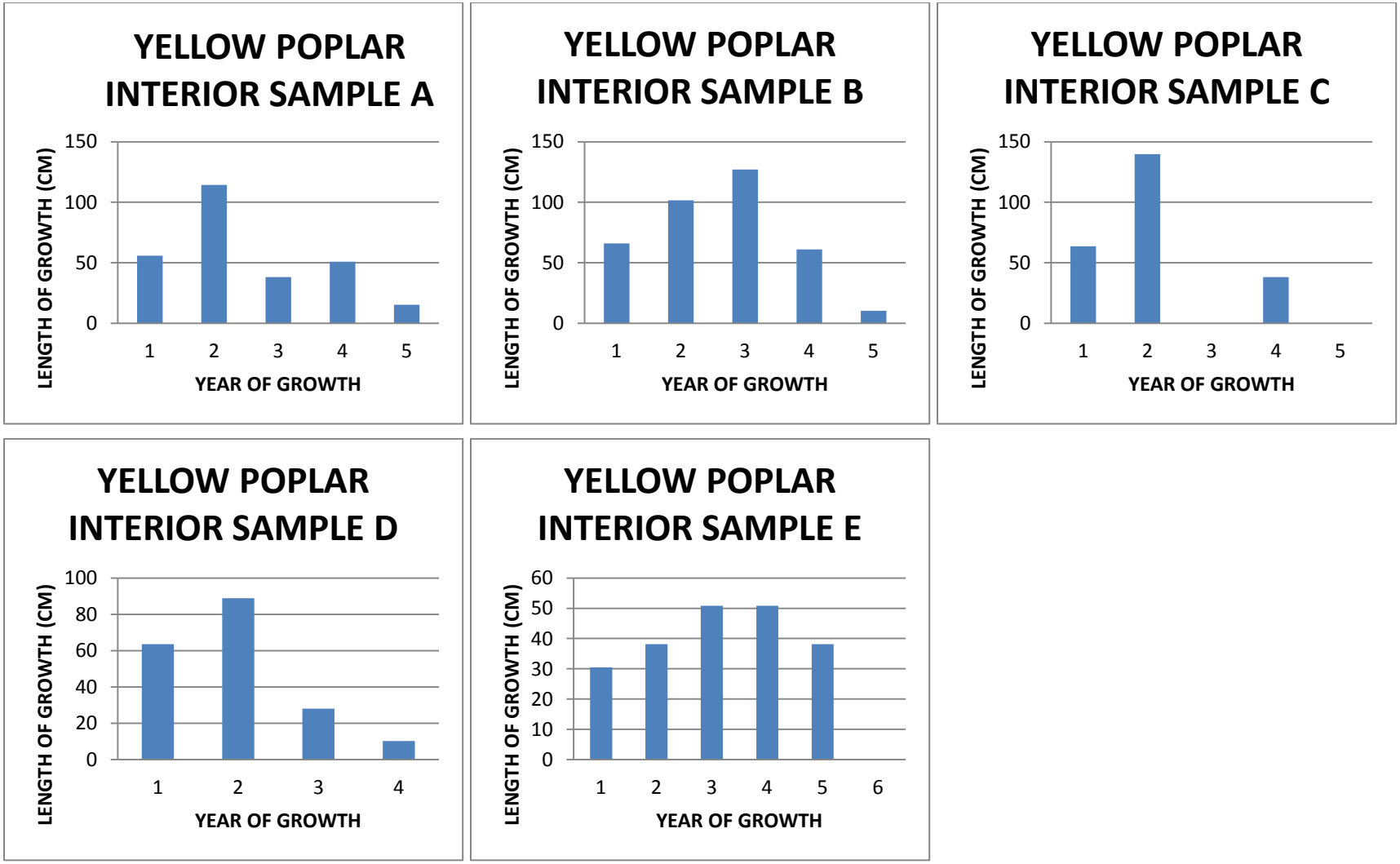

Figure 7: Length of branch growth (cm) found in each year from the base of the stem (one) for the crown abrasion study, Tennessee, 2011. All samples were from yellow-poplar and were located on the interior of the stand. Years with no length had no growth present.

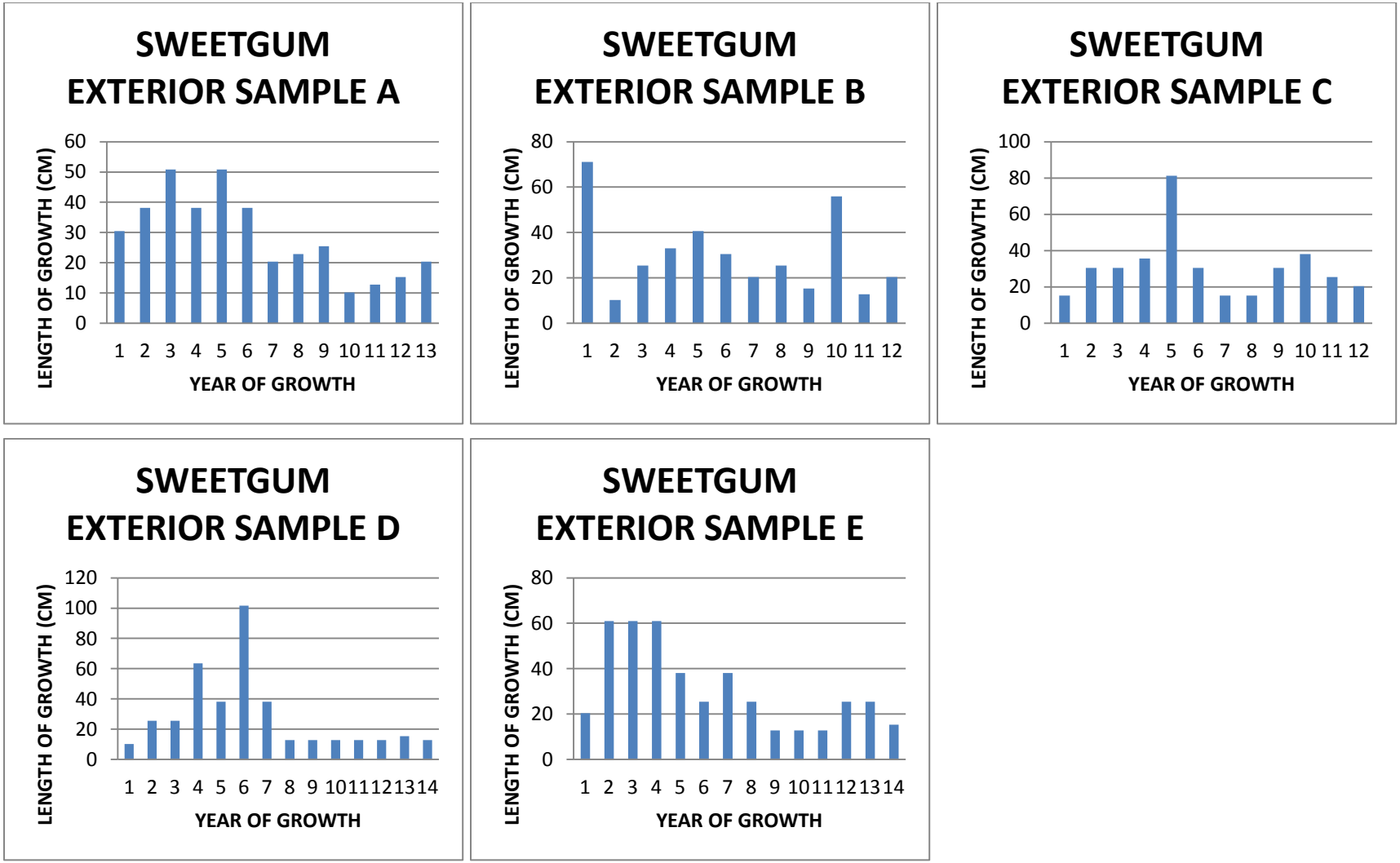

Figure 8: Length of branch growth (cm) found in each year from the base of the stem (one) for the crown abrasion study, Tennessee, 2011. All samples were from sweetgum and were located on the exterior of the stand.

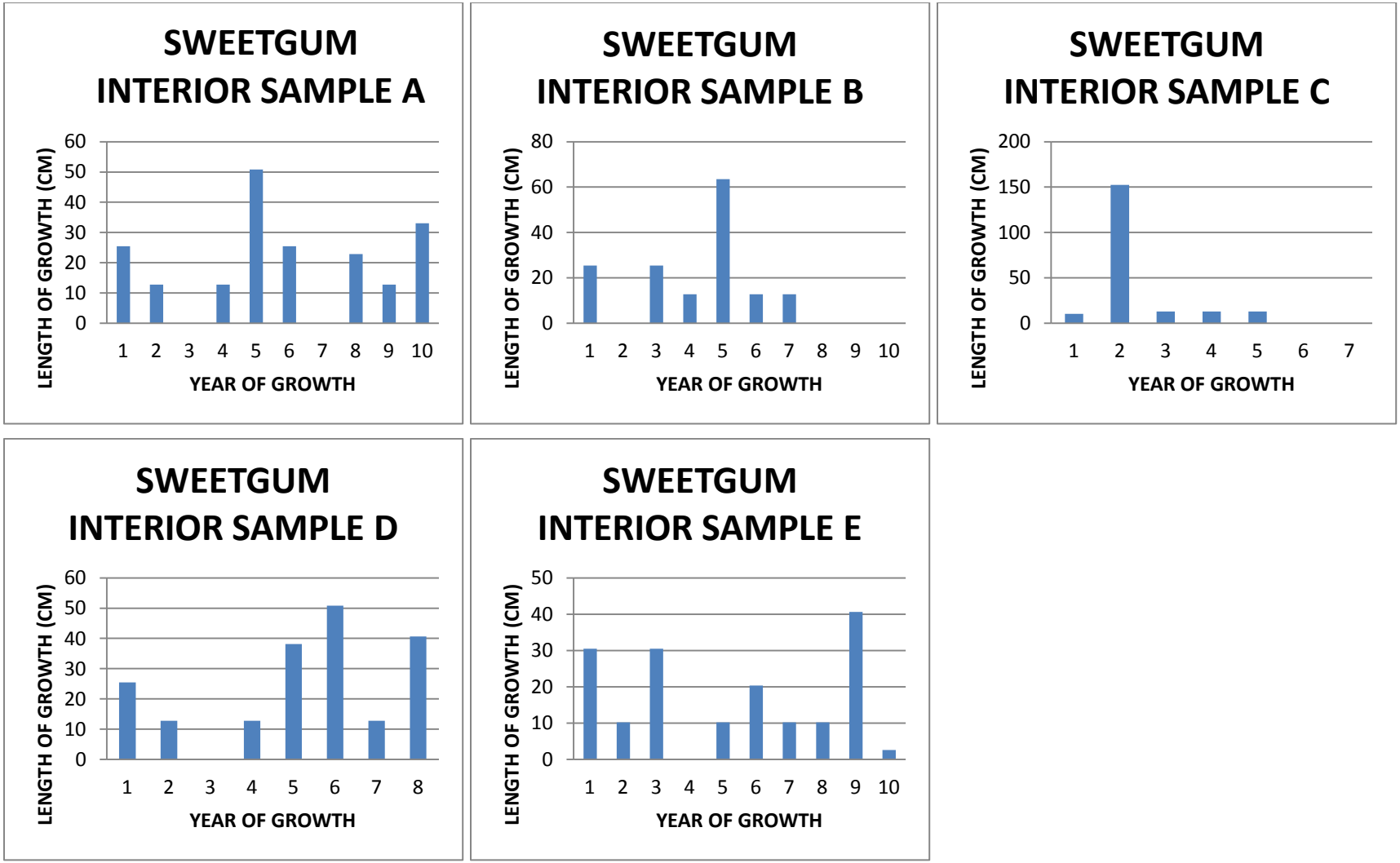

Figure 9: Length of branch growth (cm) found in each year from the base of the stem (one) for the crown abrasion study, Tennessee, 2011. All samples were from sweetgum and were located on the interior of the stand. Years with no length had no growth present.

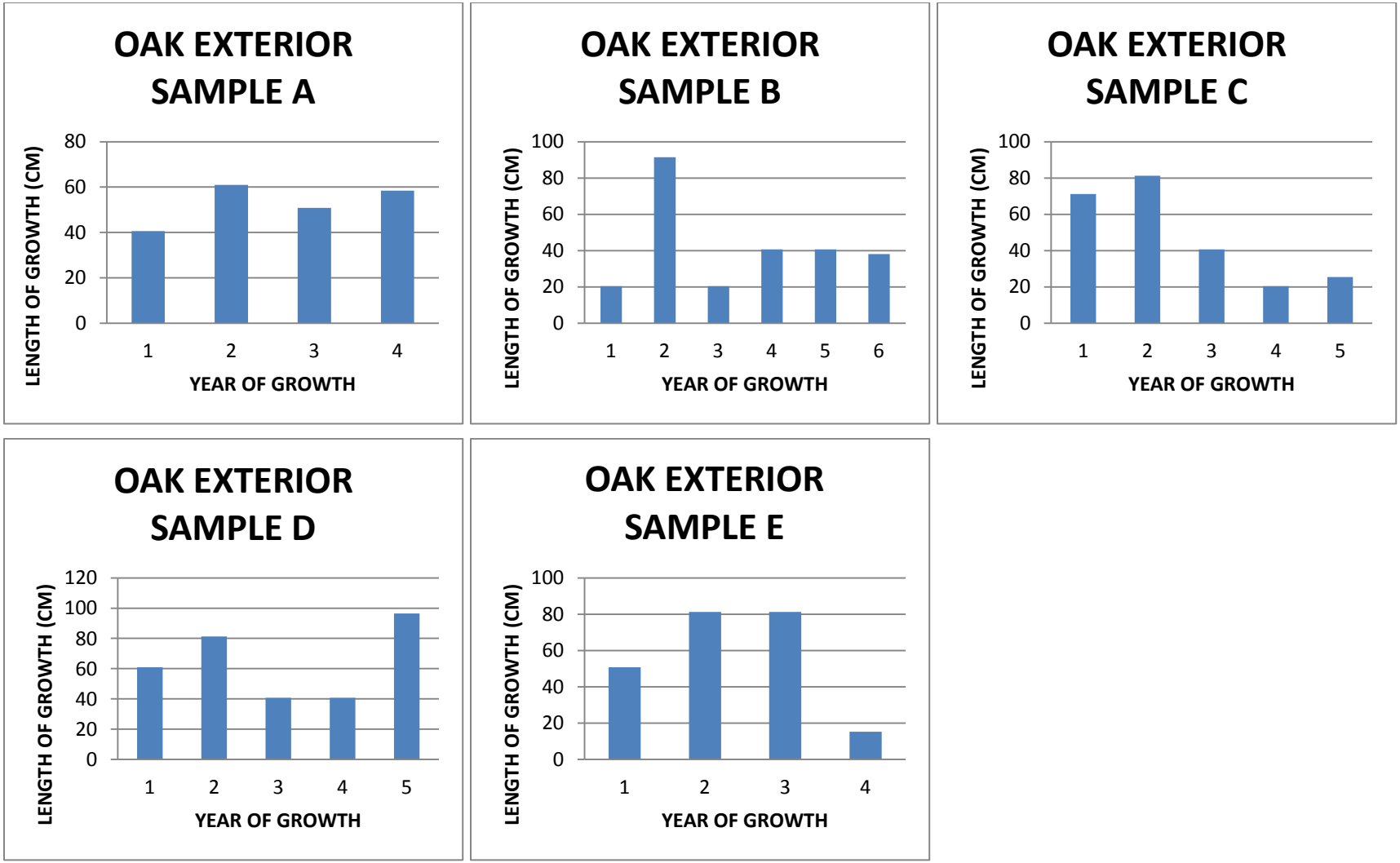

Figure 10: Length of branch growth (cm) found in each year from the base of the stem (one) for the crown abrasion study, Tennessee, 2011. All samples were from Nuttall oak and were located on the exterior of the stand.

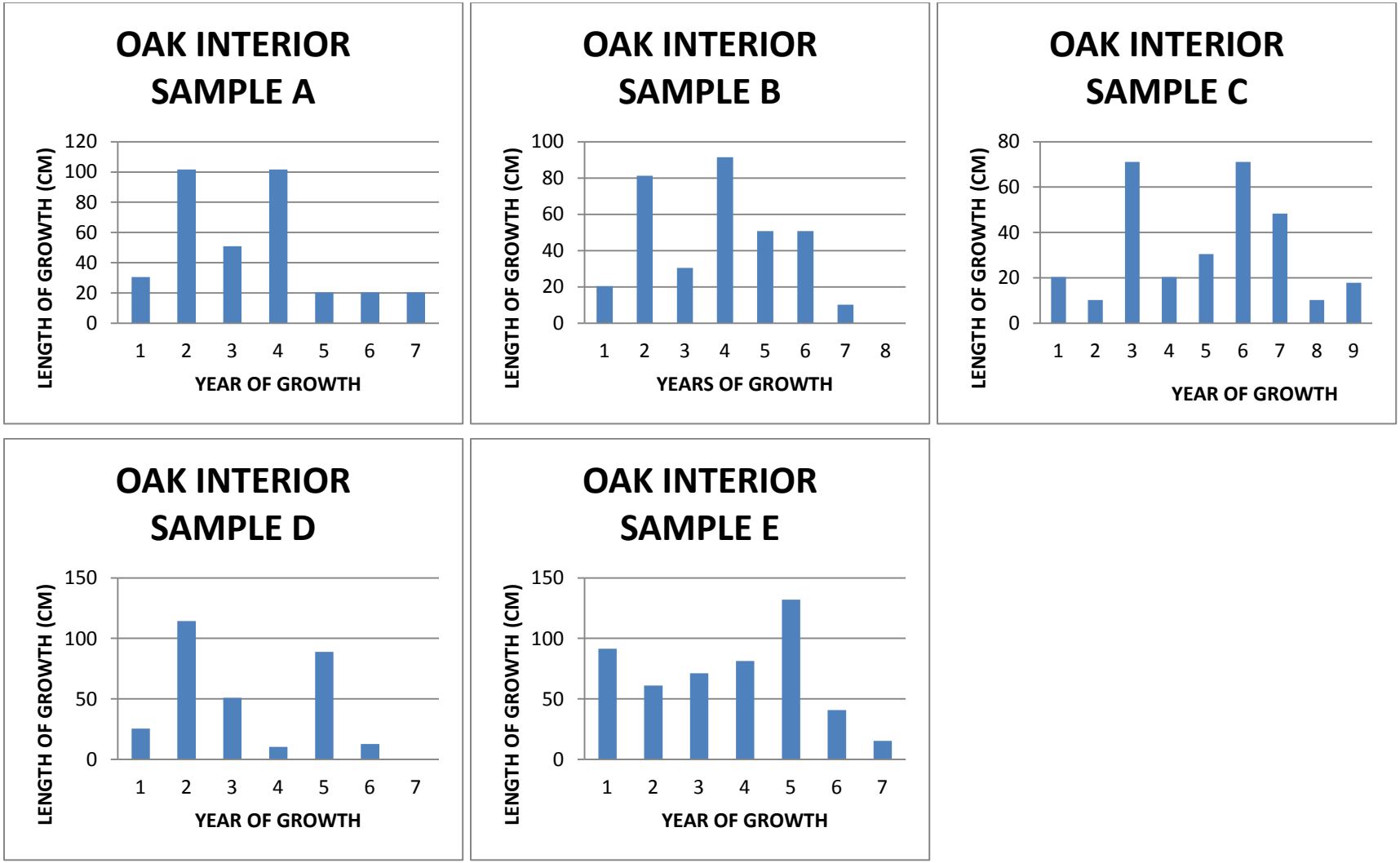

Figure 11: Length of branch growth (cm) found in each year from the base of the stem (one) for the crown abrasion study, Tennessee, 2011. All samples were from Nuttall oak and were located on the interior of the stand. Years with no length had no growth present.

Table 1: Bud parameters by species during the growing season for crown abrasion study, Tennessee, 2011. Mean and standard errors are given for bud collar diameter bud mass and moisture content. Species without data were not included in the analysis. Asterisk (*) is considered preformed bud growth form.

Species	n	Bud Collar Diameter (cm)	Standard Error	Bud Mass (g)	Standard Error	Moisture Content	Standard Error
Acer rubrum	20	0.198	0.009	0.005	0.001	93.72%	3.29%
*Carya tomentosa**	20	0.434	0.018	0.231	0.027	83.62%	0.50%
*Juglans nigra**	20	0.511	0.014	0.084	0.006	66.30%	0.74%
Liquidambar styraciflua	20	0.262	0.011	0.029	0.002	170.54%	3.78%
Liriodendron tulipifera	20	0.259	0.006	0.057	0.005	257.68%	2.94%
Platanus occidentalis	-	-	-	-	-	-	-
*Quercus alba**	20	0.236	0.007	0.009	0.000	100.91%	0.48%
*Quercus falcata**	20	0.272	0.009	0.017	0.001	69.80%	1.66%
*Quercus rubra**	20	0.338	0.011	0.040	0.003	57.03%	2.09%
*Quercus texana**	20	0.218	0.006	0.009	0.001	103.26%	2.25%

Discussion

The hypothesis that branch growth will not be consistent in crowded crowns as compared to those growing freely was supported for all species sampled. In yellow-poplar and sweetgum, growth appeared restricted on the interior branches adjacent to other tree crowns. The branch growth of Nuttall oak on the interior was not as restricted as the other two species.

Branch Elongation Analysis

The stand of Nuttall oak was the only stand sampled that had overlapping canopies that could be observed. Yellow-poplar and sweetgum both exhibited no overlap in canopies, often with empty space surrounding each individual crown in the stand. The canopy of the Nuttall oak stand was the densest which could have resulted in the reduction of wind or decreasing wind speed, and in turn, allowed branches to overlap and continue growing with little inhibition. Nuttall oak was also the only species sampled that appeared to have shorter branch growth on the exterior samples. Full sunlight on these exterior branches could have resulted in a lack of competitive growth. Although the interior branches were longer, samples "B" and "D" exhibited restricted growth around the apical tip from breakage (Figure 9). Branch elongation rates for the other samples are decreasing as well, probably because of denser crowns and lack of sunlight affecting growth rates.

Yellow-poplar did not show a particular growth pattern on the exterior or interior branch samples. Growth rates fluctuated on the outside, but there are no signs of branch elongation restriction for the species. Fluctuations could be a result of climate variations or sampling error (missing growth rings). On the interior samples, growth was limited in the most recent year on every sample. With the onset of crown closure, branch elongation is slow or stalled. Crown abrasion could be the factor that is causing restriction of branch growth, particularly on interior sample "C" (Figure 7) where the branch forked and an entire season of growth was missing.

Sweetgum also had no clear pattern of development as growth rates varied across the years. The samples from the interior side of the tree showed the most branch abrasion of all sampled species. Every sample had various damage along the branch that could have only been caused by wind or mechanical abrasion. For example, interior sample "A" had two locations where a break occurred, growth rings were missing and elongation continued on a different angle but at a much slower rate (Figure 9). The majority of the elongation for the interior sample "C" branch occurred in the second growing season. Elongation following the second growing season was minimal or more restricted every successive year, followed by a branch break before the fifth year of growth. The appearance of the branch was deformed and twisted among the later years of elongation, suggesting sunlight was not the major contributing factor limiting growth.

Bud Analysis

Although black walnut had the largest mean bud collar diameter, it did not have the highest mean bud mass. Mockernut hickory had a smaller mean bud collar, but almost tripled the mean mass of the black walnut bud. The shape of the bud probably influences the bud mass for these two species. Black walnut has a trapezoid-shaped bud with the largest portion positioned at the bud collar, while the mockernut hickory is shaped more like a rhombus with most of its mass in the center of the bud. White oak, Nuttall oak and red maple had the lowest mean bud mass because their buds were exceptionally smaller once they were separated from their bud cluster (Table 1).

Moisture contents were higher than expected overall (Table 1). Yellow-poplar and sweetgum had the highest moisture content of the buds sampled in this study. Both species have the sustained growth form and increased moisture content which makes the bud more flaccid, reducing toughness. Both were green and tender, but yellow-poplar in particular was composed

of nothing more than a tender leaf stipule protecting leaf primordia. Sweetgum buds had the same appearance as oak buds, but the sweetgum bud contained much more moisture.

APICAL BUD TOUGHNESS TESTS

Results

The mean diameter of bud collars for all species was different between dormant and growing seasons (p=.001) (Tables 2 and 3). The mean energy required to fracture the bud for all species was also different between seasons (p=.001). By analyzing each season separately, significant differences occurred between the mean bud collar diameter of the species in both the dormant and the growing seasons (p=.001) (Figures 12 and 13). The mean energy of bud fracture was different between the species for both the dormant and the growing season (p=.001) (Figures 14 and 15).

Linear regression slopes of bud collar diameter and energy to bud fracture were significant for each species (p=.001) (Figures 16-31). Sweetgum had the highest R^2 value in winter and the second lowest in summer (Figures 21 and 22). In the dormant season, 80 percent of the variation in energy required for bud fracture could be explained by the diameter of the bud collar (p=.001). For the growing season, only 10 percent of the variation in the energy requirements could be explained by the bud collar diameter. This trend of decreasing variation from winter to summer is consistent across most species.

Ratios of mean energy required for bud fracture to mean bud collar diameter were evaluated for each species in each season (Figure 32). In most species, the ratio decreased from dormant season to growing season. Red maple and Nuttall oak were the only species to show a slight increase in this ratio from the dormant to the growing season.

Table 2: Dormant season bud toughness tests by species using a pendulum impact test with average bud collar diameter (cm) and energy (Joules) needed to fracture the bud as the variables for the crown abrasion study, Tennessee, 2011. Standard errors are given for each species. R^2 value is given to explain the amount of variation in bud energy explained by bud diameter. Species without data were not included in the analysis for that season. Asterisk (*) is considered preformed bud growth form.

	Dormant Season					
Species	**n**	**Bud Collar Diameter (cm)**	**Standard Error**	**Bud Fracture Energy (Joules)**	**Standard Error**	**R^2**
Acer rubrum	77	0.2286	0.00508	0.014	0.001	0.07
*Carya tomentosa**	177	0.46482	0.008382	0.184	0.0092	0.523
*Juglans nigra**	-	-	-	-	-	-
Liquidambar styraciflua	77	0.27686	0.010668	0.037	0.004	0.795
Liriodendron tulipifera	181	0.2921	0.003048	0.045	0.0018	0.312
Platanus occidentalis	73	0.41402	0.009398	0.053	0.0034	0.471
*Quercus alba**	77	0.29464	0.008382	0.049	0.0038	0.39
*Quercus falcata**	-	-	-	-	-	-
*Quercus rubra**	-	-	-	-	-	-
*Quercus texana**	74	0.23114	0.003556	0.017	0.0011	0.272

Table 3: Growing season bud toughness tests by species using a pendulum impact test with average bud collar diameter (cm) and energy (Joules) needed to fracture the bud as the variables for the crown abrasion study, Tennessee, 2011. Standard errors are given fo r each species. R^2 value is given to explain the amount of variation in bud energy explained by bud diameter. Species without data were not included in the analysis for that season. Asterisk (*) is considered preformed bud growth form.

	Growing Season					
Species	**n**	**Bud Collar Diameter (cm)**	**Standard Error**	**Bud Fracture Energy (Joules)**	**Standard Error**	**R^2**
Acer rubrum	52	0.18288	0.004826	0.013	0.0015	0.51
*Carya tomentosa**	52	0.41656	0.01397	0.114	0.0097	0.52
*Juglans nigra**	52	0.42672	0.012954	0.063	0.0059	0.444
Liquidambar styraciflua	52	0.2667	0.005334	0.02	0.0012	0.097
Liriodendron tulipifera	52	0.2159	0.005842	0.013	0.0011	0.259
Platanus occidentalis	-	-	-	-	-	-
*Quercus alba**	51	0.24892	0.005588	0.034	0.0028	0.276
*Quercus falcata**	52	0.25908	0.00381	0.027	0.002	0.185
*Quercus rubra**	52	0.2921	0.006604	0.037	0.0048	0.42
*Quercus texana**	51	0.18034	0.003048	0.017	0.001	0.056

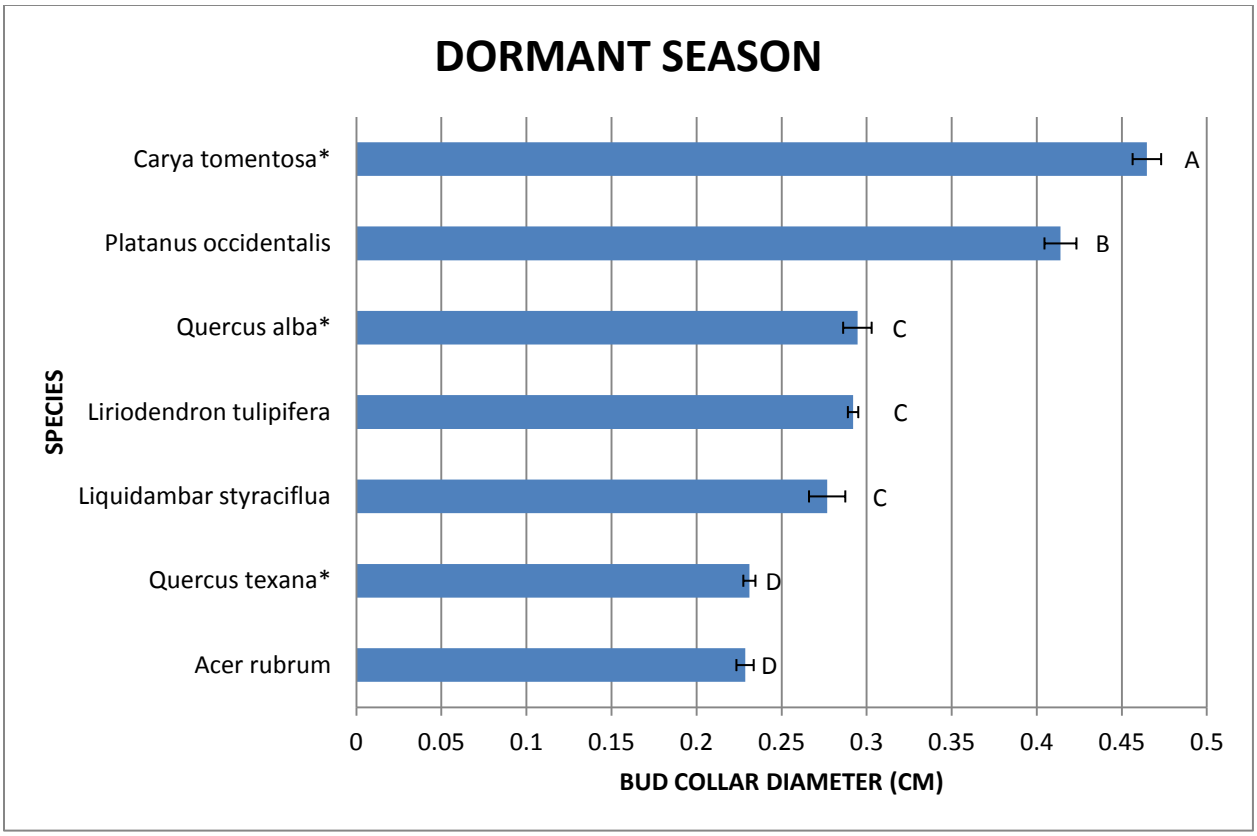

Figure 12: Mean bud collar diameter ± standard errors of each species (treatment) in the dormant season for the crown abrasion study, Tennessee, 2011. Letters represent statistically different means based on Tukey's HSD (α=0.05).

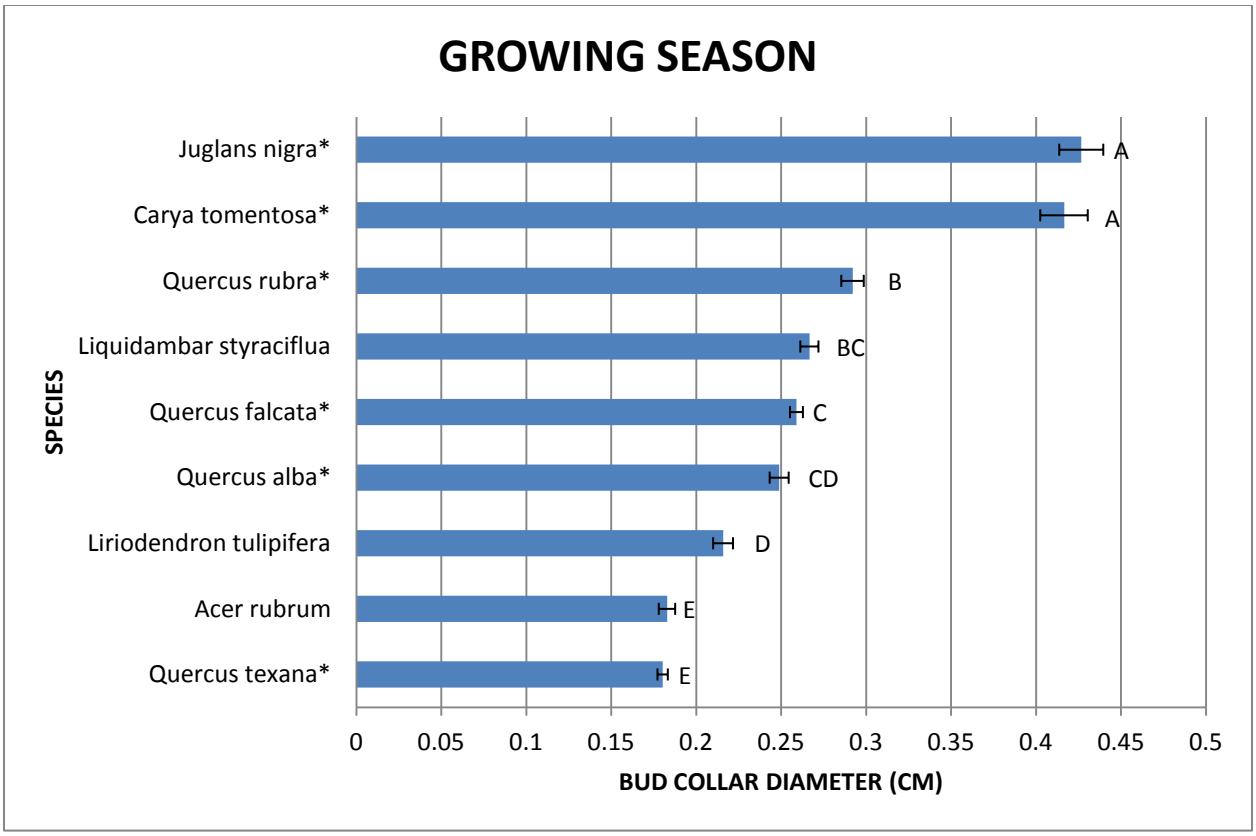

Figure 13: Mean bud collar diameter ± standard error of each species (treatment) in the growing season for the crown abrasion study, Tennessee, 2011. Letters represent statistically different means based on Tukey's HSD (α=0.05).

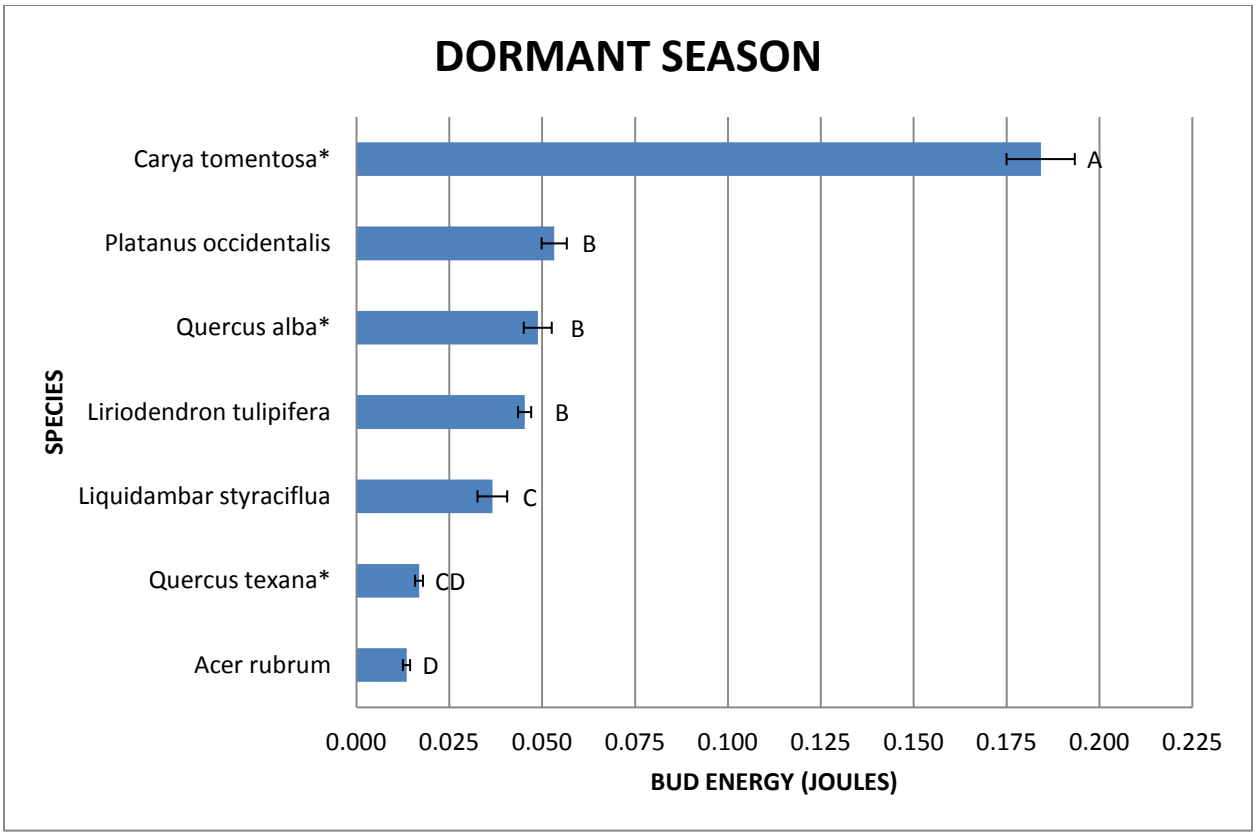

Figure 14: Mean energy ± standard error required for bud fracture for each species (treatment) in the dormant season for the crown abrasion study, Tennessee, 2011. Letters represent statistically different means based on Tukey's HSD (α=0.05).

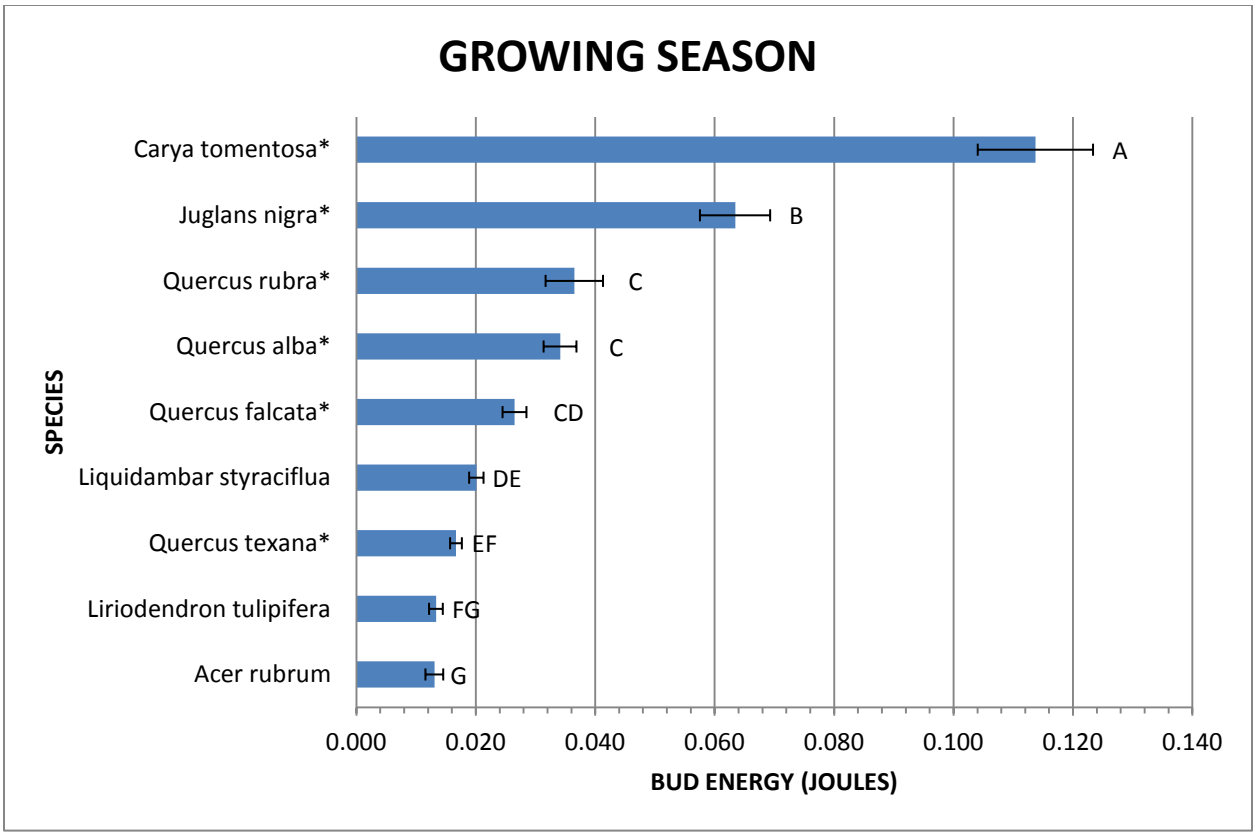

Figure 15: Mean energy ± standard error required for bud fracture for each species (treatment) in the growing season for the crown abrasion study, Tennessee, 2011. Letters represent statistically different means based on Tukey's HSD (α=0.05).

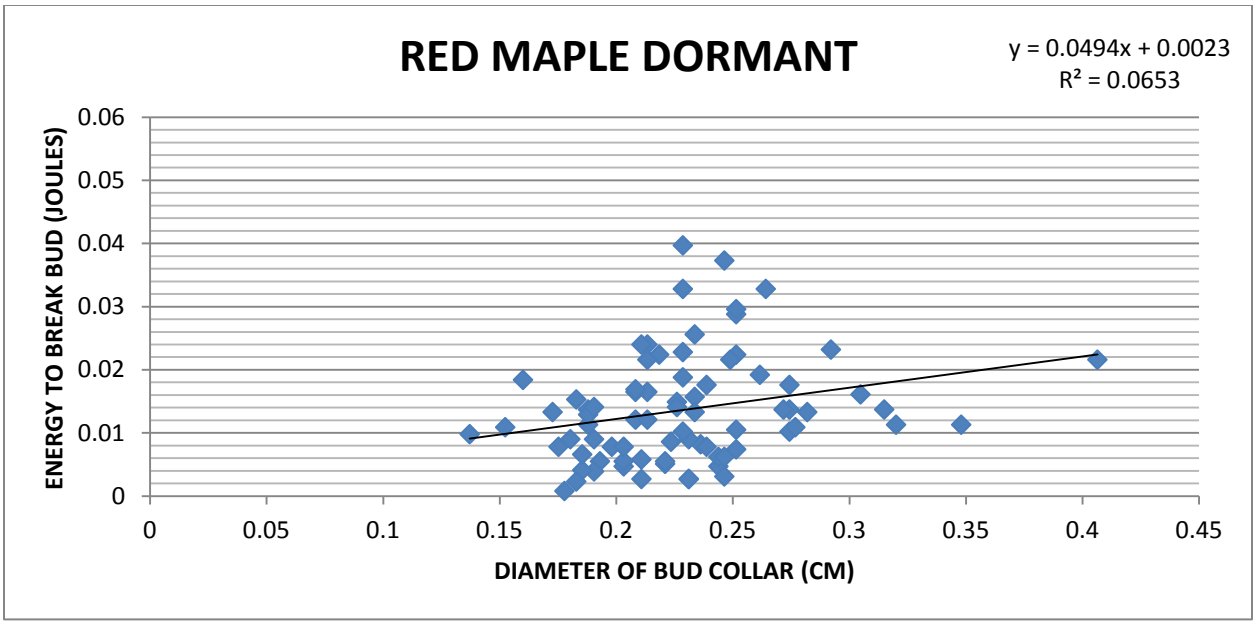

Figure 16: Linear regression relating observations of bud collar diameter and energy absorbed at bud fracture for red maple in the dormant season for the crown abrasion study, Tennessee, 2011.

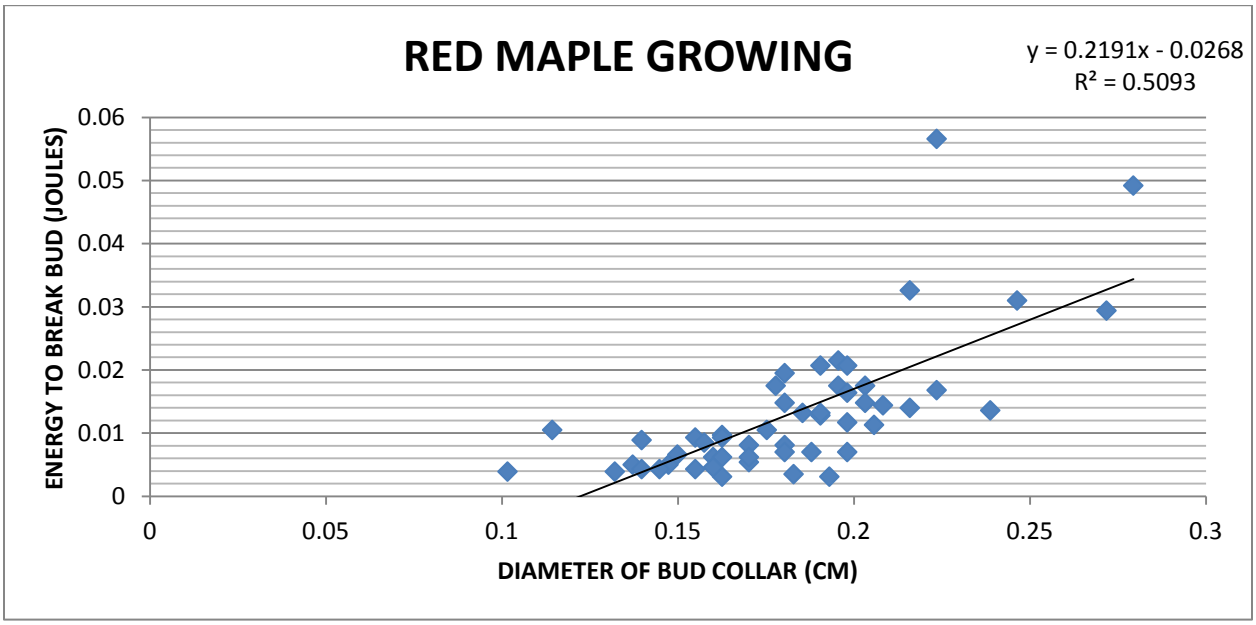

Figure 17: Linear regression relating observations of bud collar diameter and energy absorbed at bud fracture for red maple in the growing season for the crown abrasion study, Tennessee, 2011.

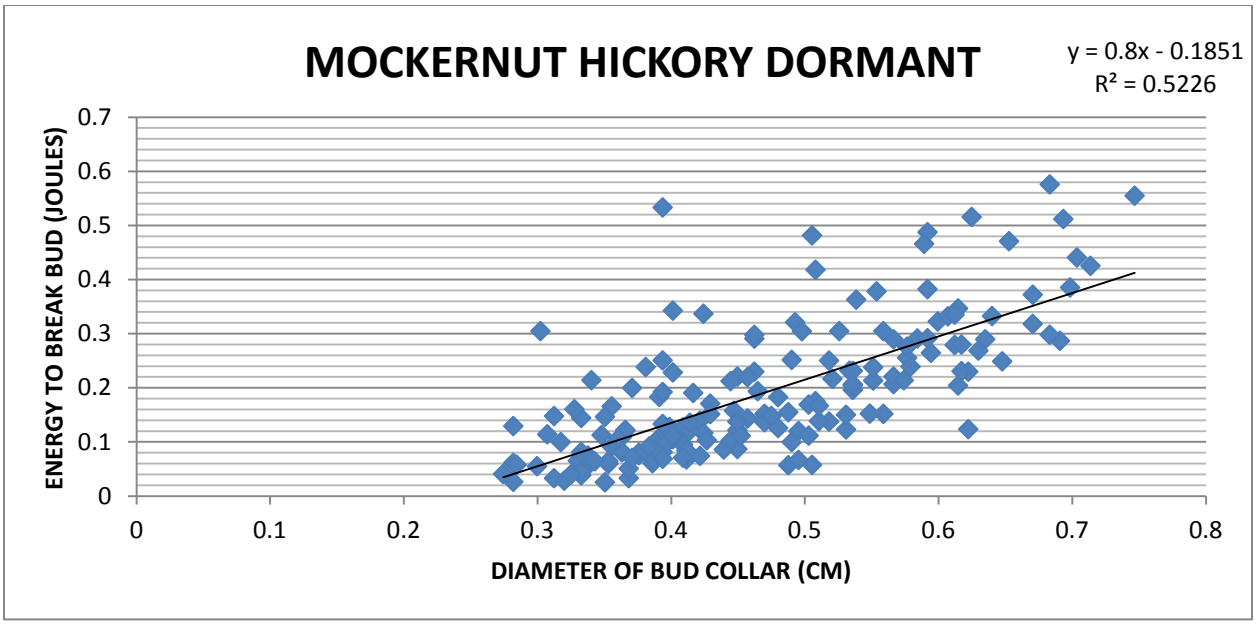

Figure 18: Linear regression relating observations of bud collar diameter and energy absorbed at bud fracture for mockernut hickory in the dormant season for the crown abrasion study, Tennessee, 2011.

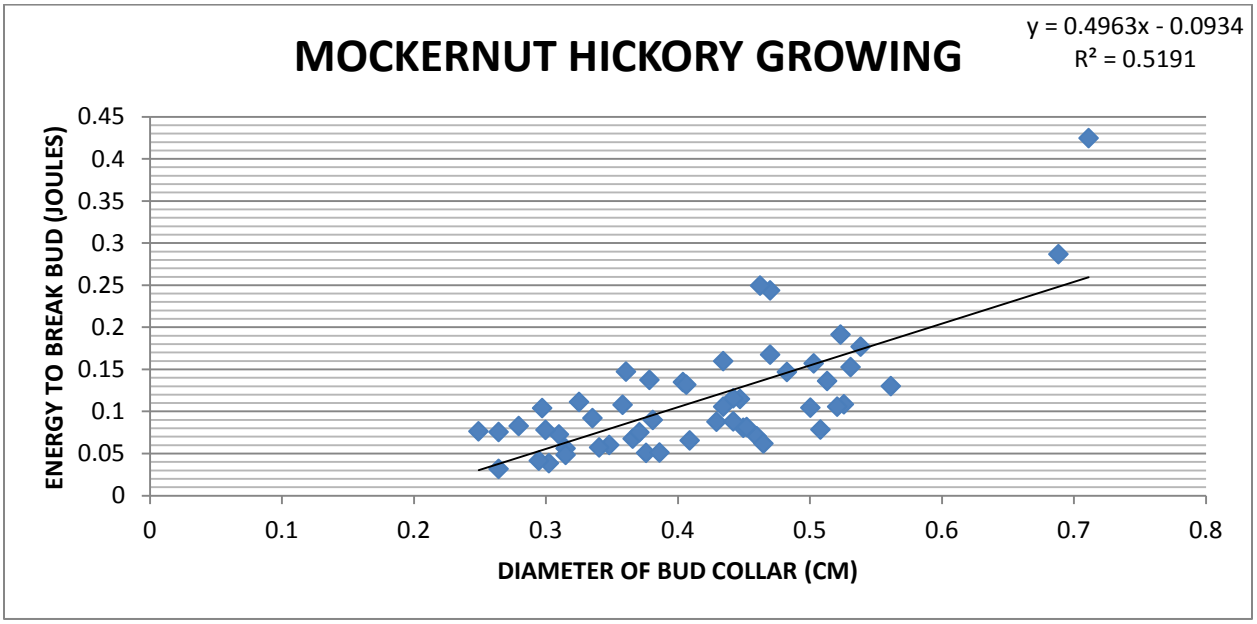

Figure 19: Linear regression relating observations of bud collar diameter and energy absorbed at bud fracture for mockernut hickory in the growing season for the crown abrasion study, Tennessee, 2011.

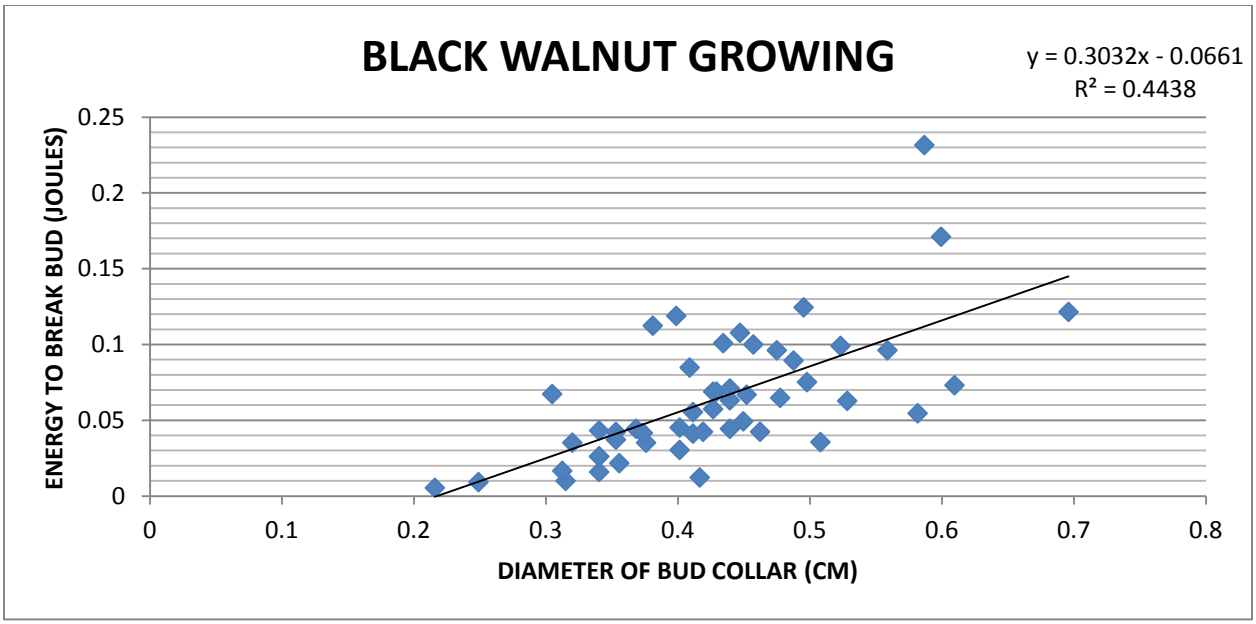

Figure 20: Linear regression relating observations of bud collar diameter and energy absorbed at bud fracture for black walnut in the growing season for the crown abrasion study, Tennessee, 2011.

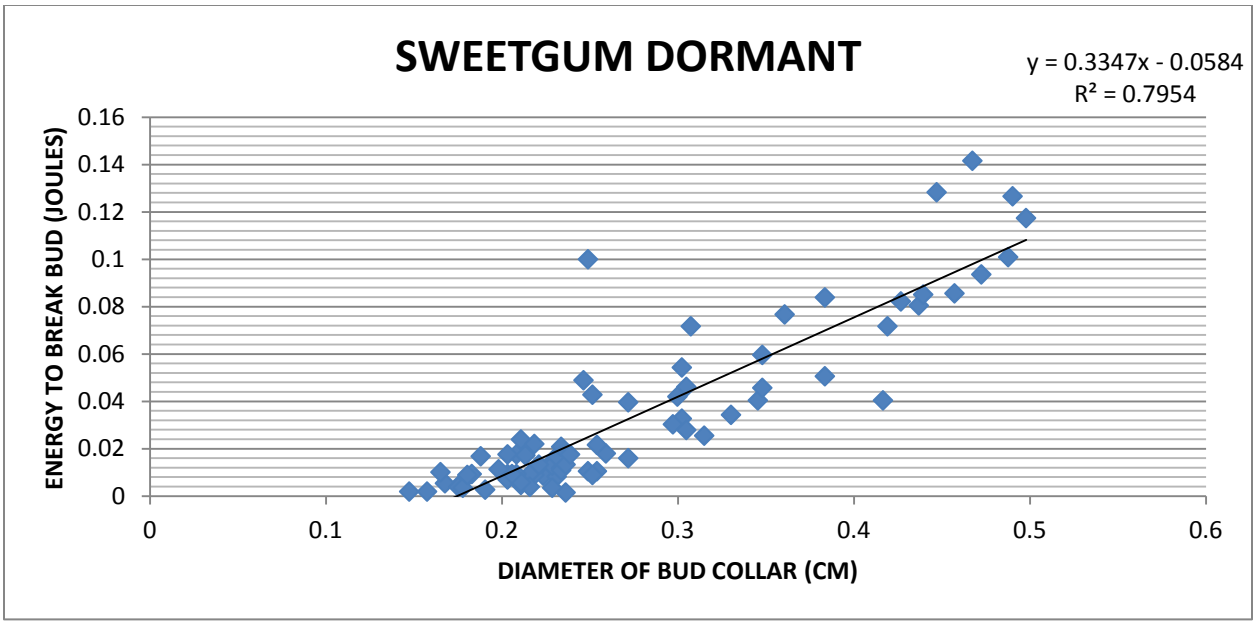

Figure 21: Linear regression relating observations of bud collar diameter and energy absorbed at bud fracture for sweetgum in the dormant season for the crown abrasion study, Tennessee, 2011.

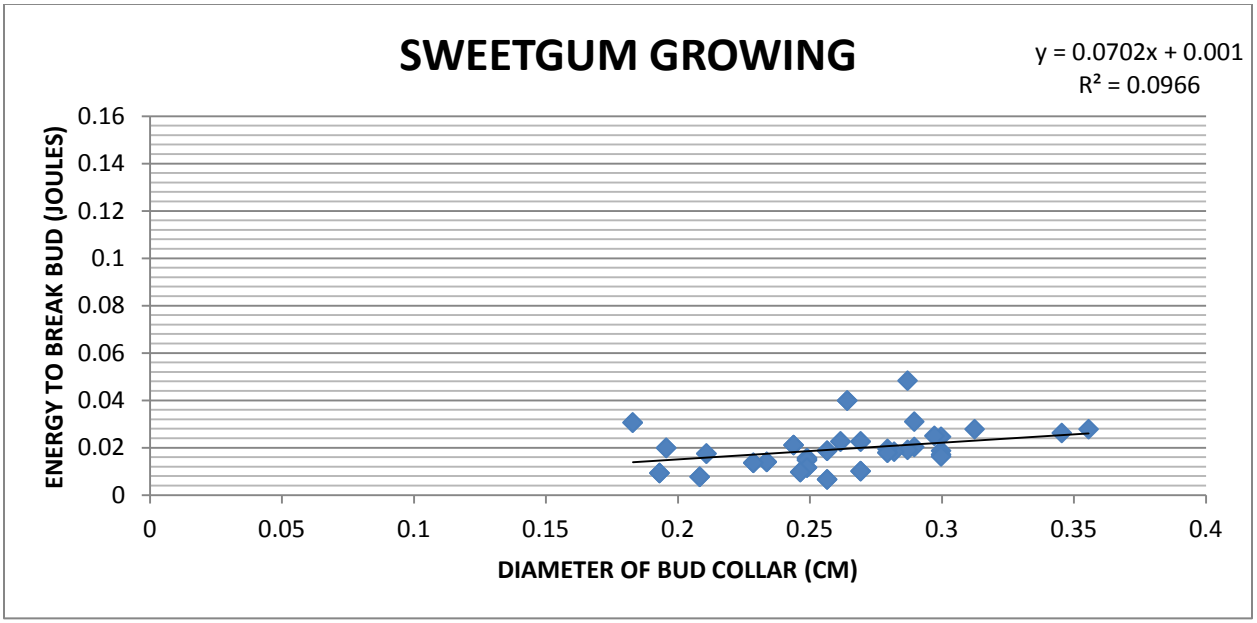

Figure 22: Linear regression relating observations of bud collar diameter and energy absorbed at bud fracture for sweetgum in the growing season for the crown abrasion study, Tennessee, 2011.

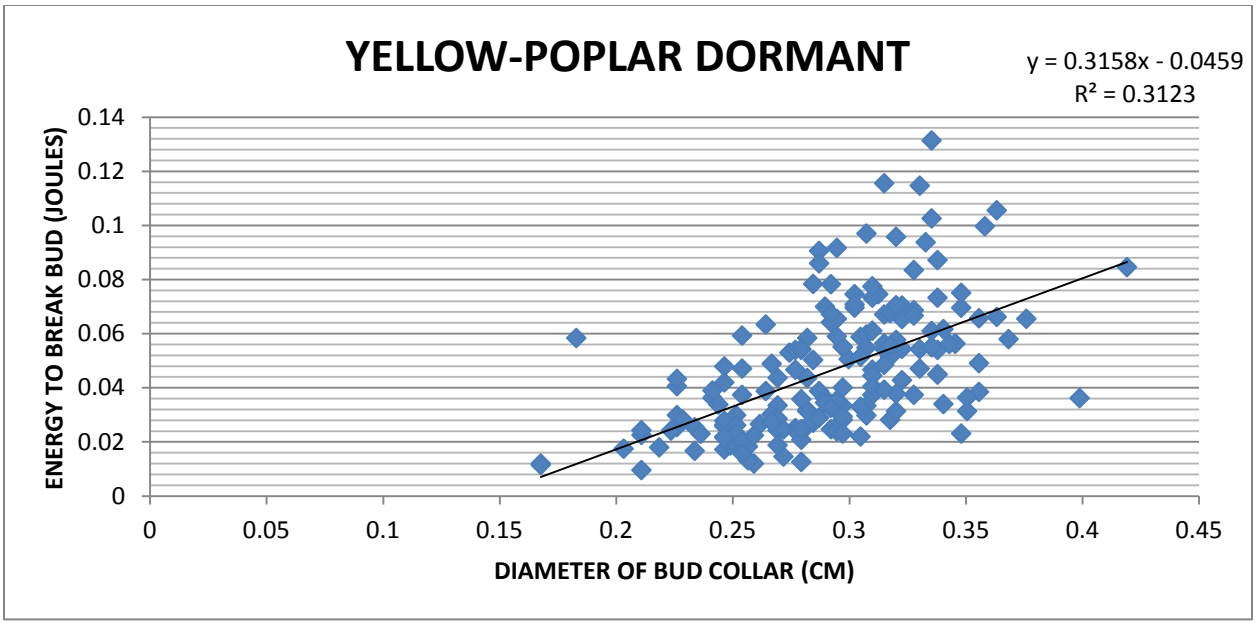

Figure 23: Linear regression relating observations of bud collar diameter and energy absorbed at bud fracture for yellow-poplar in the dormant season for the crown abrasion study, Tennessee, 2011.

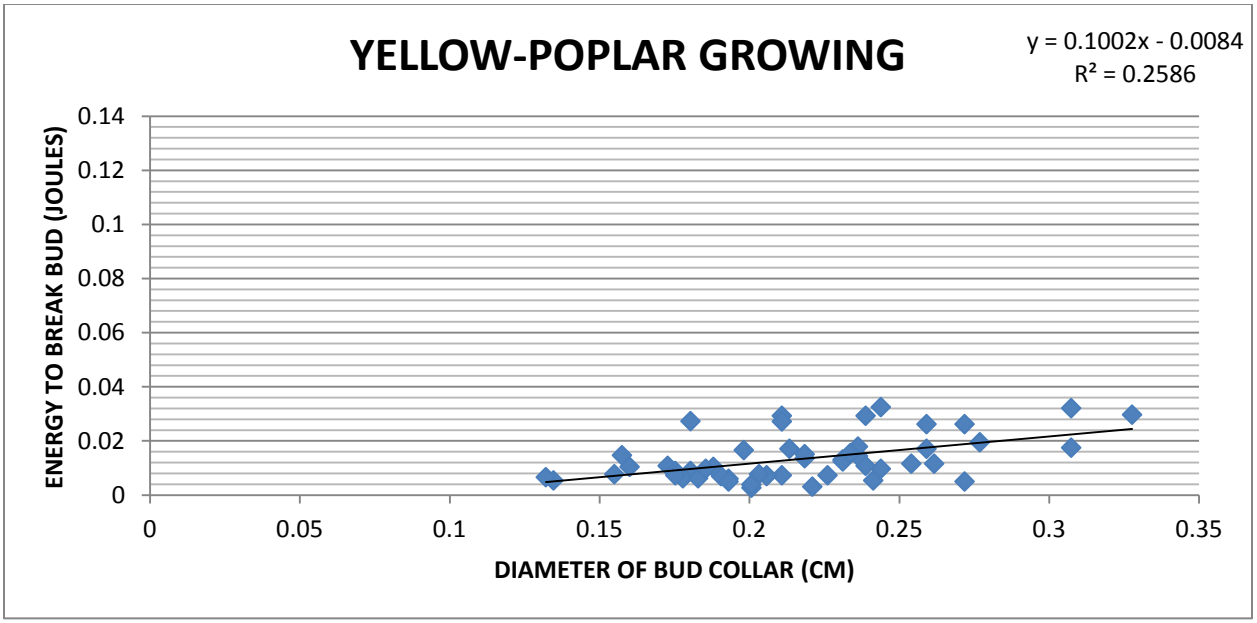

Figure 24: Linear regression relating observations of bud collar diameter and energy absorbed at bud fracture for yellow poplar in the growing season for the crown abrasion study, Tennessee, 2011.

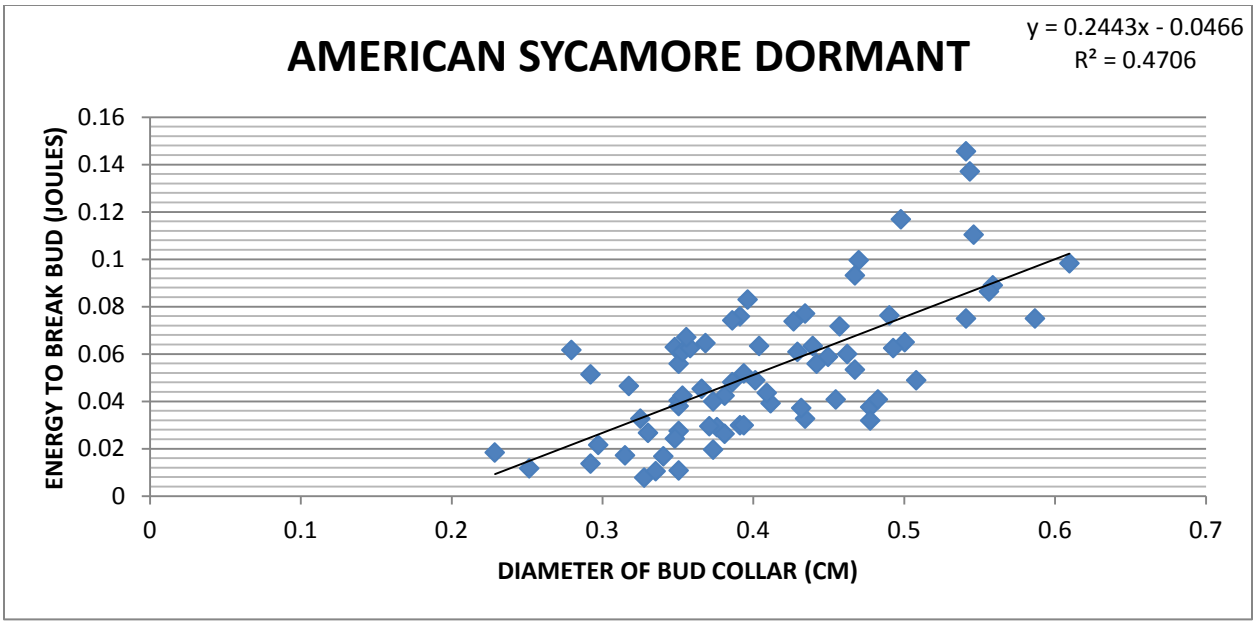

Figure 25: Linear regression relating observations of bud collar diameter and energy absorbed at bud fracture for American sycamore in the dormant season for the crown abrasion study, Tennessee, 2011.

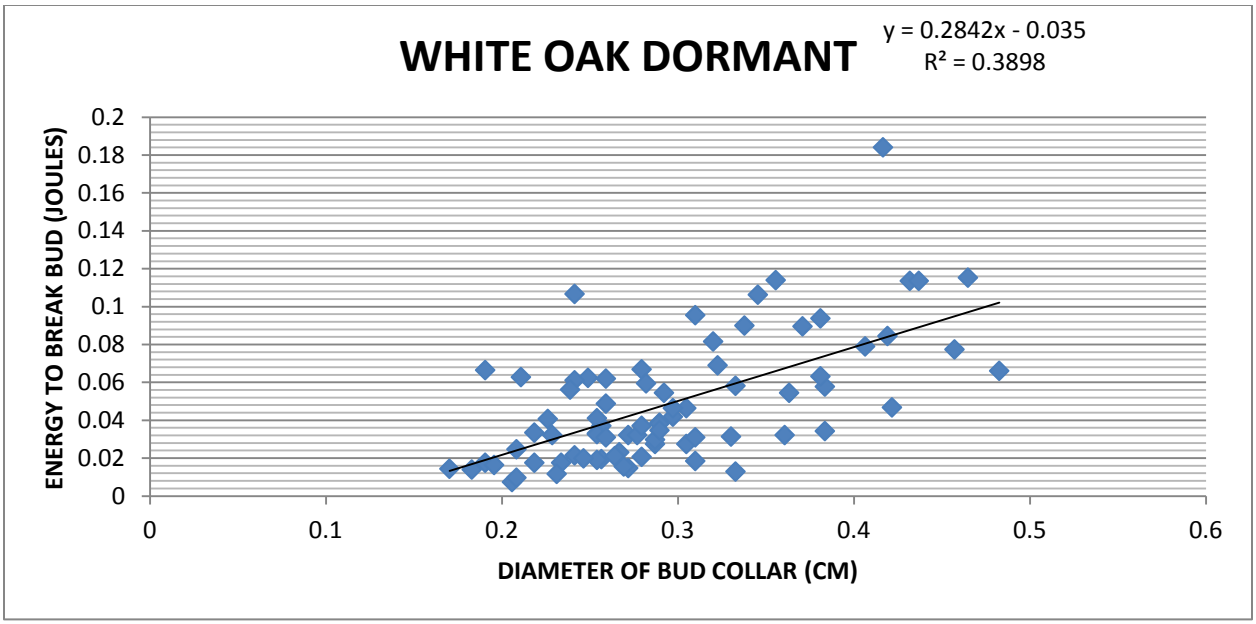

Figure 26: Linear regression relating observations of bud collar diameter and energy absorbed at bud fracture for white oak in the dormant season for the crown abrasion study, Tennessee, 2011.

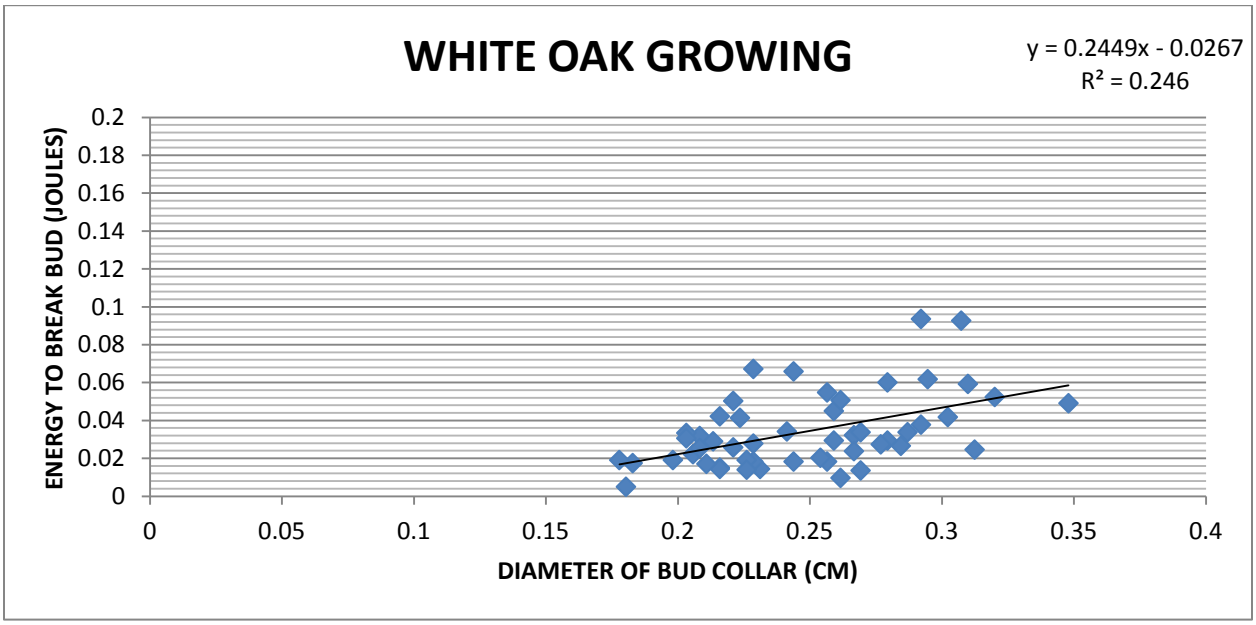

Figure 27: Linear regression relating observations of bud collar diameter and energy absorbed at bud fracture for white oak in the growing season for the crown abrasion study, Tennessee, 2011.

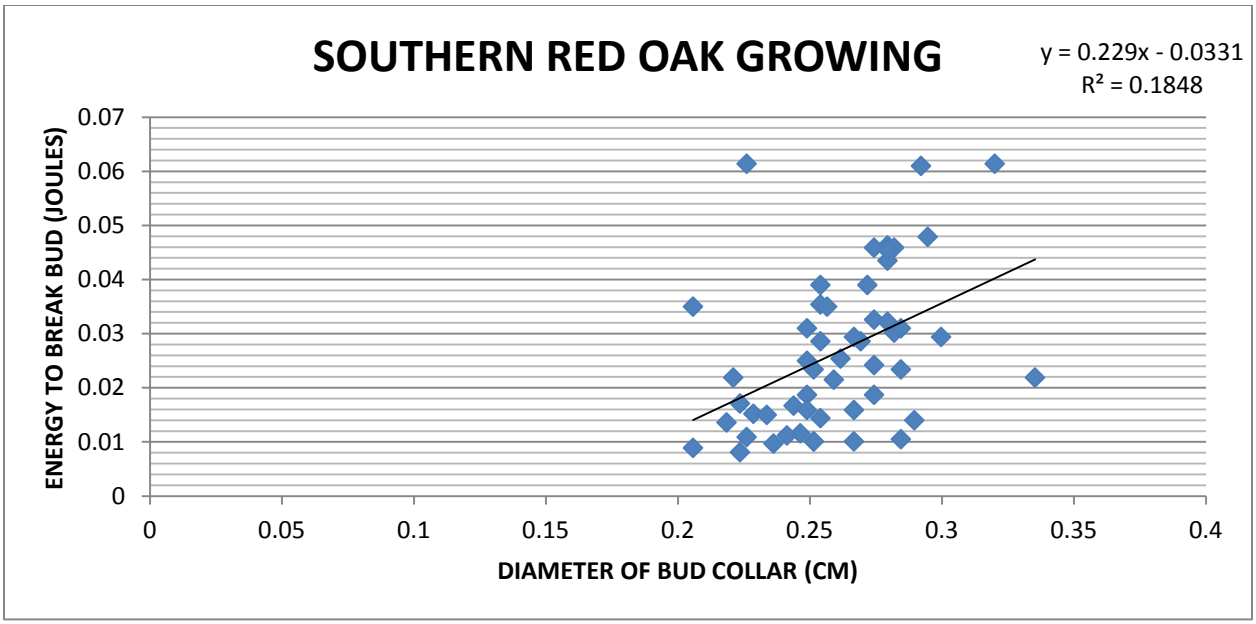

Figure 28: Linear regression relating observations of bud collar diameter and energy absorbed at bud fracture for southern red oak in the growing season for the crown abrasion study, Tennessee, 2011.

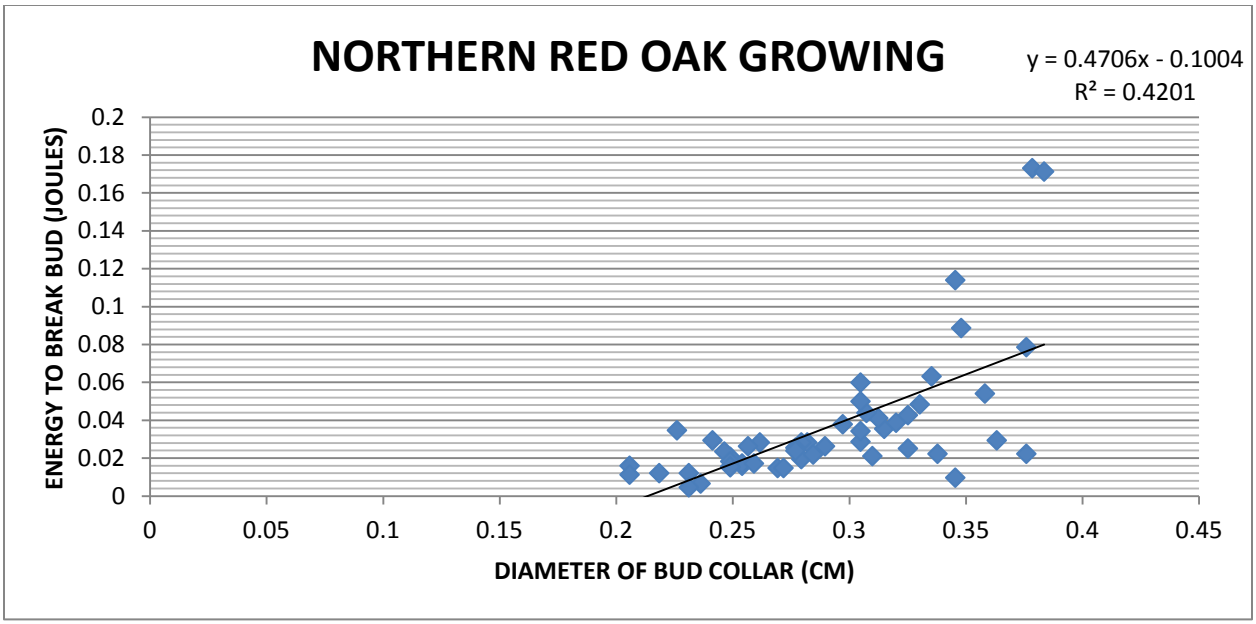

Figure 29: Linear regression relating observations of bud collar diameter and energy absorbed at bud fracture for northern red oak in the growing season for the crown abrasion study, Tennessee, 2011

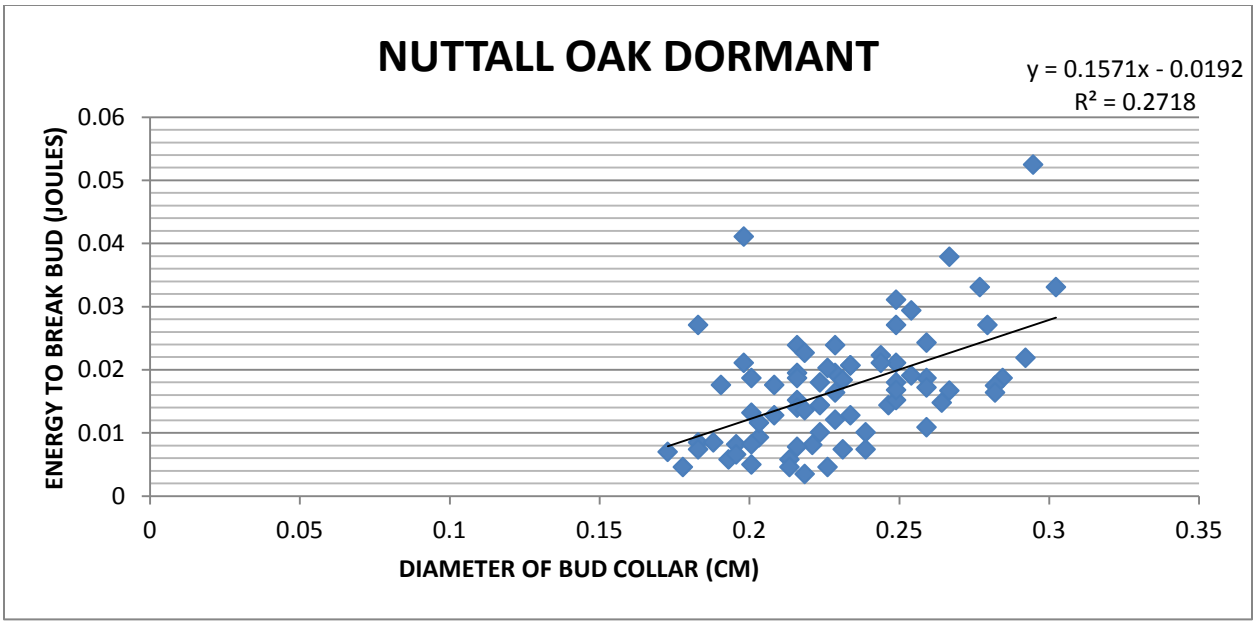

Figure 30: Linear regression relating observations of bud collar diameter and energy absorbed at bud fracture for Nuttall oak in the dormant season for the crown abrasion study, Tennessee, 2011.

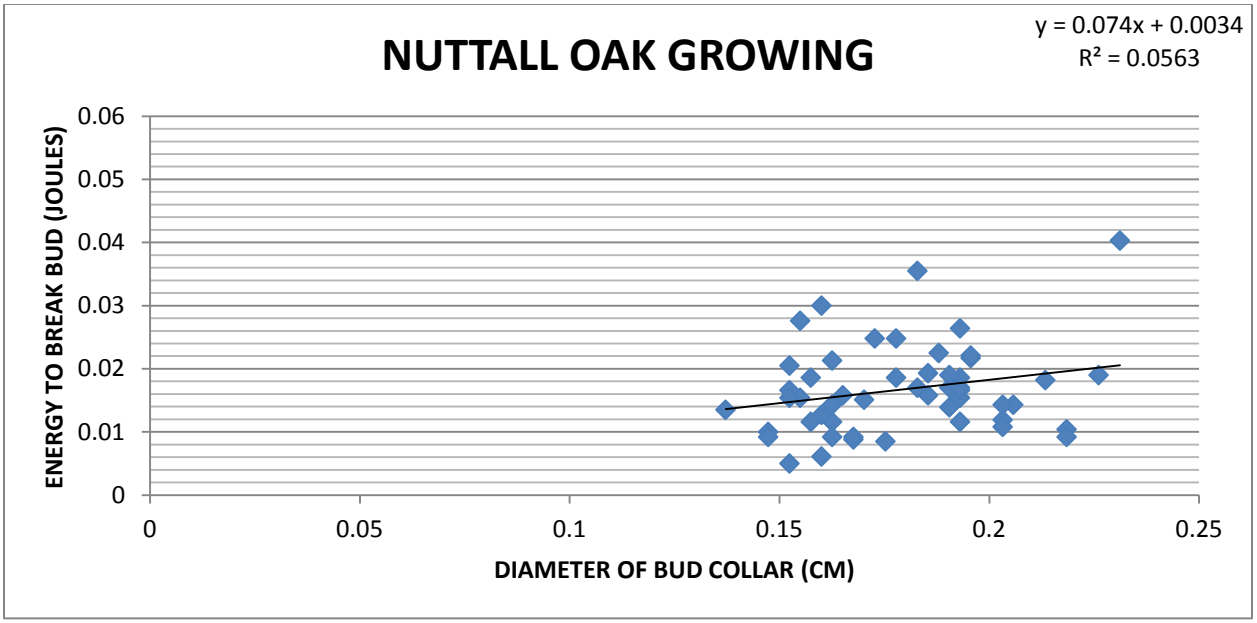

Figure 31: Linear regression relating observations of bud collar diameter and energy absorbed at bud fracture for Nuttall oak in the growing season for the crown abrasion study, Tennessee, 2011.

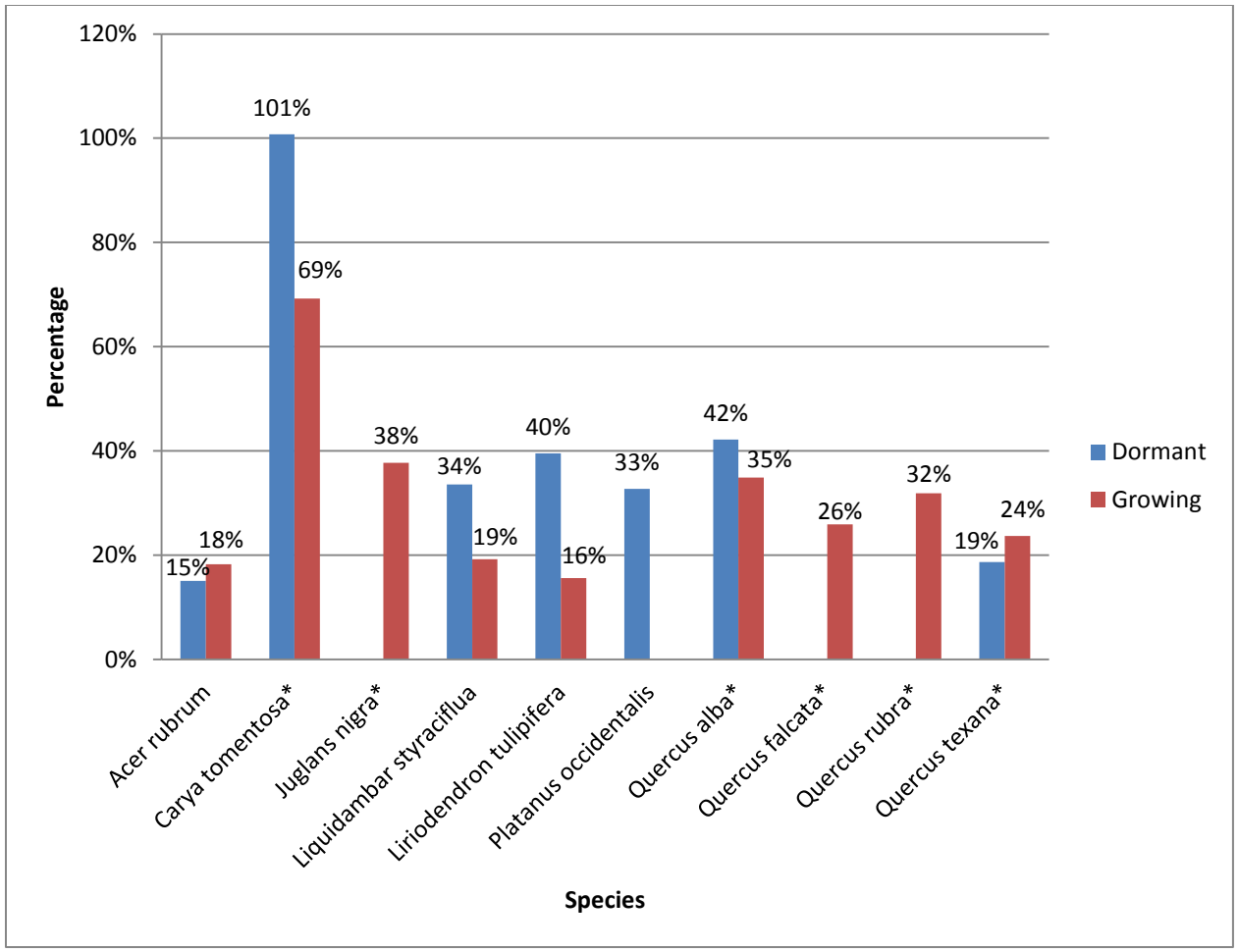

Figure 32: Ratios of mean energy required for a bud fracture to mean bud collar diameter for each species in each season for the crown abrasion study, Tennessee, 2011. Species with one ratio were not sampled in that missing season. Asterisk (*) is considered preformed bud growth form.

Discussion

The hypothesis that preformed bud growth will require more energy to fracture the bud than sustained bud growth was supported for all preformed (determinate) species in the growing seasons except for Nuttall oak (Tables 2 and 3). Nuttall oak was the weakest preformed species tested and had energy values in the same range as sustained growth (indeterminate) species. Nuttall oak is known to be one of the faster growing oak species (Filer 1990).

Bud Diameter and Structure

Mockernut hickory and black walnut have the largest buds of the species sampled (Figures 12 and 13). Nuttall oaks and red maples have the smallest bud diameters statistically in both the dormant and the growing season. The determinate growth species are generally larger than the indeterminate growth species in both seasons.

Bud structure varies for each species. Some species, such as hickory, will have a single terminal bud. Other species, such as oak, can have several terminal buds emanating from the same point. When buds were broken using the impact tester, care was taken to only fracture the largest terminal buds on the terminal shoot. Oak buds may appear more fragile than the data indicates. Several terminal buds could serve as protection for interior buds. Having several buds allows the tree to continue terminal growth even if one or more of the exterior terminal buds are damaged or abraded. Species such as sweetgum without the cluster of terminal buds would not have this ability. If oak were growing adjacent to a sweetgum while both were abrading each other, over time oak would have the opportunity to elongate more.

Energy to Cause Bud Fracture

Mockernut hickory absorbed the most energy from the impact test before fracture occurred in both the dormant and growing season (Figures 14 and 15). In the dormant season, a clear pattern was not apparent between the energy required to fracture buds of determinate and indeterminate growth species. However, in the growing season, all determinate growth species required more energy than the indeterminate species statistically, except for the Nuttall oak. In the growing season, all the oaks are statistically the same in terms of toughness, excluding Nuttall oak.

Most indeterminates, such as red maple and yellow-poplar, were forming buds in the growing season, but the buds varied in size and most were undergoing elongation. Buds of American sycamore were minimal and not apparent during the growing season sampling period and thus were not sampled. The determinate species all had newly formed buds and showed no signs of elongation.

Relating Bud Collar Diameter to Toughness

Not all species sampled in this study were collected in both seasons. For species collected in both seasons, all R^2 values changed between those seasons. Red maple and sweetgum had the most change. Red maple in the dormant season exhibited no relationship between toughness and bud collar diameter (Figure 16). Only 6.5 percent of the variation in energy could be explained by bud collar diameter. The growing season data that bud collar diameter explained 50.9 percent of the variation in bud toughness (Figure 17). Alternatively, sweetgum dropped from a fairly strong positive relationship (79.5 percent) between energy and bud collar diameter in the dormant season, to almost no relationship (9.7 percent) in the growing season (Figures 21 and

22). Bud collar diameter should not be used to explain the seasonal variation in toughness for red maple and sweetgum.

For every species collected in both seasons, observations for both the energy and the diameter of the bud collar were more tightly clustered than the observations from the dormant season (Figures 16-31). The standard error for either bud fracture energy or collar diameter, and in some cases both, decreased from dormant season to growing season (Tables 2 and 3).

Bud Toughness to Diameter Ratio

Mockernut hickory had the largest diameter buds and those buds required the most energy for fracture. In the dormant season, the ratio of mean energy required for bud fracture to mean bud collar diameter for hickory was about 1:1 (Figure 32). The ratio of all species that were sampled in both seasons decreased from winter to summer except red maple and Nuttall oak. These two species slightly increased. The species that decreased the most between seasons had sustained growth buds (indeterminate), resulting in larger buds that required less energy to fracture.

TREE SWAY ACCELERATION

Results - Acceleration

Mean acceleration on each axis was significantly different between seasons within the 0 to 8.1, 16.2 to 24.1 and 16.2 to 32.2 KPH wind categories (p=.001) (Tables 4-6). On each axis, the 8.2 to 16.1 KPH categories were not different between seasons (p=.999). The growing season was consistently greater in mean acceleration for all wind categories. Within seasons, the mean acceleration did not show a clear pattern between wind speeds because of variations in wind gusts (Table 7). The standard deviation did, however, show a steady increase as wind speed increases for each season on every axis. Data in the growing season had higher deviations from the mean at lower wind speeds, as compared to the dormant season data. On every axis, the 16.2 to 32.2 KPH wind speed during the growing season has three times the deviation compared to the dormant season.

Maximum acceleration during dormant and growing seasons increased as wind gusts increased (Table 8). The Z-axis experienced the most acceleration in almost all wind categories for both seasons. As wind gusts increased in the dormant season, the rate of change in acceleration fluctuated. During the growing season, rate of change in acceleration was more consistent (Table 9).

Figures 33 and 34 present branch acceleration information for wind gusts. Figures 35-46 are energy maps using branch acceleration information by X- and Z-axis. Figures 47-52 use standardized branch acceleration from the dormant and growing season on the X-, Y- or Z-axis.

Table 4: Mean branch acceleration and standard deviation of Nuttall oak in southeast Tennessee, 2011, for each wind speed category during the dormant and growing seasons for the X-axis. Observations were averaged every ten counts to obtain per second measurements. Wind events above 32.2 KPH (kilometers per hour) were not captured in the growing season.

Wind Speed	Dormant Season			Growing Season		
	n	Mean (G)	Standard Deviation	n	Mean (G)	Standard Deviation
0-8.1	99	0.008	0.005	298	0.012	0.007
8.2-16.1	480	0.008	0.006	480	0.041	0.012
16.2-24.1	180	0.121	0.005	415	0.074	0.045
24.2-32.2	480	0.009	0.013	157	0.321	0.030
32.3-40.2	414	0.136	0.017	-	-	-
40.3-48.3	419	0.038	0.020	-	-	-
48.4-56.3	117	0.143	0.024	-	-	-
56.4-64.4	180	0.078	0.026	-	-	-

Table 5: Mean branch acceleration and standard deviation of Nuttall oak in southeast Tennessee, 2011, for each wind speed category during the dormant and growing seasons for the Y-axis. Observations were averaged every ten counts to obtain per second measurements. Wind events above 32.2 KPH (kilometers per hour) were not captured in the growing season.

Wind Speed	Dormant Season			Growing Season		
	n	Mean (G)	Standard Deviation	n	Mean (G)	Standard Deviation
0-8.1	99	0.214	0.004	298	0.522	0.008
8.2-16.1	480	0.216	0.004	480	0.364	0.008
16.2-24.1	180	0.450	0.004	415	0.835	0.024
24.2-32.2	480	0.674	0.010	157	0.313	0.031
32.3-40.2	414	0.370	0.010	-	-	-
40.3-48.3	419	0.477	0.008	-	-	-
48.4-56.3	117	0.361	0.011	-	-	-
56.4-64.4	180	0.462	0.015	-	-	-

Table 6: Mean branch acceleration and standard deviation of Nuttall oak in southeast Tennessee, 2011, for each wind speed category during the dormant and growing seasons for the Z-axis. Observations were averaged every ten counts to obtain per second measurements. Wind events above 32.2 KPH (kilometers per hour) were not captured in the growing season.

Wind Speed	Dormant Season			Growing Season		
	n	Mean (G)	Standard Deviation	n	Mean (G)	Standard Deviation
0-8.1	99	0.955	0.0041	298	0.741	0.0138
8.2-16.1	480	0.958	0.0062	480	0.816	0.0076
16.2-24.1	180	0.851	0.0058	415	0.789	0.026
24.2-32.2	480	0.767	0.0121	157	0.844	0.0347
32.3-40.2	414	0.948	0.0166	-	-	-
40.3-48.3	419	0.866	0.0122	-	-	-
48.4-56.3	117	0.953	0.0248	-	-	-
56.4-64.4	180	0.82	0.0301	-	-	-

Table 7: Mean vector branch acceleration of Nuttall oak in southeast Tennessee, 2011, for each wind speed category during the dormant and growing seasons for the Z-axis. Observations were averaged every ten counts to obtain per second measurements. Wind events above 32.2 KPH (kilometers per hour) were not captured in the growing season.

Wind Speed	Dormant Season Mean Vector (G)	Growing Season Mean Vector (G)
0-8.1	0.958	0.821
8.2-16.1	0.964	0.800
16.2-24.1	0.941	1.325
24.2-32.2	1.043	0.913
32.3-40.2	1.054	-
40.3-48.3	0.979	-
48.4-56.3	1.059	-
56.4-64.4	0.892	-

Table 8: Maximum branch acceleration (G) from all Nuttall oak data within each wind gust category for the X, Y and Z axes during the dormant and the growing seasons for the crown abrasion study, Tennessee, 2011. Wind speed categories are given in kilometers per hour (KPH). Wind gust events above 32.2 KPH were not captured in the growing season.

	Dormant Season			Growing Season		
KPH	**X**	**Y**	**Z**	**X**	**Y**	**Z**
0-8.1	0.02	0.06	0.07	0.143	0.078	0.189
8.2-16.1	0.19	0.09	0.24	0.223	0.169	0.436
16.2-24.1	0.24	0.09	0.25	0.454	0.325	0.917
24.2-32.2	0.62	0.24	0.79	0.99	0.68	1.62
32.3-40.2	1.317	0.398	0.883	-	-	-
40.3-48.3	1.321	0.62	1.38	-	-	-
48.4-56.3	1.499	0.648	1.831	-	-	-
56.4-64.4	1.394	0.571	2.105	-	-	-

Table 9: Rate of change of maximum branch acceleration (G) from all Nuttall oak data within each wind gust category for the X, Y and Z axes during the dormant and the growing seasons for the crown abrasion study, Tennessee, 2011. Wind speed categories are given in kilometers per hour (KPH). Wind gust events above 32.2 KPH were not captured in the growing season.

	Dormant Season			Growing Season		
KPH	**X**	**Y**	**Z**	**X**	**Y**	**Z**
0-8.1	-	-	-	-	-	-
8.2-16.1	912%	57%	225%	56%	117%	131%
16.2-24.1	32%	-3%	5%	104%	92%	110%
24.2-32.2	154%	178%	215%	119%	108%	77%
32.3-40.2	113%	69%	11%	-	-	-
40.3-48.3	0%	56%	56%	-	-	-
48.4-56.3	13%	5%	33%	-	-	-
56.4-64.4	-7%	-12%	15%	-	-	-

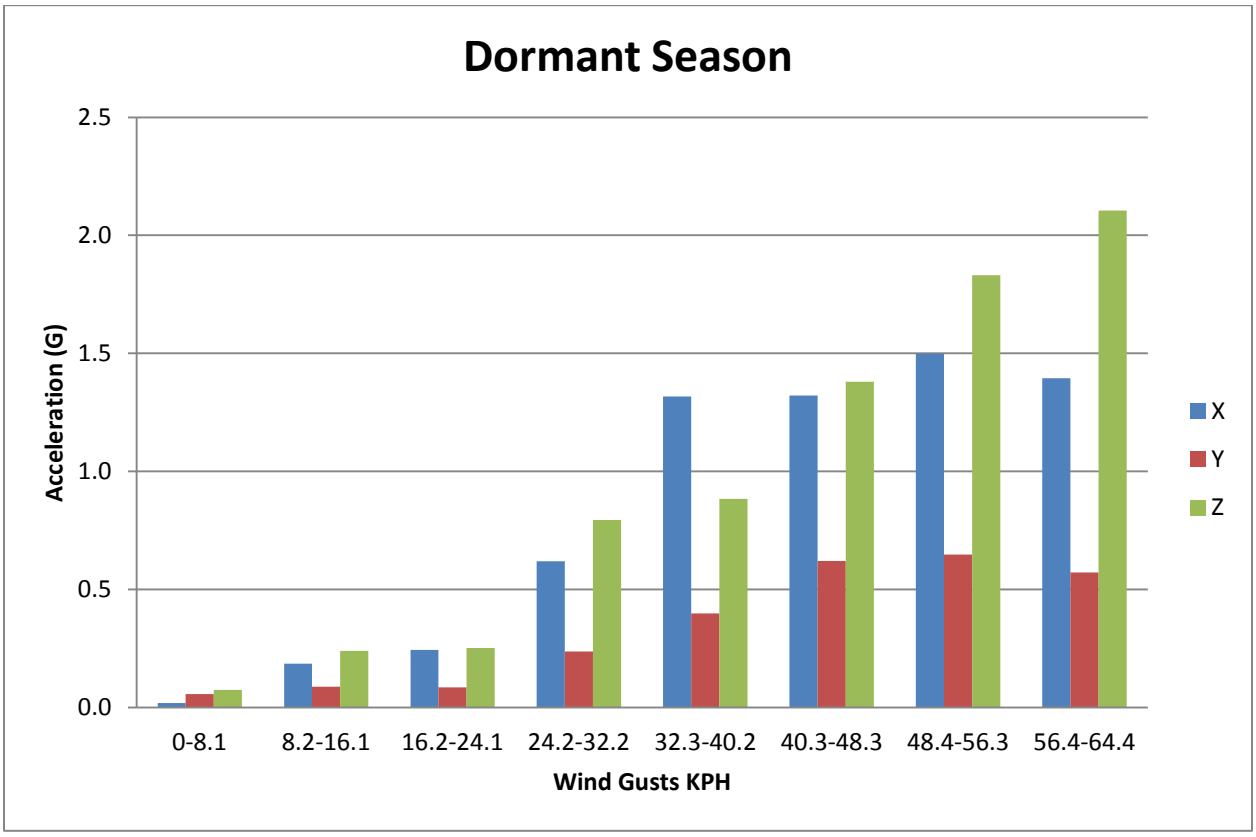

Figure 33: Dormant season branch acceleration (G) for Nuttall oak as a function of maximum wind gusts for the crown abrasion study, Tennessee, 2011. Maximum acceleration was analyzed from all accelerometers at the time of the wind events.

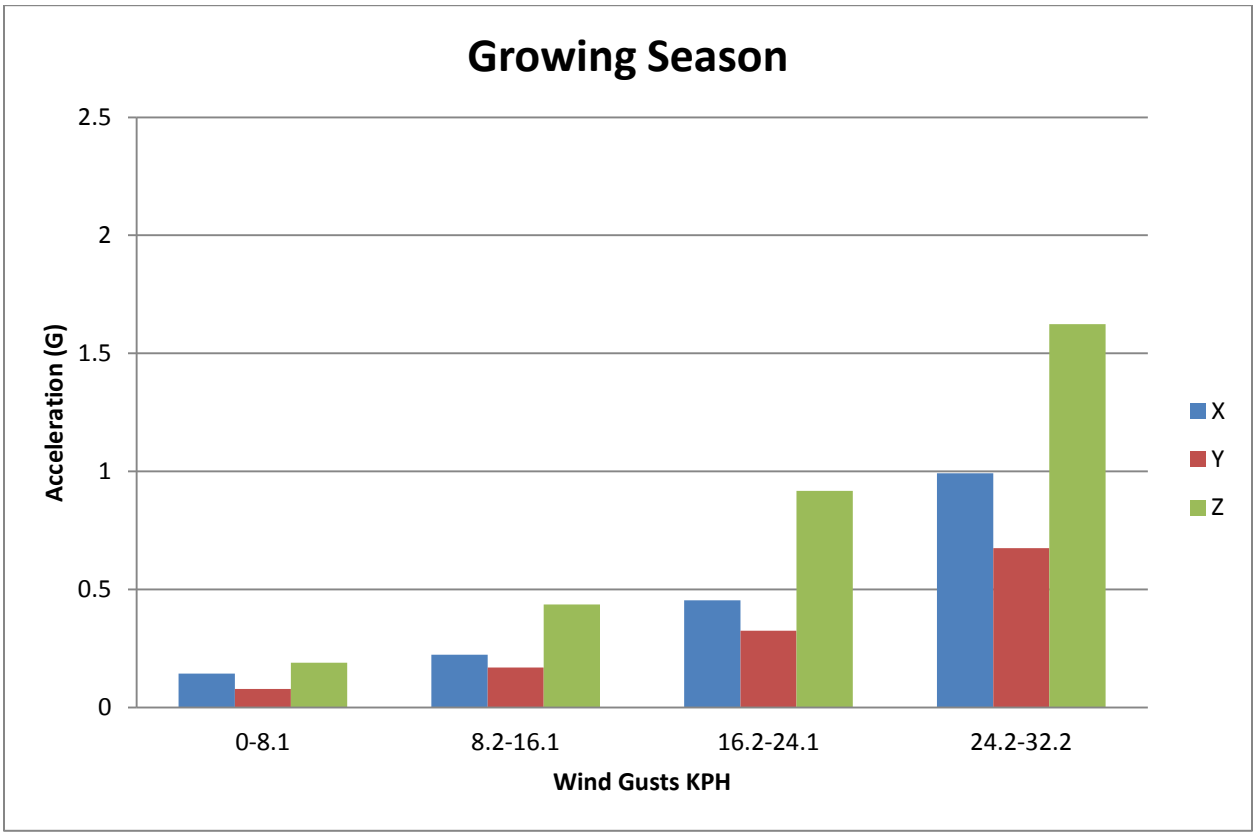

Figure 34: Growing season branch acceleration (G) for Nuttall oak as a function of maximum wind gusts for the crown abrasion study, Tennessee, 2011. Maximum acceleration was analyzed from all accelerometers at the time of the wind events.

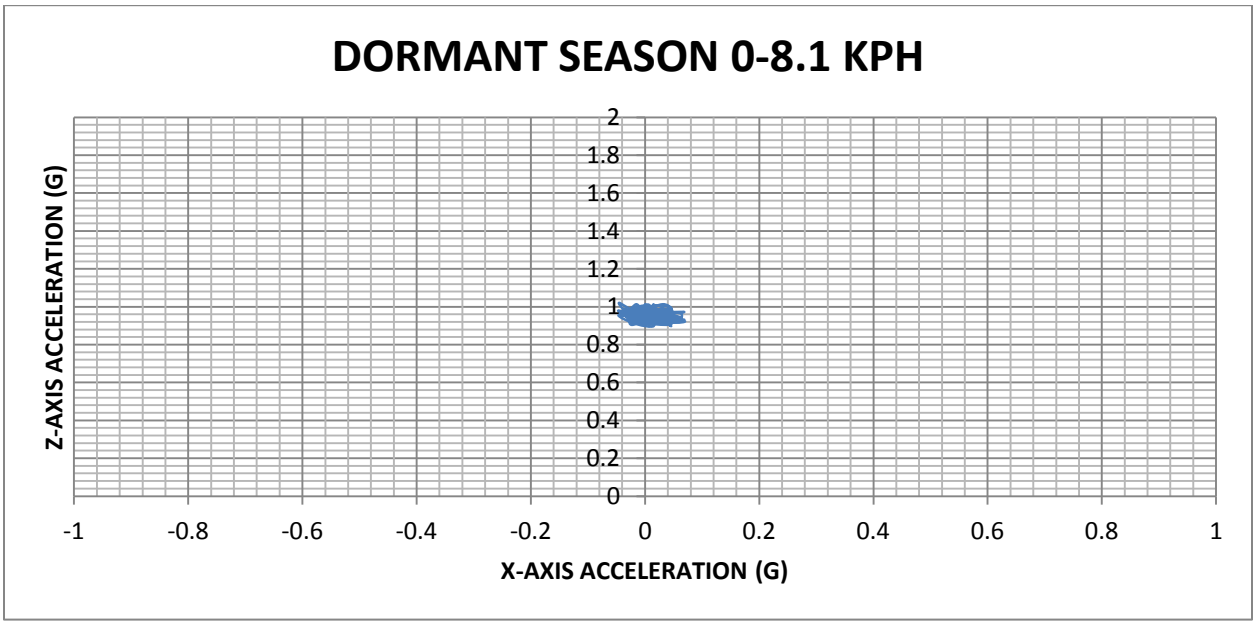

Figure 35: Dormant season Nuttall oak branch acceleration on the Z-axis as a function of acceleration on the X-axis for the crown abrasion study, Tennessee, 2011. Acceleration is taken from the 0 to 8.1 KPH wind gust category.

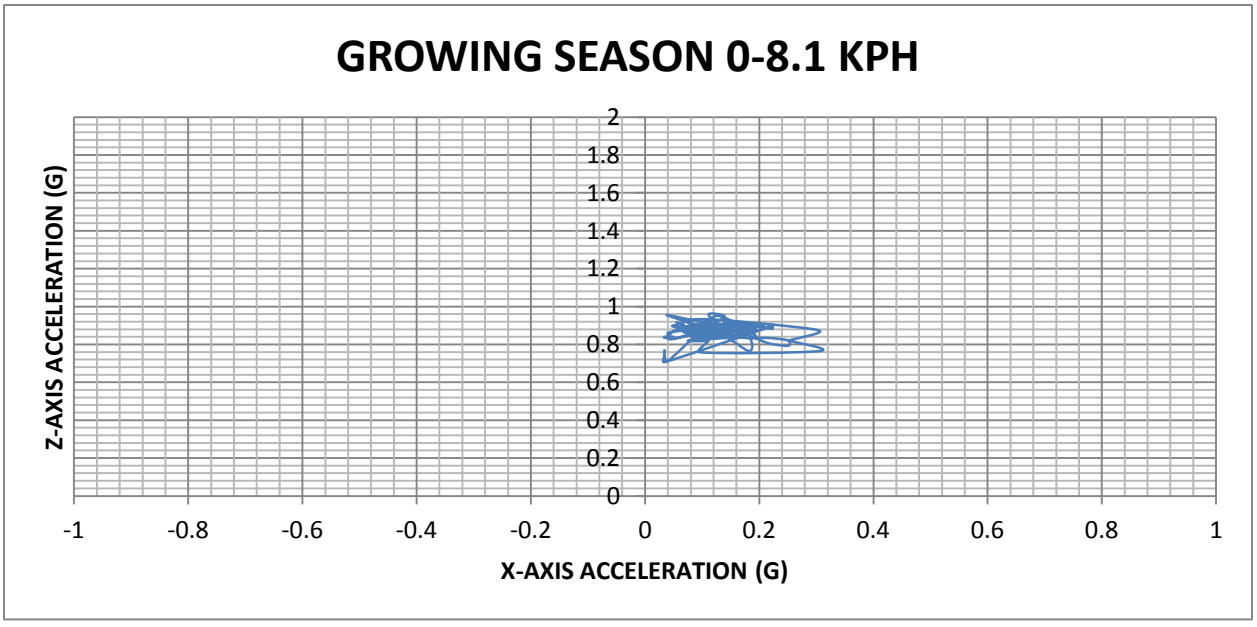

Figure 36: Growing season Nuttall oak branch acceleration on the Z-axis as a function of acceleration on the X-axis for the crown abrasion study, Tennessee, 2011. Acceleration is taken from the 0 to 8.1 KPH wind gust category.

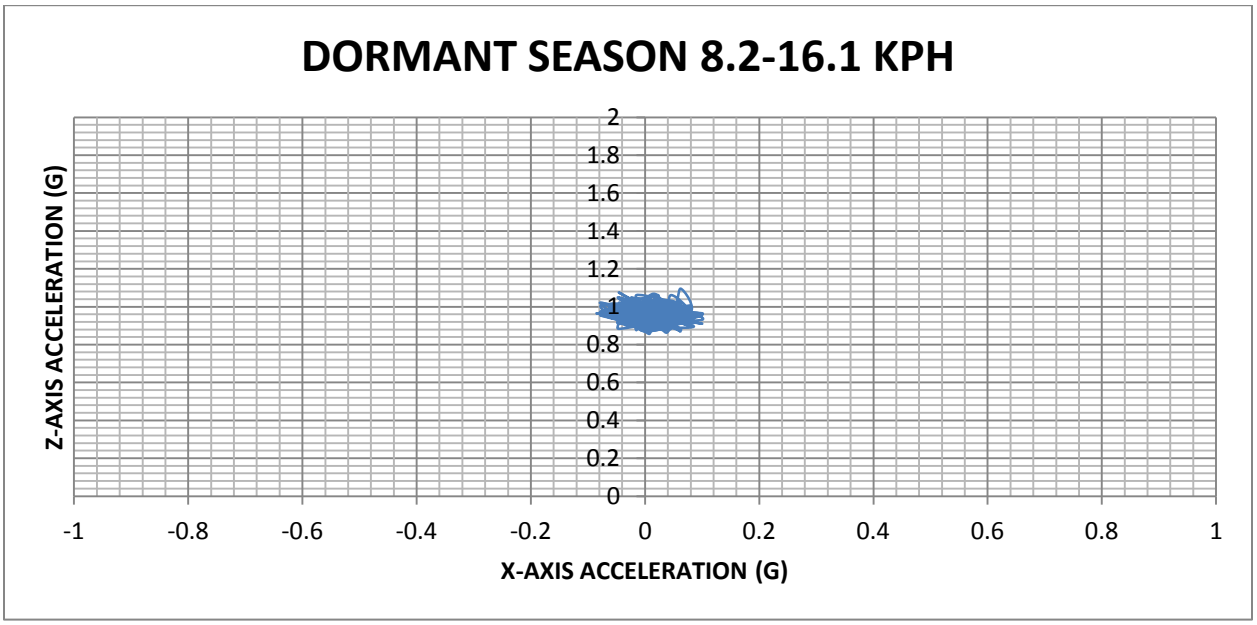

Figure 37: Dormant season Nuttall oak branch acceleration on the Z-axis as a function of acceleration on the X-axis for the crown abrasion study, Tennessee, 2011. Acceleration is taken from the 8.2 to 16.1 KPH wind gust category.

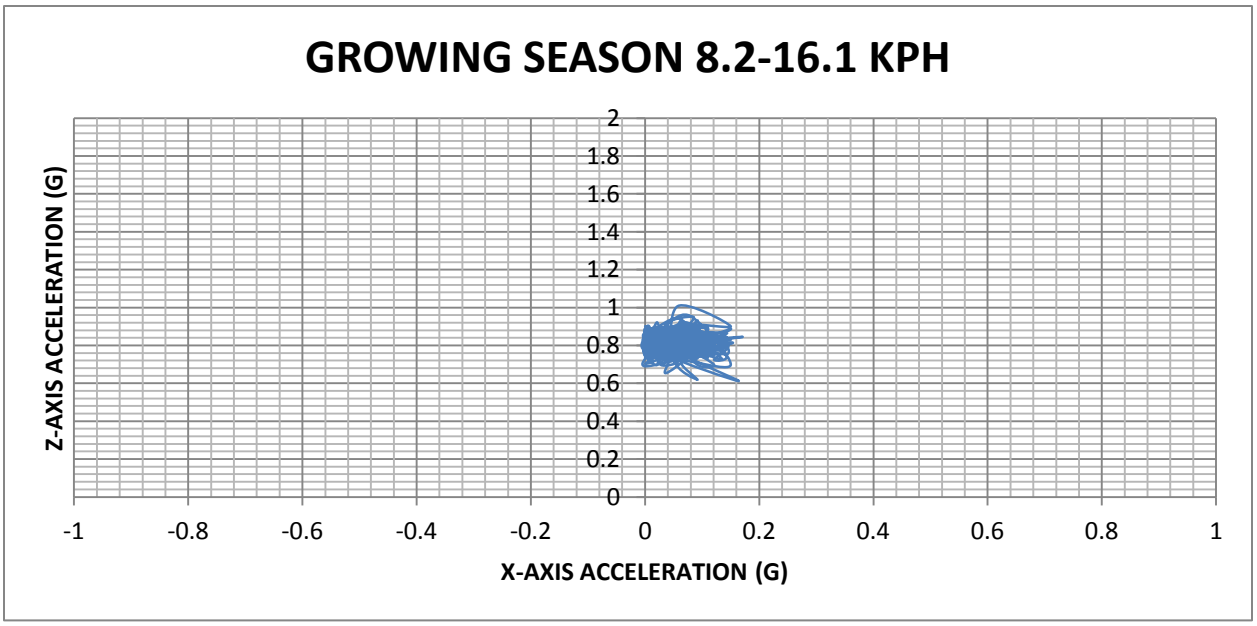

Figure 38: Growing season Nuttall oak branch acceleration on the Z-axis as a function of acceleration on the X-axis for the crown abrasion study, Tennessee, 2011. Acceleration is taken from the 8.2 to 16.1 KPH wind gust category.

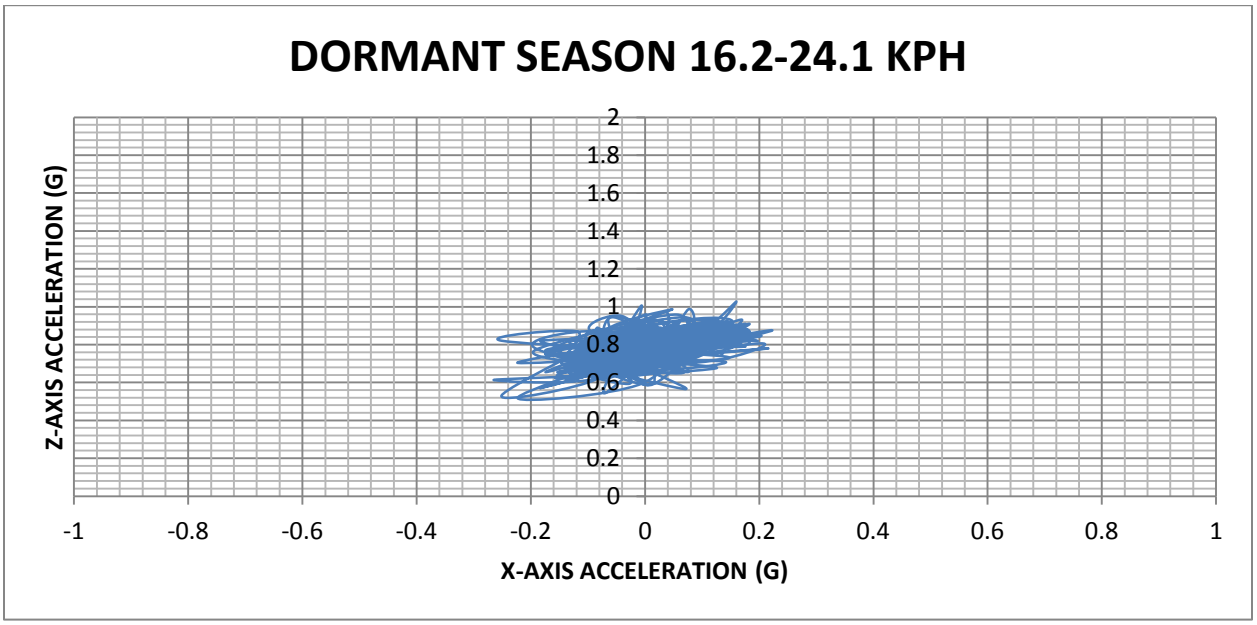

Figure 39: Dormant season Nuttall oak branch acceleration on the Z-axis as a function of acceleration on the X-axis for the crown abrasion study, Tennessee, 2011. Acceleration is taken from the 16.2 to 24.1 KPH wind gust category.

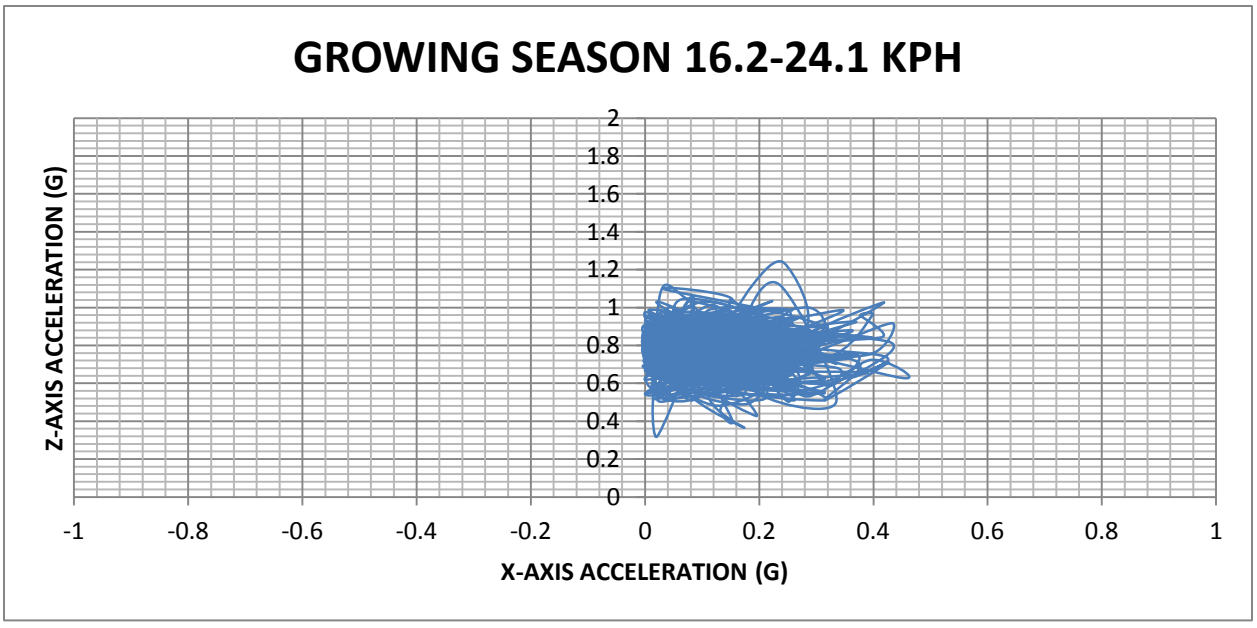

Figure 40: Growing season Nuttall oak branch acceleration on the Z-axis as a function of acceleration on the X-axis for the crown abrasion study, Tennessee, 2011. Acceleration is taken from the 16.2 to 24.1 KPH wind gust category.

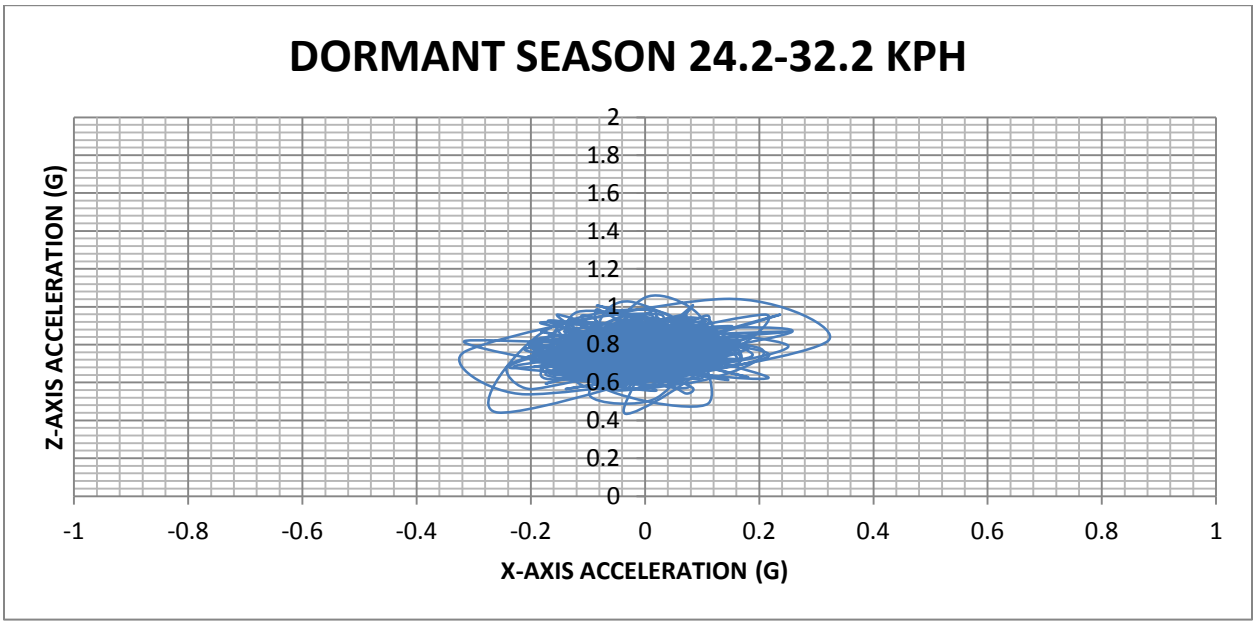

Figure 41: Dormant season Nuttall oak branch acceleration on the Z-axis as a function of acceleration on the X-axis for the crown abrasion study, Tennessee, 2011. Acceleration is taken from the 16.2 to 32.2 KPH wind gust category.

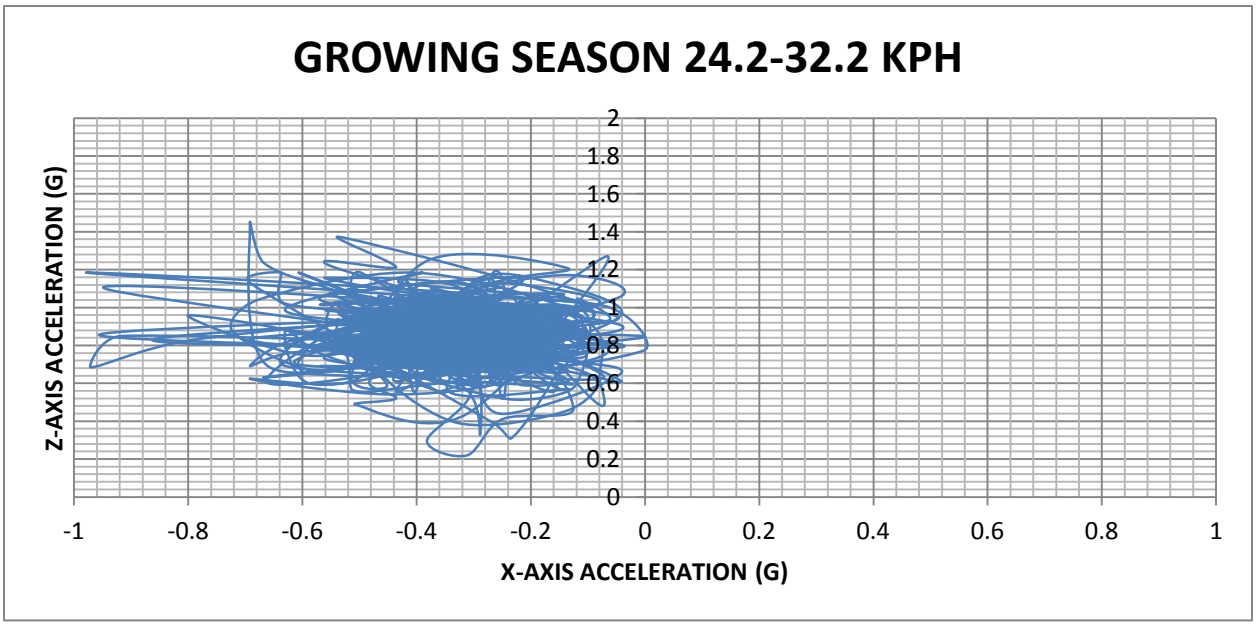

Figure 42: Growing season Nuttall oak branch acceleration on the Z-axis as a function of acceleration on the X-axis for the crown abrasion study, Tennessee, 2011. Acceleration is taken from the 16.2 to 32.2 KPH wind gust category.

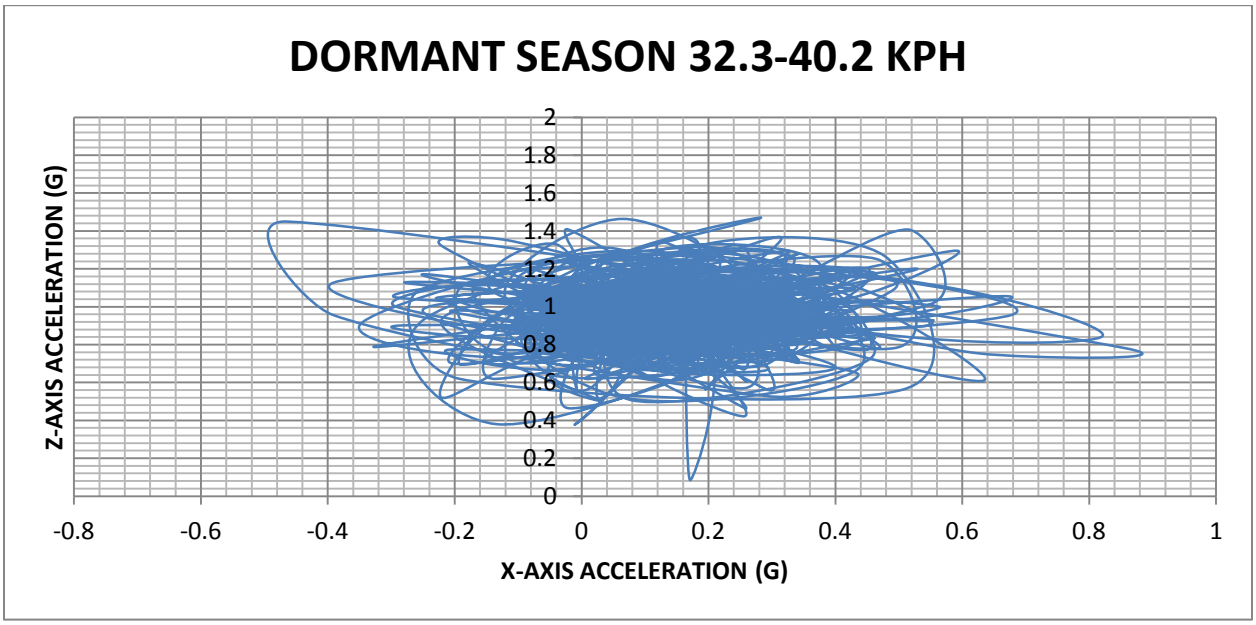

Figure 43: Dormant season Nuttall oak branch acceleration on the Z-axis as a function of acceleration on the X-axis for the crown abrasion study, Tennessee, 2011. Acceleration is taken from the 32.3 to 40.2 KPH wind gust category.

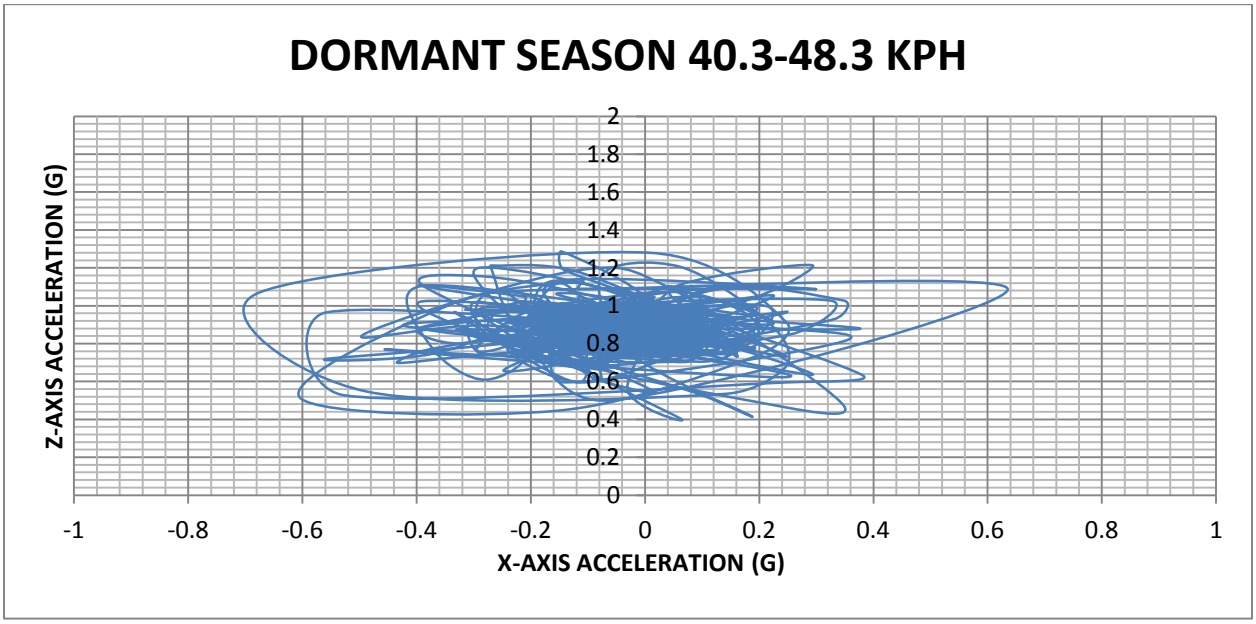

Figure 44: Dormant season Nuttall oak branch acceleration on the Z-axis as a function of acceleration on the X-axis for the crown abrasion study, Tennessee, 2011. Acceleration is taken from the 40.3 to 48.3 KPH wind gust category.

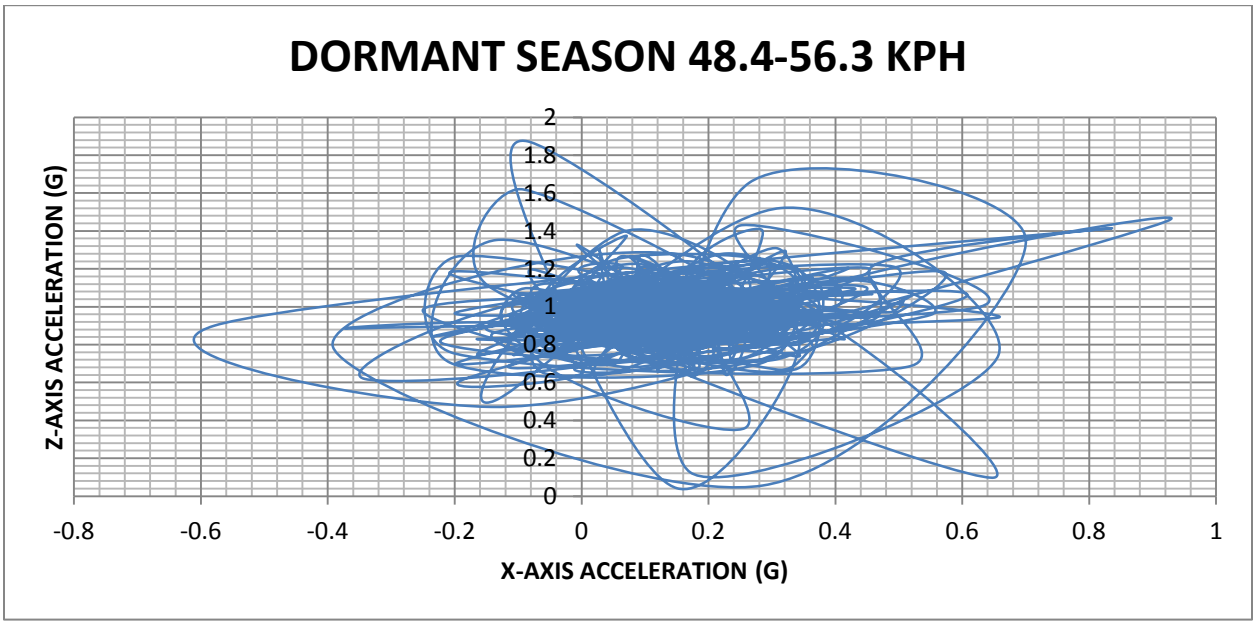

Figure 45: Dormant season Nuttall oak branch acceleration on the Z-axis as a function of acceleration on the X-axis for the crown abrasion study, Tennessee, 2011. Acceleration is taken from the 48.4 to 56.3 KPH wind gust category.

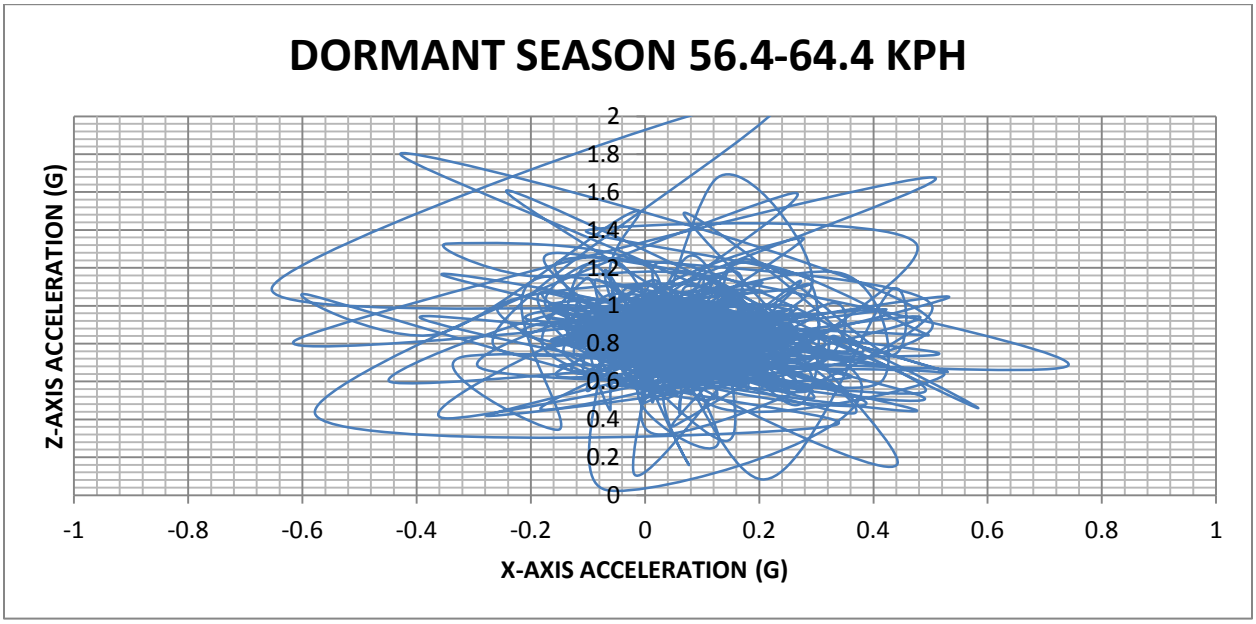

Figure 46: Dormant season Nuttall oak branch acceleration on the Z-axis as a function of acceleration on the X-axis for the crown abrasion study, Tennessee, 2011. Acceleration is taken from the 56.4 to 64.4 KPH wind gust category.

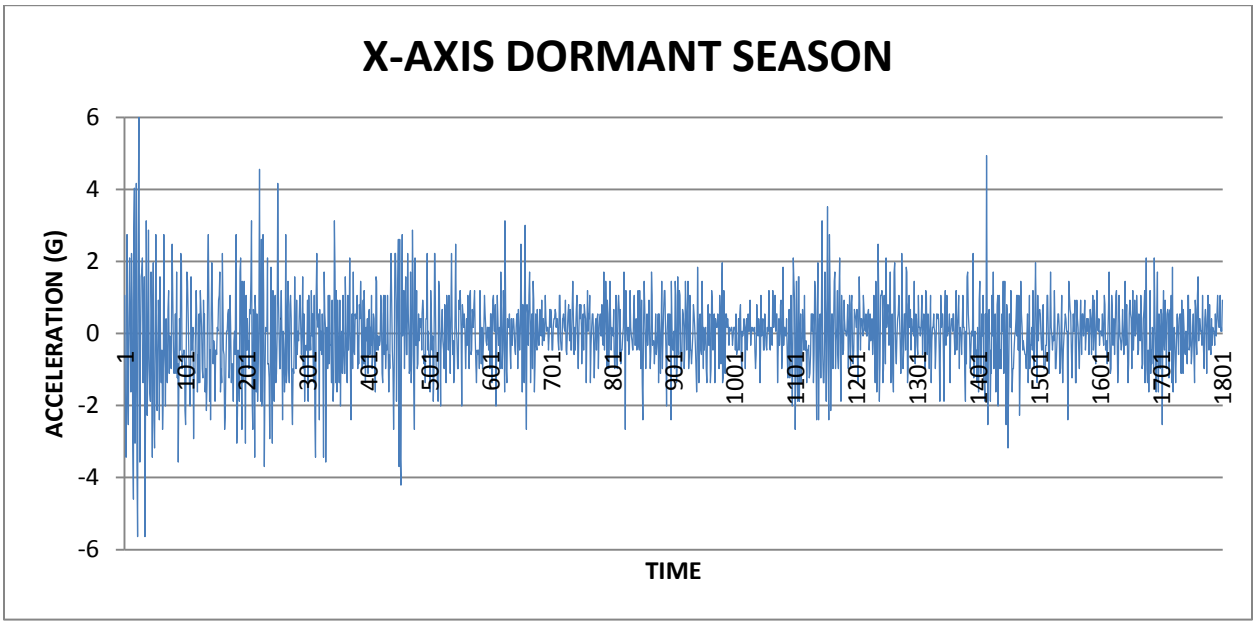

Figure 47: Standardized dormant season Nuttall oak branch acceleration on the X-axis as a function of time from the 16.2 to 32.2 KPH wind gust category for the crown abrasion study, Tennessee, 2011. Data were recorded at 10 observations a second. Time represents observations.

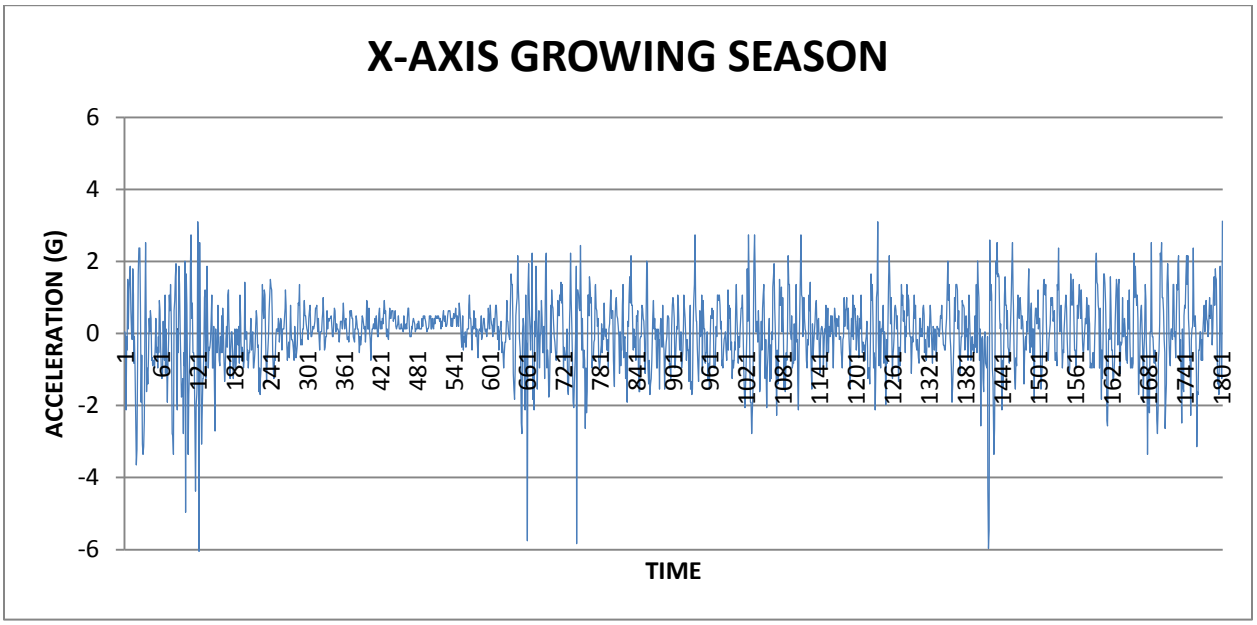

Figure 48: Standardized growing season Nuttall oak branch acceleration on the X-axis as a function of time from the 16.2 to 32.2 KPH wind gust category for the crown abrasion study, Tennessee, 2011. Data were recorded at 10 observations a second. Time represents observations.

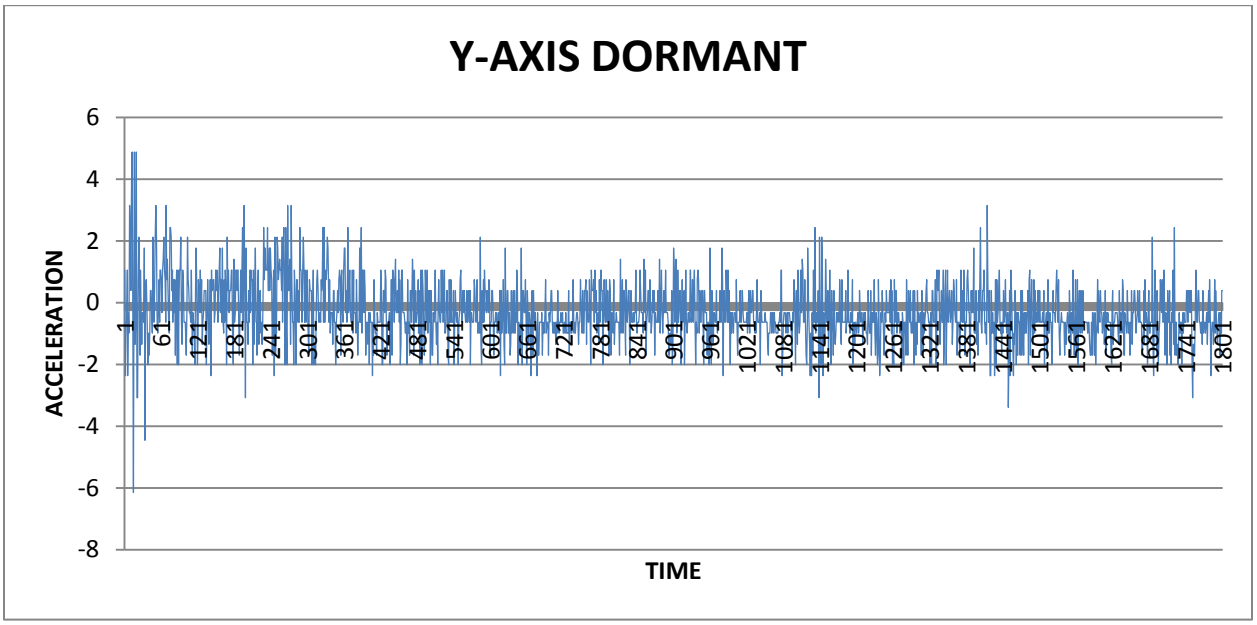

Figure 49: Standardized dormant season Nuttall oak branch acceleration on the Y-axis as a function of time from the 16.2 to 32.2 KPH wind gust category for the crown abrasion study, Tennessee, 2011. Data were recorded at 10 observations a second. Time represents observations.

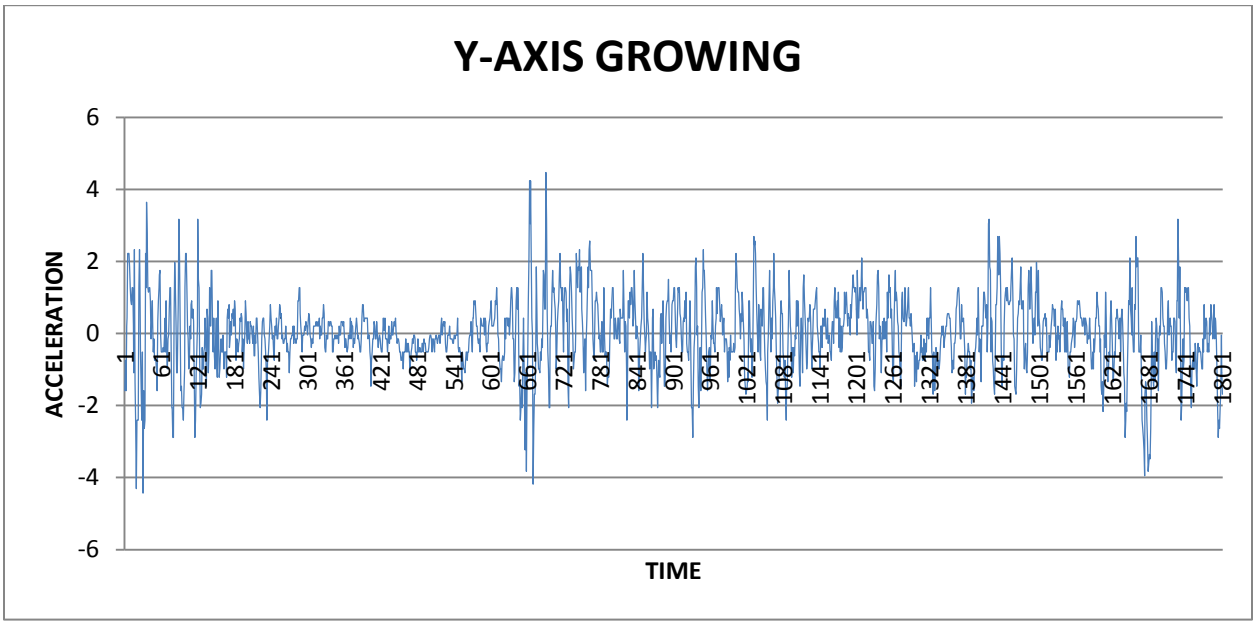

Figure 50: Standardized growing season Nuttall oak branch acceleration on the Y-axis as a function of time from the 16.2 to 32.2 KPH wind gust category for the crown abrasion study, Tennessee, 2011. Data were recorded at 10 observations a second. Time represents observations.

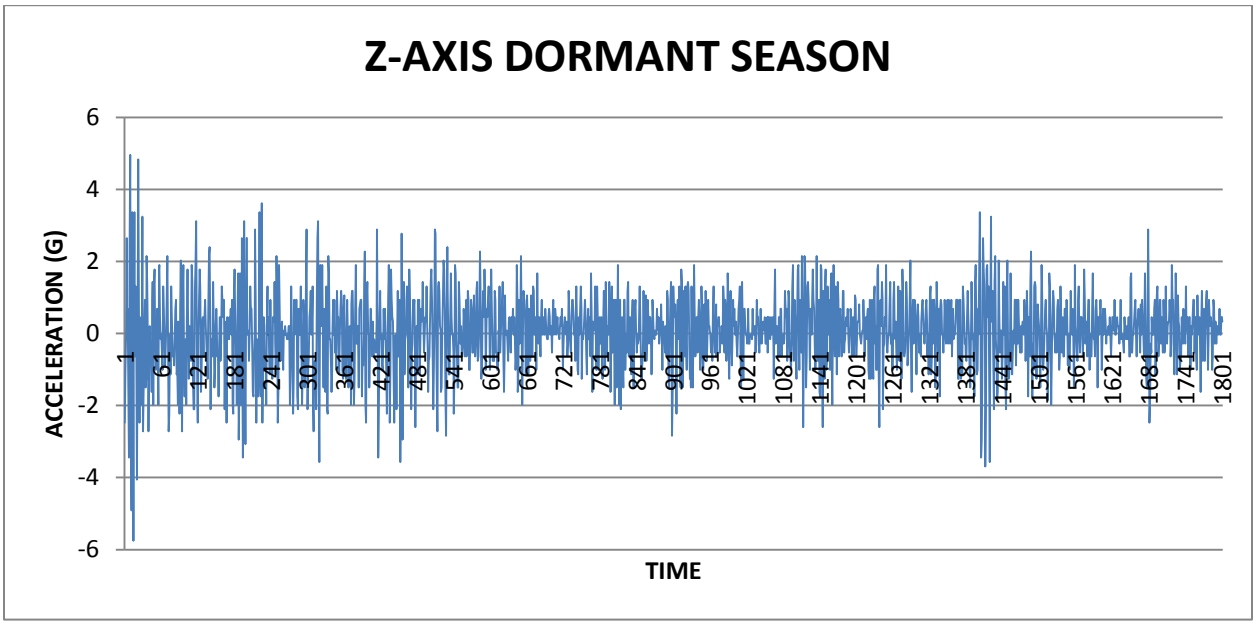

Figure 51: Standardized dormant season Nuttall oak branch acceleration on the Z-axis as a function of time from the 16.2 to 32.2 KPH wind gust category for the crown abrasion study, Tennessee, 2011. Data were recorded at 10 observations a second. Time represents observations.

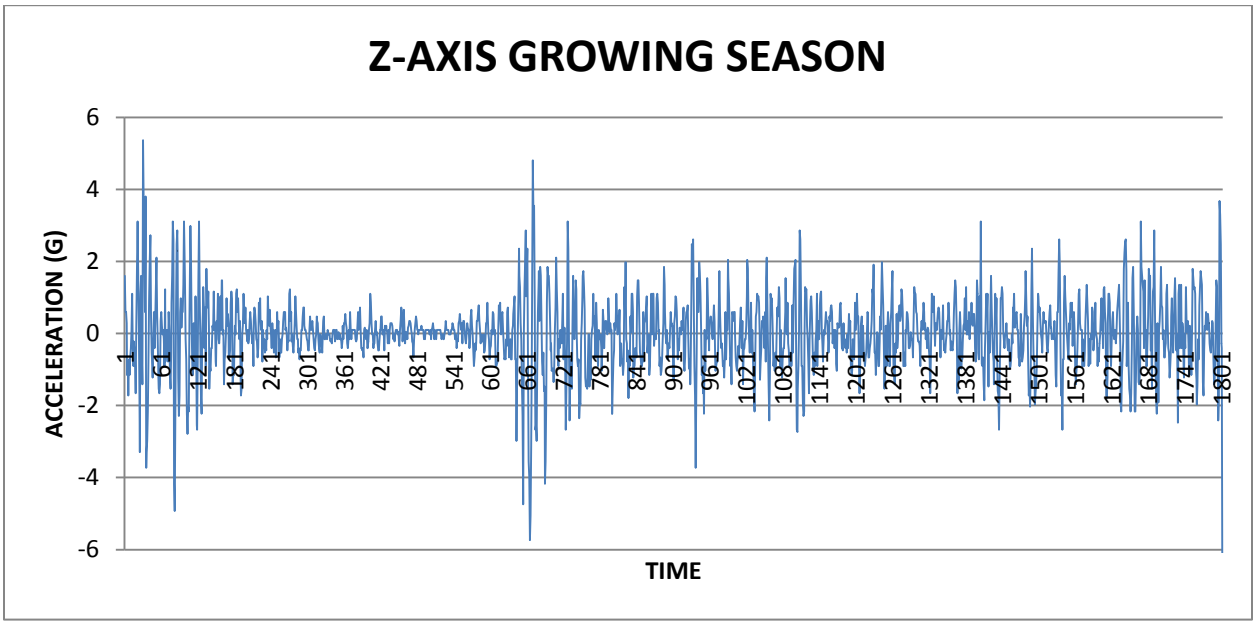

Figure 52: Standardized growing season Nuttall oak branch acceleration on the Z-axis as a function of time from the 16.2 to 32.2 KPH wind gust category for the crown abrasion study, Tennessee, 2011. Data were recorded at 10 observations a second. Time represents observations.

Results - Force

Mockernut hickory required the most force to cause bud failure at around 0.19N (Table 10). Black walnut also required a large amount of force before failure occurred at around 0.1N. The sustained growth species had a lower minimal force mean than the preformed growth species. Nuttall oak, a fast-growing bottomland oak with preformed buds had a mean minimal force at around 0.01N, similar to those species with sustained growth.

Table 10: Growing season mean minimal force for bud break in Newtons (N) for each species for the crown abrasion study, Tennessee, 2011. Maximum possible force (N) was calculated for each kilometers per hour wind speed category. Red values represent force at which bud failure is possible. Species without data were not included in the analysis. Asterisk (*) is considered preformed bud growth form.

		Estimated Force Possible (N)			
		Wind Categories			
Species	Minimal Force (N)	0-8.1	8.2-16.1	16.2-24.1	24.2-32.2
Acer rubrum	0.021	0.001	0.002	0.004	0.008
*Carya tomentosa**	0.187	0.044	0.101	0.212	0.375
*Juglans nigra**	0.104	0.016	0.037	0.077	0.136
Liquidambar styraciflua	0.031	0.005	0.012	0.026	0.046
Liriodendron tulipifera	0.022	0.011	0.025	0.052	0.092
Platanus occidentalis	-	-	-	-	-
*Quercus alba**	0.056	0.002	0.004	0.008	0.015
*Quercus falcata**	0.043	0.003	0.007	0.016	0.028
*Quercus rubra**	0.060	0.008	0.017	0.037	0.065
*Quercus texana**	0.012	0.002	0.004	0.008	0.015

The lowest wind speed category yields no force that is powerful enough to cause breakage. In the wind speed category of 8.2 to 16.1 KPH, yellow-poplar begins to move at forces that cause bud failure. At 16.2 to 24.1 KPH, mockernut hickory began to experience enough force to also cause mechanical failure. At 24.2 to 32.2 KPH in the growing season, most all species can expect to see bud failures except for southern red oak, white oak and red maple.

Discussion

The hypothesis that crown movements would display more acceleration in the growing season than in the dormant season was supported by the accelerometer data for each axis. However, the maximum acceleration that occurred during wind gusts in the growing and dormant seasons was probably a more effective measure of branch movement than the mean acceleration within each wind speed category. Most acceleration occurred in small bursts and was negated by using the mean.

Wind Speed and Acceleration

Most wind events are a result of differences in temperatures across a large area land, often arriving with cold fronts (Henson 2007). Wind is a force that is not constant, nor is it consistent. The data collected in this case study suggests that wind speed had a heavy influence on maximum accelerations, but not on mean accelerations. Large accelerations were masked among several smaller accelerations once the mean was calculated, even in the mean vector calculations where all three axes were included (Table 7).

The gravity of the earth causes the accelerometer to give a constant reading of 1.00G when an axis is level. The branch orientation differed on every axis of every measurement device, resulting in inconsistent baseline readings. Each branch tested would tend to return from

its displacement to a place of rest, even in a steady wind could have also caused mean accelerations for the three axes not to be representative of what happened on the branch.

The X- and Z-axis were the two axes that experienced the most movement because they represented left and right, and up and down movements respectively. The Y-axis was limited by the forward and back movement of the stem of the tree. Although there was some acceleration on the Y-axis, a taller tree would experience a greater amount of sway.

Acceleration during Wind Gusts

Seasonality illustrated differences in tree movement with leaves on and off. During the dormant season, accelerations increased more sharply when wind speeds were more than 24.1 KPH. At less than 24.1 KPH, 0.25G or less were recorded. At 32.2 KPH, accelerations were over 1.3G. Between 56.4 and 64.4 KPH, accelerations almost doubled to 2.1G (Figure 33). During the growing season, acceleration increased more steadily during the dormant season (Figure 34). Growing season wind speed of 16.2 to 24.1 KPH had accelerations near 1.0G, which did not occur in the dormant season until winds reached 32.3 to 40.2 KPH. With winds of 16.2 to 32.2 KPH during the growing season, acceleration doubled that found in the dormant season. Leaf-on growing season acceleration caused the crown to be more affected by wind because of the extra drag and mass produced by the leaf cover.

Wind gusts produced the greatest branch acceleration. Crown abrasion would likely occur if there were friction from low wind speeds between branches for an extended period of time, causing minor damage, followed by a large gust which could mechanically abrade the weaker branch.

Energy Maps and Seasonality

Seasonality influenced the energy patterns of the branches. The location of mean clusters is not of great consequence because of the differences in branch orientation. In the 0- to 8.1-

KPH wind category, a small divergence appears between the two energy maps (Figures 35 and 36). Both maps have the same area, but the growing season map has traces of energy that loop from the cluster. Even in low wind gusts, more dramatic energy occurs during growing season. In the 8.2 to 16.1 KPH category, the energy pattern demonstrates the same configuration as both maps have the same cluster size with growing season looping away from the cluster (Figures 37 and 38). Wind gusts of 16.2 to 24.1 KPH show the same pattern as previous wind gusts, but the energy in the growing season does not occur on the left side of cluster (Figures 39 and 40). A drastic cutoff such as this could take place from the branch being physically stopped (colliding) by an adjacent branch or by a recording error produced by the accelerometer as a result of water damage. Gusts of 16.2 to 32.2 KPH offer the same energy arrangement of more deviation from the mean cluster in the growing season than in the dormant season (Figures 41 and 42).

All the mean clusters of energy display more movement along the X-axis than the Z-axis until wind gusts reach 48.4 to 56.3 KPH (Figures 43-45). The acceleration on the Z-axis begins to approach two Gs but only in one instance did the accelerometer record a wind gust that caused drastic movement. Wind gusts in the 56.4 to 64.4 KPH category show extreme branch acceleration deviation from the mean cluster (Figure 46). These deviations are where the most branch damage would occur if two adjacent crowns were to abrade during wind movement.

Oscillations

Dewit and Reid (1992) observed that wind during the winter (dormant season) caused tree crowns to be displaced less, but more frequently, while summer winds caused greater displacement with less frequency. The findings in this case study are similar. On the X-axis, standardization of the data across time shows varying oscillations between dormant and growing seasons (Figures 47 and 48). During the dormant season, the period is shorter than during the growing season. The waves in the dormant season are narrow because the wind is moving the

branch a small amount and the branch is quickly returning to its neutral state. Alternatively, the growing season waves are more stretched as it takes longer for the branch to complete its movement. The leaf mass is catching more wind. When comparing the amplitude of the two seasons, the growing season acceleration is consistently larger than during the dormant season. These patterns also appear on the Y- and Z-axis (Figures 49-52). Crown abrasion is probably more prevalent in the growing season as branches of competing trees oscillate with greater accelerations.

Potential for Crown Abrasion

The estimated maximum possible force was calculated for each wind speed category for each species. Mass and acceleration are the two factors that dictate force. Although the bud of mockernut hickory is the toughest of the species sampled, mockernut hickory is the first of the preformed species to experience enough force to cause a bud to break (Table 10). The breakage is attributed to the greater mass of hickory buds. At the highest wind speed category recorded in the growing season, only red maple, white oak and southern red oak cannot receive enough force to cause breakage probably because of the smaller bud mass.

Spring and summer storm fronts can easily create winds well above 32.2 KPH. The National Oceanic and Atmospheric Administration (NOAA) does not classify a storm as "severe" until it reaches winds of at least 93.3 KPH. During calm weather periods when branch elongation is rapid, particularly in early growing season, crowns may have the opportunity to overlap before the next wind event arrives. Accelerometers were not placed at the tips of branches and because of this, all force calculations can be considered conservative. Greater movement and acceleration would be expected at the end of the branch. Based on the results of this study, crown abrasion could occur during wind events if friction were present in the growing season.

CONCLUSION

Crown abrasion as a mechanism of stand development of mixed species stands has not been studied extensively and methodology has not been developed, especially in eastern deciduous hardwoods. Evidence from these three studies (analysis of branch elongation and buds, apical bud toughness and tree sway acceleration) corroborates that crown abrasion occurs and influences tree and stand development.

Branch Elongation and Bud Analysis

Crowns that are colliding with the crowns of neighbors can cause a branch elongation restriction. Abrasion that occurs at the apical buds restricts branch elongation. Growth disruption of branches occurred more on the interior side of trees (next to adjacent tree crowns) than the exterior edge where branches were free to growth and adjacent trees were not present to influence growth. This growth disruption occurred in all sampled stands and is a result in part of crown abrasion. Future research should consider the influence of crown dynamics in quantity and quality of sunlight received by the interior branches as well as abrasion in limiting crown expansion.

Interacting crowns of adjacent trees with different species and growth habits in mixed species stands experience crown abrasion. The crown abrasion process may be playing a critical role in stratification of slower growing, hardier and preformed bud species such as oaks into the upper canopy. Preformed growth species have the opportunity to abrade the sustained growth form species examined in this study under certain conditions. Once a preformed species, such as an oak, abrades a sustained growth form, such as sweetgum, the oak crown creates and utilizes more growing space for itself. If this process is repeated several times during a growing season

and occurred every year, then eventually a slower growing species could stratify above an initially faster growing species.

Apical Bud Toughness

The differences in bud toughness between growing and dormant seasons suggest that buds do not have the ability to absorb as much energy in the growing season as they do in the dormant season. The new growth of buds during the growing season is tenderer due to a higher moisture content, making them more susceptible to abrasion than the hardened, stout buds of the dormant season. Species with preformed buds and buds that occur in clusters tended to absorb more energy (tougher) than species with sustained growth buds. In general, all species decreased in bud collar diameter size after bud break and new growth began. Although there were various strong relationships for some species between bud collar diameter and bud toughness, this relationship was not consistent across all species and seasons.

Tree Sway Acceleration and Force

Branch movement was altered at various wind speeds and gusts between seasonality. Branch acceleration increasingly deviated from the mean as wind speeds increased. Wind gusts displayed differences in branch acceleration as the wind speed of gusts increased. With both mean acceleration and maximum acceleration, the growing season had a larger influence on acceleration as leaves created more drag. When the same wind speed was compared for the two seasons, the growing season wind created greater movement in the crown than occurred with dormant season.

The minimal force required for bud break was calculated during the growing season for several species using bud mass from the bud toughness study and acceleration from the tree sway acceleration study. As winds gust speeds increased, the amount of force that can occur on apical buds also increased. For most species, wind gust speeds of 24.2 to 32.2 KPH caused enough

force to cause an apical bud to break. In the spring, when new branch elongation and apical buds are tender, a strong storm can easily reach wind gusts well above 32.2 KPH. Generally, buds of sustained growth species break at a lower force than buds of the preformed growth species. Even though mockernut hickory had the most bud mass and required the greatest force to cause breakage, it was also one of the first of the preformed growth species to experience enough force to cause bud break. The breakage is attributed to the greater mass of the large hickory buds. White oak, southern red oak and red maple did not receive enough force, even at the highest wind category, to cause breakage due to smaller bud mass.

Implications

Few stand development studies have investigated how crown abrasion takes place and the mechanics associated with physical crown abrasion. This research through several studies elucidates that branch acceleration, bud toughness, bud mass and force varies for species, suggesting a wide range of stand development patterns are possible depending on species present. In addition to crown abrasion, other crown influences that impact stand development include differing crown forms and growth habits of various species. The present research provides baseline information and insight for developing working hypotheses and methodologies for further research of stand development processes and patterns in mixed species stands.

The strength of this research was investigating and evaluating various methodologies as an exploratory first step to describe and characterize crown abrasion. The methodology that provides the most physical evidence of crown abrasion was the branch analysis study. A more direct way to sample abrasion after wind events would be placing nets on the ground in both overstocked and understocked stands to collect vegetation from crown abrasion. Shortcomings of using nets are the understory would need to be relatively void of vegetation and the irregularity of wind events (unknown time periods) to monitor crown abrasion. The apical bud toughness and

tree sway acceleration studies are more controlled investigations describing the mechanical influences of the tree branches on abrasion.

Future research should include a greater species selection in the dormant season for conducting bud analyses and evaluating crown dynamics and branch movement. Better sampling and measurement of wind data could be accomplished by using automatic data loggers to capture every wind event that occurred. Increasing the number of trees used in a sample and placing accelerometers on branches in the interior of the stand would yield more robust information about crown growth and patterns of stand and crown development. Future studies should also have a tree physiology focus to better assess bud formation and growth as well as interactions between adjacent tree crowns for growing space.

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