EFFECT OF PRUNING TYPE, PRUNING DOSE, AND WIND SPEED ON TREE RESPONSE TO WIND LOAD

By

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To tree care professionals – in all their varieties.

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Three to four inch caliper, clonally propagated live oak trees (*Quercus virginiana* 'QVTIA' PP 11219, Highrise®) were used to test the effect of five pruning types and four pruning doses on trunk movement at four wind speeds. Pruning types evaluated were lion's tailing, raising, reduction, structural, and thinning. Pruning doses were 15, 30, 45, and 60 percent foliage dry mass removed. Wind speeds were 15, 30, 45, and 60 mph. Of the affects tested, wind speed had the greatest impact on trunk movement. However, interactions of wind speed with pruning type and wind speed with pruning dose were also significant. At high wind speeds, thinning did not reduce trunk movement as effectively as other pruning types. Trunk movement increased with each increase in wind speed for all pruning types except structural; for structural, differences in trunk movement were only significant between 15 mph and 60 mph wind speeds. Trunk movement also increased with each increase in wind speed when 15% or less of the foliage was removed. Removal of 30% to 45% foliage prevented increases in trunk movement until wind speeds reached 30 mph. Forty-five mph wind speeds were required to increase trunk movement when 60% foliage was removed. At low wind speeds, 15 mph or less, trunk movement was similar among all pruning types averaged across pruning doses, and across all pruning doses averaged across pruning types. Results indicate no pruning type effectively minimizes wind loads at currently recommended pruning doses.

CHAPTER 1
INTRODUCTION

Large landscape trees contribute an irreplaceable dimension to urban landscapes, but they also present a significant, yet oddly acceptable hazard. Large trees, weighing several thousand pounds, are often found hanging precariously over homes, roads, recreational areas and other frequently populated sites. Yet relatively little is known about their construction and less about their response to external loading. Some of the most damaging external loads trees confront include static loads generated by snow and ice accumulation and dynamic loads generated by strong winds. This investigation focused on tree response to loads generated by strong winds.

Wind storms often break and topple trees resulting in damaged property, interrupted utility service, and personal injury. Pruning is regularly recommended as a method of abating wind damage in trees. Data supporting that recommendation is scarce – largely because interactions between wind and trees are elaborate. Large trees are complex, dynamically built structures and wind is extremely variable in time and space. Small trees have therefore been used in generated wind fields to simplify the relationship for investigation.

This study investigated the use of pruning to reduce wind loads on young (5 to 6 year old), *Quercus virginiana*, live oak trees. Five common pruning practices were evaluated. Effects of pruning dose and wind speed were also included. Wind velocities were generated by an airboat elevated so the propeller was at canopy height. Results from this experimental study can be used by tree care professionals to better manage individual trees in our urban forests.

CHAPTER 2
LITERATURE REVIEW

Significance

Trees break apart and fall over in the wind (Allen 1992). Matheny and Clark (1994) and many others note there are factors (internal decay, poor architecture, age, human encroachment, etc.) which cause defects that predispose trees to failure – even in normally tolerable wind events. Many of the defects that lead to mechanical failure are visible, and efforts have been made to teach tree care professionals to recognize and proactively address structural defects (Robbins 1986; Mattheck and Breloer 1994; Smiley and Bones 2000). However, some defects are not visible and some wind events are severe enough to damage and destroy even healthy, structurally sound trees (Duryea, Blakeslee et al. 1996).

Wind damage to trees causes tremendous loss. Economic loss is clearly visible in forest systems where wind damage results in lost materials that might have been harvested for lumber or paper production. "Wind damage is believed to cost countries in the European Union approximately 15 million Euros per year, and on occasions substantially more" (British Forestry Commission 2005). Economic loss can also be attributed to clean-up and restoration of damaged property in urban environments (Ham and Rowe 1990). Costs are associated with debris removal (Whittier, Rue et al. 1995), insurance claims, and restoration of utilities. Repair and replacement of the urban forest are also viewed as necessary in maintaining a functioning society with an acceptable standard of living (Westphal 2003). Worst of all, injury and loss of life are often associated with wind damage in both forests and urban settings (Graham 1990).

History

In 1977 J. Grace published a monograph entitled Plant Response to Wind . One of his main objectives was to review the literature so that botanists, foresters, agronomists, etc. could evaluate the state of information about how plants respond to wind physiologically, anatomically, ecologically, and mechanically. The interaction between plants and wind is a complex matter. In July 1993, the International Union of Forestry Research Organizations (IUFRO) brought together scientists from many disciplines for a first conference on "Wind and Wind-Related Damage to Trees." Proceedings of that conference were published in 1995 in a volume titled Wind and Trees (Coutts and Grace 1995). In 1998, IUFRO held its second conference on "Wind and other Abiotic Risks to Forests". Selected papers from that conference were published in Forest Ecology and Management issue 135 (Peltola, Gardiner et al. 2000). Most recently, a third international conference, "Wind Effects on Trees," was held in September 2003 and its proceedings were published in text as were the first (Ruck, Kottmeier et al. 2003) but public copies are scant (in 2005 the University of Florida's Marston Science Library was unable to purchase a copy or acquire one through interlibrary loan). All three conferences aimed at understanding the effects of wind on forest systems and most of the work presented was done on coniferous species. Roodbaraky et al. (1994) remarked that by 1990, there was already a body of literature dealing with "the effect of wind on woodland conifers" but very little existed for broad-leaved species. In the decade following his remarks, more research was conducted using broad leaf species (Vogel 1995; Niklas and Spatz 2000; Rebertus and Meier 2001; Vollsinger, Mitchell et al. 2005), but information is still scarce. Arborists in America, interested in the interaction between wind and trees in urban settings, organized another conference on tree biomechanics held in March of 2001. Proceedings of that conference were published by the International Society of Arboriculture (Smiley and Coder 2002).

A few other texts merit attention here for their influence on the primary literature. Steven Vogel's Life in Moving Fluids (1994) is an excellent resource for biologists and engineers interested in the interface between biology and fluid mechanics. Pertinent subjects discussed include: principles of fluid flow, drag, drag coefficients, biological strategies to reduce drag, and complexities of fluid flow like unsteady flows, velocity gradients, and boundary layers. Structures: or Why Things Don't Fall Down (Gordon 1981) is both an instructive and enjoyable read introducing pertinent material properties like stress, strain, shear, torsion, and fracture as well as pertinent design considerations like safety and efficiency – but always in man-made structures. Many of those same material and design principles are discussed in relation to plants in Plant Biomechanics (Niklas 1992). Finally, Wood – the Internal Optimization of Trees (Mattheck and Kubler 1997) presents an engineering approach to developmental biology of trees including a discussion of stress transfer through live wood, tree response to wounding, and the proposed "axiom of uniform stress."

Engineering Principles

Wind damage to trees (as it is considered here) is a structural rather than biological issue. Biological functions, like photosynthesis, nutrient assimilation, hydraulics, growth, reproduction, etc, are all determinants of tree growth and development (Ryan and Yoder 1997). Growth and development are determined even more significantly by a tree's genetics and evolutionary fitness – with the latter not only influenced by the organism but by its species (Niklas 1998; 2000b). Still, trees are subject to the same physical laws of nature as any other engineered structure (Niklas 1992; Savidge 1996). Engineering principles should therefore apply to tree structures just as they apply to any man-made structure, and indeed they do (Schuler and Bruhn 1973; Mattheck and Vorberg 1991; Spatz, Kohler et al. 1999; Niklas 2000a; Fourcaud and Lac 2003). Constraints governing man-made construction differ from those governing tree growth and development. As a result, trees are able to employ strategies that human engineering avoids such as bending, twisting, and reconfiguration (Vogel 1995). In order to analyze a tree's mechanical design, engineering principles have to be expanded to deal with complications like "large deflections" (Kemper 1968), "complex loading" (Morgan and Cannell 1987), and composite material properties (Spatz, Kohler et al. 1999). Conversely, tree structure is restrained by efficiency in the allocation of resources. Therefore, factors of safety (load capacity / self weight) in trees are much smaller than those found in man-made designs (Niklas 1999). It should be clear that an engineering approach to tree biomechanics is useful only with an appropriate consideration for biological elegance.

Scientific Approach

Mechanically, wind damage in trees has been classified as wind tilt, wind throw, wind prune, and wind snap, (Allen 1992). Wind tilt and wind throw are defined as the inability of the roots and soil to resist uprooting either partially or completely when lateral forces acting on a tree reach critical limits. Wind prune and wind snap are the inability of branches and trunks respectively to resist breaking under those same conditions. Catastrophic mechanical failure has been classified in similar fashion as soil failure, root failure, or trunk failure (Sommerville 1979; Moore 2000). Soil failure is distinguished as wind tilt or wind throw accompanied by extraction of a characteristic root plate. Root failure is wind tilt or wind throw with minor soil heaving at the base of the trunk, but no noticeable root plate. Trunk failure is wind snap. An analytical approach to studying and predicting wind damage (especially catastrophic mechanical failure) was adopted in the 1970's and consisted of comparing forces imposed by wind to forces required to break or topple trees (Mayhead 1973; Grace 1977).

Wind Forces

Wind associated forces acting on a tree are shown in Figure 2.1. Detailed reviews of the mechanics associated with interactions between wind and trees are available (Blackburn, Petty et al. 1988; Wood 1995; Spatz and Bruechert 2000). The primary wind associated force acting on a tree is the drag force as given by Equation 2.1 (f_1 in Figure 2.1).

$$D = \frac{1}{2}\rho_{air} C_D(z) U^2(z) A(z) \tag{2.1}$$

Drag force (D) is equal to ½ density of the fluid (ρ – in this case air) multiplied by the drag coefficient (C_D), velocity of the fluid squared (U^2) and surface area projected into the fluid flow (A) at a given elevation (z). Drag force is compounded by the height of the stem over which it acts as described by Equation 2.2.

$$M_1 = (D) l_1 \tag{2.2}$$

In Equation 2.2, M_1 is the drag force moment, D is the drag force as in Equation 2.1, and l_1 is the height on the stem over which the drag force acts.

Drag coefficients

Drag is the sum of bluff body pressure and skin friction components that vary in their magnitude depending on the shape and roughness of an object (Niklas 1992). The drag coefficient is a dimensionless constant that accounts for variation in shape, roughness, and all other "oddities in the behavior of drag" which are described more thoroughly by Vogel (1994). Drag coefficients for forest trees were reported as early as 1962 (Mayhead 1973). Wind tunnels were used to generate known wind speeds and resultant drag was measured on both individual trees and model forests (Fraser 1964). Mayhead (1973) reports drag coefficients for eight coniferous species at wind speeds "likely to cause wind throw (i.e. [68.0 mph], 30.5 m/sec)" and proposes their use in predicting critical heights of trees (the height at which the given wind speed causes wind throw). He notes however that "they are a dangerous extrapolation" and that "good predictive work will require more accurate values for the drag coefficient". Yet his values have been used in risk assessment studies as late as 2001 (Moore and Gardiner 2001).

Rudnicki et al. (2004) and Vollsinger et al. (2005) followed up the work of Mayhead with improvements in the determination of drag coefficients by accounting for streamlining, the speed specific reorientation of branches and leaves in the wind. Using digital video to capture wind speed specific frontal area (A_d), they showed that at the highest wind speeds tested (20 m/s) A_d decreased by as much as 54% in the conifers and 37% in the hardwoods. Still, drag coefficients for hardwood species were "less than half the values typically reported for needled conifers at equivalent speeds" (Vollsinger, Mitchell et al. 2005). Also, drag coefficients for both conifers and hardwoods were greater and didn't decrease as sharply with increasing wind speed when calculated using A_d, as when using the still air frontal area. Both papers confirmed Mayhead's findings that drag coefficients vary among species, and they discouraged extrapolation to other species. Both groups also revisited some of Mayhead's unpublished work and reported a linear relationship between drag and the product of wind speed (U) and canopy mass (M_c) in all conifer and hardwood species tested. Therefore, they proposed a simplified drag equation for risk assessment, Equation 2.3 that eliminates the need for calculating frontal area and errors associated with using inaccurate drag coefficients.

$$D = M_c U \tag{2.3}$$

With this they recognized that the trees used were small (saplings 3-5 m in height) and that their individual branches behaved independently. Further work is needed to define drag relationships in older and larger trees.

In a commentary A. R. Ennos (1999) argued "there is little unequivocal evidence of drag reduction in large trees as a result of reconfiguration". He cites McMahon (1973) and Bertram (1989) while reminding readers that mature trees have thicker stems to cope with larger gravitational loads so they are less flexible. Vogel (1989) showed that leaves and clusters of leaves will often streamline when oriented appropriately in a straight line wind and thus reduce their drag, but stiffer leaves did not follow suit. Instead of scaling proportional to the first power of wind speed, drag on mature trees may scale like Vogel's (1989) white oak leaf, at a power even larger than that seen in the classical drag equation (Equation 2.1). Attempts have been made to measure drag coefficients in field grown trees but they are fraught with uncertainty and are not reliable (Ennos 1999).

Wind speed

Definition of the vertical wind profile and spectra that cause damage to trees is an almost esoteric subject that is beyond the scope of this work. However, Lee (2000) and Finnigan and Brunet (1995) reviewed the literature on this subject for the 1998 and 1993

IUFRO conferences, respectively. Wind profiles are reported as mean predicted wind speeds. Calculations of drag coefficients in wind tunnels were conducted with straight line wind profiles (Mayhead 1973; Rudnicki, Mitchell et al. 2004; Vollsinger, Mitchell et al. 2005). Wind profiles used in theoretical modeling (Hedden, Fredericksen et al. 1995; Peltola, Nykanen et al. 1997; Kerzenmacher and Gardiner 1998) typically follow the theoretical profile presented by Oliver and Mayhead (1974), which is an exponential profile within the canopy and a logarithmic profile above it. Niklas (2000a) measured the wind profile used when calculating safety factors and Nilas and Spatz (2000) measured the wind profile when calculating wind induced stem stresses in an open-grown cherry tree. These profiles were best described by a third order polynomial equation. Stem stresses were then recalculated using logarithmic, constant speed (straight line), square root, and square (exponential) profiles to compare among different vertical wind profiles commonly used or seen in nature (Spatz and Bruechert 2000). They reported that "stress levels generated were insensitive to the 'shape' of the wind speed profile" (Niklas and Spatz 2000) compared to other factors. None the less, variations in wind spectra are still thought to explain the random nature of wind damage in trees (Luley, Sisinni et al. 2002). Lee (2000) noted there was still a dearth of information on wind flow over undulating terrain, in extreme wind events, and in inhomogeneous canopies with irregular, more realistic edge transitions and forest clearings; all of which are common in urban forests. There is also very little information about wind speeds within and around individual trees. Zhu et al. (2000) reported that vertical and horizontal wind profiles within the canopy of a single Japanese black pine followed exponential functions described by elevation and crown thickness, respectively. They noted that average wind speeds within the crown were only about half what they were outside it. They also proposed equations for calculating interior wind speeds at any elevation in a crown based on a single measurement outside a crown, and anywhere within a horizontal plane in a crown based on a single measurement outside a crown at the same elevation.

Tree Resistance

The second part of the analytical approach introduced above is a determination of the force required to break or topple a tree. Before any additional force is considered, a tree must first cope with the load of gravity or its self weight as described by Equation 2.4 and illustrated in Figure 2.1.

$$f_2 = m(l_1)g \tag{2.4}$$

In Equation 2.4 f_2 is the force of gravity; m (l_1) is the mass of the canopy at an elevation along the trunk l_1; and g is gravitational acceleration. Calculations based on scaling of trunk diameter with tree height predicted a safety factor against elastic buckling under self-weight near four (McMahon 1973). Niklas (1994) and Mattheck et al. (1993) independently confirmed earlier calculations through experimentation. However, Niklas (1997a) later argued that estimates of wood density used in previous calculations were unrealistically low and safety factors against elastic buckling are probably closer to two. He also reported (Niklas 1997b; c) that ontogenetic changes in size, shape, and wood properties occurred of necessity, or imposed stresses would reach critical levels as trees grew in size. Ontogenetic development allows for trunk and proximal branches to be rigid in support of larger gravitational loads resulting from increased mass. At the same time distal branches remain flexible so the canopy maintains an ability to reconfigure and reduce its drag in the wind. As a matter of perspective, most trees are capable of successfully resisting gravitational loads.

Bending and wind snap

Wind drag increases gravitational load on a tree by generating a moment (Equation 2.5) as the trunk and stems bend (Grace 1977; Spatz and Bruechert 2000).

$$M_2 = f_2 l_2 \tag{2.5}$$

In Equation 2.5, M_2 is the gravitational moment; f_2 is as before; and l_2 is the magnitude of deflection. The magnitude of deflection is described by engineering beam theory and depends not only on the drag force exerted on the crown, but on the geometry and material properties of the stem as given in Equations 2.6 and 2.7 (Grace 1977; Gordon 1981).

$$l_2 = \frac{(D)I^3}{3EI} \tag{2.6}$$

In Equation 2.6, l_2 and D are as before, I is the second moment of area of a cross section, and E is the modulus of elasticity (Young's modulus).

$$I = \frac{\pi d^4}{64} \tag{2.7}$$

In Equation 2.7, I is as before, d is the diameter of the stem, and π is the area of the unit circle. It should be noted that there are many equations for I and the one chosen depends on the specific cross sectional area – Equation 2.7 is specific for a circular cross section. Introductory information about mechanics of materials and beam theory is provided by Gordon (1981) and Salvadori (1980).

Trunk taper accounts for the change in I over the length of the stem and influences stress distribution within the stem. Petty and Swain (1985) have suggested that "taper is probably the most important factor affecting susceptibility to stem breakage". Niklas and Spatz (2000) found that because of changes in taper and canopy shape, safety factors against wind induced stress likely decrease as trees mature. They also submit that wind induced stresses and related safety factors are not uniform throughout the canopy of a tree (Niklas 2000a). Niklas and Spatz (2000) found that material yield stresses decreased with increasing stem diameter for all trees examined, while stress levels were lowest at the most distal and basal portions of the tree for all but the oldest tree. For the oldest tree, stress levels were highest at the trunk base. Leiser and Kemper (1973) had earlier demonstrated that assuming homogeneity of material properties, taper determines the location of maximal stress in a sapling tree trunk. Severely tapered trunks had the greatest maximal stresses of all trunks analyzed with those stresses located high on the trunk near the point of loading. Untapered trunks also had large maximum stresses but they were located at the trunk base. Both of these findings support ecological adaptations that are proposed in the literature. Distribution of maximal bending stresses to the distal portions of the tree may allow for preferential branch shedding (a form of "self pruning") to reduce drag in high winds (Hedden, Fredericksen et al. 1995; Mattheck and Kubler 1997; Niklas 2000a; Beismann, Schweingruber et al. 2002). It may also be an evolutionary strategy facilitating asexual reproduction (Blackburn, Petty et al. 1988).

From a purely mechanical perspective, the best designs distribute stress uniformly along an entire structure. With that in mind, Mattheck and Kubler (1997) presented the "axiom of uniform stress" based on their work using the Finite Element Method to analyze notch stresses and allometry of trunks, branches, and unions. Uniform stress was originally proposed by Metzger, who discovered that taper of spruce trees (height ~

diameter^3) assured a uniform distribution of bending stresses along the trunk. Other analyses of shapes of stems (Morgan and Cannell 1994) and scaling factors of trees (McMahon 1973) provide further evidence of the “axiom of uniform stress”. However, in all these studies, wood mechanical properties were assumed to be uniform or to change negligibly throughout the specimen. The assumption of uniform stress has been made repeatedly (Fraser 1962; Petty and Worrell 1981; Milne 1991; Peltola, Nykanen et al. 1997; Saunderson, England et al. 1999) and appears to be valid at least in young trees (Leiser and Kemper 1973; Petty and Worrell 1981). Still, Wood (1995) admits there are questions as to the accuracy of the assumption of uniform stress. And those who include measures of wood anatomical features along with taper in their analysis of stress distribution report variations in the longitudinal stress distribution within the stem (Ezquerra and Gil 2001).

From Equation 2.6 it is clear that the modulus of elasticity or Young’s modulus is another important factor determining bending stresses in stems. Young’s modulus is a measure of the “stiffness” of a material (Salvadori 1980; Gordon 1981). Tabulated values of average Young’s moduli for both kiln dried and green wood are readily available on a number of commercially important species (Green, Winandy et al. 1999). It should be noted however, that tabulated values are averages taken from small clear specimens of wood (Green, Winandy et al. 1999; Bailey 2000a) and it has been shown that there is tremendous variability in the Young’s modulus within a tree (Niklas 1997a; b; Niklas and Spatz 2000). Cannell and Morgan (1987) reported that Young’s moduli measured in intact branches and trunks are lower than tabulated green wood values and suggested that a structural modulus of elasticity (the modulus of the intact living stem) be used to more accurately represent material properties of live wood. Accordingly, efforts have been made to measure the modulus of elasticity for living trees but with the assumption that it is uniform throughout the trunk (Milne 1991; Peltola, Kellomaki et al. 2000).

Foresters have long known that material properties of wood are not isotropic (Green, Winandy et al. 1999).Wood scientists have shown that 86% of the variability in the longitudinal Young's modulus is accounted for by orientation of cellulose microfibrils (microfibril angle (MFA)) in cell walls (Evans and Ilic 2001). Barnett and Bonham (2004) recently reviewed the literature on MFA. High MFA's are associated with low Young's moduli and are common in "juvenile wood" and "compression wood" while low MFA's convey a high Young's modulus and are associated with "adult wood" and "tension wood". Factors that control the orientation of cellulose microfibrils in cell walls are still unknown (Baskin 2001). Work on MFA refutes the assumption of material homogeneity of stems but does not disprove the possibility of uniform stress.

Wind throw

Sommerville (1979) suggested that widespread wind snap poses a greater economic threat to forest systems than wind throw. However, widespread wind throw is more prevalent (Blackburn, Petty et al. 1988; Papesch, Moore et al. 1997; Moore 2000) and as such it has received far more attention in the literature. In an effort to elucidate factors involved in wind throw, Fraser (1962) introduced a pull test using a winch and cable and demonstrated that *Fomes annosus* root rot caused lower resistance to lodging while improved drainage had an opposite affect in Douglas fir (*Pseudotsuga menziesii*). Others used similar pull tests to demonstrate that lodging is dependent on taper (Petty and Swain 1985), rooting depth and root morphology (Sommerville 1979), soil type and moisture content (Moore 2000), and species (Peltola, Kellomaki et al. 2000; Moore and Gardiner 2001). Coutts (1986) used tree pulling tests to demonstrate that applied wind loads were much more significant in causing wind throw than associated gravitational loads – a finding that was later confirmed by Papesch et al. (1997). Coutts also annotated the sequence of wind throw in shallow rooted Sitka Spruce (Coutts 1983) and defined components of root anchorage (Coutts 1986). Collectively, pull tests have been used to determine maximum bending moments of trees in order to make comparisons with maximum applied loads. Those comparisons are then used to create wind throw prediction models (Peltola, Nykanen et al. 1997; Kerzenmacher and Gardiner 1998; Saunderson, England et al. 1999; Moore and Quine 2000; Talkkari, Peltola et al. 2000) and to develop improved cultural practices (Cremer, Borough et al. 1982; Brüchert, Becker et al. 2000; Gardiner and Quine 2000; Mitchell 2000). However, pull tests have mainly been used to evaluate static loads (Fraser 1962; Blackburn, Petty et al. 1988) and Oliver and Mayhead (1974) revealed that wind damage occurs at mean wind speeds well below those predicted by tree pulling tests. Static tests are a crude approximation of actual loads experienced by trees in wind events.

Tree Dynamics

Wind is a dynamic force that generates complex loads in stems as trees sway. Moore and Maguire (2004) recently reviewed the literature investigating tree dynamics. Most of the research has been conducted in forest systems where trees are in close proximity and exhibit strongly excurrent growth habits. Milne (1991) used pull tests to study natural frequency and damping of Sitka spruce (*Picea sitchensis*) in a forest setting. He reported that the greatest component damping a tree's sway was interaction between crowns and branches of neighboring trees. Moore and Maguire (2005) followed up on

Milne's work and found that interactions between trees were insignificant. They reported that aerodynamic damping of foliage had the greatest effect on tree sway. They also reported that it is inappropriate to represent tree crowns as a series of lumped masses when calculating wind and gravitational loads, something that Mayhead had discovered earlier but never published (Moore and Maguire 2005). Still, Mayhead (1973), Rudnicki et al. (2004), and Vollsinger et al. (2005) have all shown strong relationships between canopy mass and drag. A model describing a tree crown as a series of independent mass dampers was presented by Kerzenmacher and Gardiner (1998) and again by James (2003). Mass damping seems very likely and research is underway to evaluate the effect of branches as coupled mass dampers (James 2003; Moore and Maguire 2005).

As a final note on tree dynamics and wind loading in general, Denny (1994) warned that the probability of wind damage calculated from extreme measurements is much greater than that calculated from an average as is typically done. Therefore, if models that are generated to predict catastrophic failure in trees are to be used in urban settings, consideration needs to be given to the severity of a single catastrophic failure. Since trees do not construct to man-made factors of safety, models should compensate to some degree.

Pruning

Mechanical pruning is commonly thought to reduce wind damage from strong winds because it reduces the surface area of the tree canopy (Mattheck and Breloer 1994). Duryea et al. (1996) noted that pruned trees withstood wind damage from Hurricane Andrew better than their unpruned counterparts. Ham and Rowe (1990) felt that despite losing over 4800 street trees, damage to the city of Charlotte, NC from Hurricane Hugo was "lessened by their program of routine [tree] maintenance."

However, a survey of street trees in Rochester, NY showed no difference in the frequency of storm damaged trees in pruned versus unpruned areas of the city (Luley, Sisinni et al. 2002). Pruning is one of the most prominent tree maintenance practices (Accredited Standards Committee A300 2001), and it is widely recommended as a means of reducing wind damage to trees (Matheny and Clark 1994; Brown 1995; Gilman 2002; Harris, Clark et al. 2004). Never the less, research supporting recommendations for pruning trees to reduce wind damage is almost nonexistent in the primary literature. Moore and Maguire (2002) mention that the natural frequency of Douglas fir trees does not appear to be significantly affected by pruning until the topmost third of the canopy is removed. They suggest this is due to the paucity of foliage in the lower canopy and higher wind velocities at higher elevations. Rudnicki et al. (2004) and Vollsinger et al. (2005) evaluated whole branch removal in their calculation of drag coefficients and reported that pruning did not influence streamlining in coniferous or hardwood species tested. However, they noted that their test specimens were small with branches that behaved independently, so effects of streamlining were inconclusive. Even with these recent reports, the primary literature appears void of evidence for pruning as a means to mitigate wind damage. There is even less information about how pruning should be accomplished.

The American National Standards Institute (ANSI) A-300 (2001) pruning standard and other pruning references (Lilly, Clark et al. 1993; Brown 1995; Brickell and Joyce 1996; Lang and Editors 1998; Gilman 2002; Harris, Clark et al. 2004) list four primary pruning practices: cleaning, thinning, raising (also called lifting or skirting), and reduction. Other colloquial terms defining specific pruning practices include utility, structural, risk reduction, balancing, vista, restoration, topping, tipping, or lion's tailing but each of those are a type or combination of the primary four. There are also specialty pruning practices such as coppicing, pollarding, pleaching, topiary, espalier, bonsai, and fruit tree pruning (Accredited Standards Committee A300 2001) which have historically been used for specific effects, but those are not commonly used in landscapes. For definitions of the four primary pruning practices refer to the ANSI A-300 (2001) pruning standard section 5.6 or Gilman (2002).

Dose

Pruning dose is "the amount of live tissue removed at one pruning" (Accredited Standards Committee A300 2001). ANSI recommends limits to pruning as defined by a "percent of the foliage removed [from a tree] within an annual growing season" (Gilman 2002; Gilman and Lilly 2002; Harris, Clark et al. 2004). However, ANSI provides no information about how to quantify the percent of foliage removed. Other resources for arborists refer back to the ANSI pruning standard on questions of dose (Gilman 2002; Gilman and Lilly 2002). They also advise practitioners to quantify pruning dose based on the desired objective (Brown 1995; Harris, Clark et al. 2004), or appearance of the tree following the pruning (Waring, Schroeder et al. 1982). Thus measurement of pruning dose by practitioners is largely qualitative and subjective.

The most reliable way to quantify pruning dose is destructive. Following pruning, the foliage and stems removed and the remaining canopy are cut into small pieces and dried to a constant weight. Pruning dose is then calculated as a percentage of total dry mass of foliage removed. Alternative, nondestructive methods for determining pruning dose could be considered using biomass prediction equations calculated from sapwood area or from trunk diameter at breast height (DBH). However, while those alternatives may prove useful to investigators, they would need some modifications before finding their way to the practitioner.

Sapwood cross sectional area has been used to generate prediction equations for leaf area based on the pipe model theory (Kaufmann and Troendle 1981; Waring, Schroeder et al. 1982; Meadows and Hodges 2002). Prediction equations are species specific (Rogers and Hinckley 1979), but have been generated for a number of species including *Quercus velutina* and *Q. alba* (White 1993), *Q. rubra* (Meadows and Hodges 2002), *Q. falcata* var. *pagodifolia* and *Fraxinus pennsylvanica* (Kaufmann and Troendle 1981), *Picea engelmannii*, *Pinus contorta*, *Abies lasiocarpa*, and *Populus tremuloides* (Ohara and Valappil 1995; Meadows and Hodges 2002; Medhurst and Beadle 2002). Leaf area is first correlated to leaf biomass, and then to sapwood area. Within a species, correlation is independent of age, site, strata, crown class, crown condition, and stand density (Rogers and Hinckley 1979). However, there is debate as to whether leaf area should be correlated to current sapwood area (Meadows and Hodges 2002) or total sapwood area (McDowell, Barnard et al. 2002). There are also complications to the models because leaf area: sapwood area generally decreases as total height of the tree increases (Meadows and Hodges 2002), and leaf area: unit weight is larger in the lower, more shaded, parts of the canopy than in the intermediate and upper parts (Ter-Mikaelian and Korzukhin 1997). Prediction equations need to be determined for more species before this method becomes useful to a large degree. Prediction equations using DBH are more commonly used.

There is a sizeable amount of information relating various biomass components to DBH. Ter-Mikaelian and Korzukhin (1997) provide an extensive review of the literature for 65 North American tree species. Prediction equations reviewed are all of the same form but there are often multiple prediction equations for the same biomass component. As a result, the authors present all the different prediction equations together, as well as various components used to generate these equations such as the range, sample size, and standard error of the estimate; as well as geographic region of the sample, and a reference to the paper where it was cited. The additional information is included as an aid in determining which prediction equation is most appropriate for individual circumstances. There are a considerable number of non-coniferous species listed, but species included are limited to those important in forest systems. Additional work is needed to generate similar equations for commonly used landscape species. Another impasse to using the biomass equations based on DBH is that they predict the oven-dry weight of the individual component. This is fine for a researcher in predicting pruning dose but completely impractical for a practitioner.

Conclusions

This review presents a summary of work published in the primary literature associated with wind damage and pruning of amenity trees. Tremendous strides are being made towards the understanding of wind forces on trees and trees associated mechanical response. Additional information is needed in many areas including: wind profiles and wind spectra for both forests and individual trees, drag coefficients of large, open grown, broad-leaved species, root and soil interactions affecting anchorage, and wood material properties. There is especially a dearth of practical information that can be used by tree care providers in urban settings. The subsequent study is aimed at providing useful information regarding pruning as a means for reducing wind damage in amenity trees.

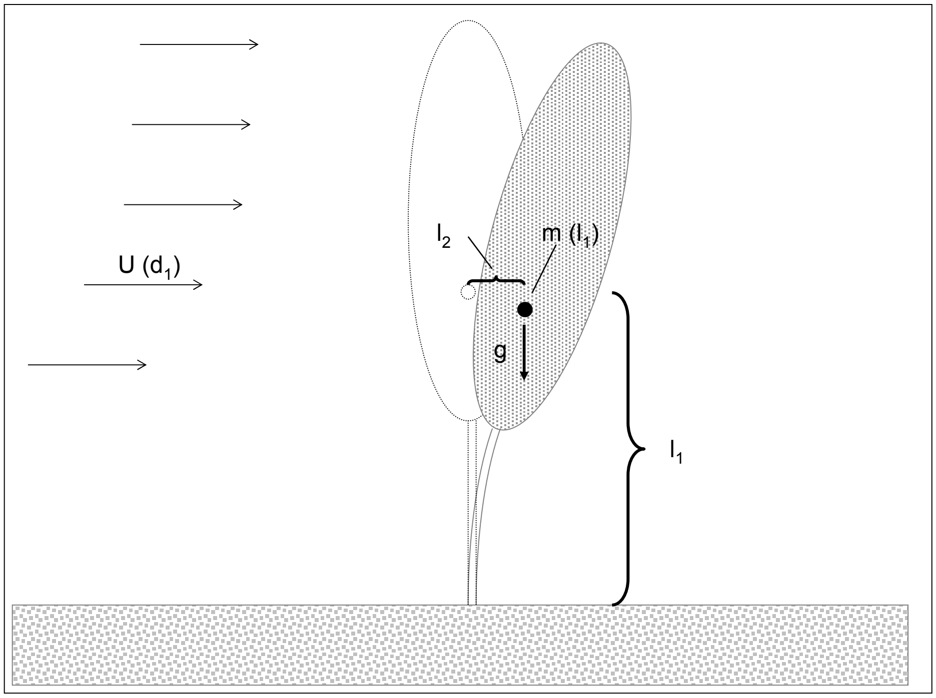


Figure 2.1. Wind forces affecting trees (modified from Grace (1977)).

Wind force: $(f_1) = \frac{1}{2}\rho_{air}C_d(l_1)U^2(l_1)A(l_1)$.

Wind moment: $M_1 = (f_1)l_1$.

Gravitational force: $f_2 = m(l_1)g$.

Gravitational moment: $M_2 = f_2 l_2$.

Magnitude of deflection: $l_2 = \frac{(f_1)I^3}{3EI}$.

Second moment of area: $I = \frac{\pi d^4}{64}$.

Constants are as follows: ρ_{air} = density of air, C_d =drag coefficient, l_1 = elevation to the point of loading, U = wind speed, A = projected surface area of the canopy, m =mass of the canopy at l_1 , g = acceleration of gravity, l_2 magnitude of deflection, E = modulus of elasticity, d = diameter of cross section, and π = area of the unit circle.

CHAPTER 3
MATERIALS AND METHODS

Tree Selection

Clonally propagated trees were chosen as subjects for testing to improve similarity among trees assigned to different experimental treatments. Live oak trees (*Quercus virginiana* ‘QVTIA’ PP 11219, Highrise®) were used because they are a commonly planted species in the southeastern United States and were readily available from a local nursery. Trees were selected for physical similarity from a population of Highrise® live oaks grown at Marshall Tree Farm (MTF; Morriston, FL, U.S.A.). Marshall Tree Farm transplanted the trees from five gallon containers into native soils (Orlando fine sand or Sparr fine sand) in June 2000. In May 2003, clear trunk, total canopy height and diameter, trunk taper parameter, rootball diameter, height to vertical center of a canopy, projected area of a canopy and canopy volume were measured on 50 trees and used as characteristics for selection (Table 3-1). English units were chosen for use throughout this thesis in order to follow American engineering convention. Clear trunk was the distance between the top-most root and first main branch. A minimum clear trunk of 54 in. was required for selection. Total canopy height (Tch) was determined by measuring maximum (Mxch) height (distance from top of the rootball to top of the canopy), minimum (Mnch) height (distance from top of the rootball to origin of the lowest branch), and subtracting Mnch from Mxch Canopy diameter (Cd) was the average width of a canopy measured at its widest point in two perpendicular directions. A visual estimate of the canopy outline was used to determine Cd – single shoots extending beyond the canopy outline were neglected. Trunk taper parameter (Taper) was calculated as -(R-r)/R (Leiser and Kemper 1973) where R = radius at 6 in. above the top-most root, and r = radius at 54 in. above the top-most root. Rootball diameter (Rd) was average width measured at the soil surface in two perpendicular directions. Height to vertical center of a canopy (Hvcc) was one half Tch plus Mnch. Projected area (Area) was calculated as 0.5 × the vertical surface area of a cone (whose dimensions were: height = 0.667 × Tch and radius = 0.5 × Cd) plus 0.25 × the surface area of an ellipsoid (whose dimensions were: radius of the long axis = 0.333 × Ch and radius of the short axis = 0.5 × Cd). Canopy volume (Volume) was calculated as the volume of a cone (calculated as before) plus one half the volume of an ellipsoid (calculated as before). Measurement of any characteristic that was greater than three standard deviations from its sample mean was cause for rejection. This eliminated obvious outliers according to the Empirical Rule in statistics (Ott and Longnecker 2001).

On November 6, 2003 forty-four trees were moved from MTF to the Environmental Horticulture Teaching Unit (Tree Unit, Gainesville, Florida, U.S.A.). Trees met Roots Plus Growers™ standards (Roots Plus Growers Association of Florida 2005); meaning they were dug and completely hardened-off at the nursery with visible roots on the outside of the root ball prior to shipment. Upon arrival, trees were weighed (rootball included) using a dynamometer (Model WT-1-1000H John Chatillon & Sons, New York, NY) then healed into pre-dug holes. Holes were the same dimensions as the root balls and trees were healed in without removing burlap, wire, or nylon bag that secured the rootball. Trees were irrigated three times per day with approximately four gallons of water per irrigation. After healing in, tree movement was minimized prior to testing. None of the trees suffered significant defoliation resulting from transport to the Tree Unit.

Experimental Design

Three effects were evaluated: 1) pruning type, 2) pruning dose, and 3) wind speed. From those three effects, 100 treatment combinations were constructed. Trees were randomly assigned to a pruning type following a completely randomized design. Five pruning types were included: 1) lion's tailing, 2) raising, 3) reduction, 4) structural, and 5) thinning. Each tree, within a type, was pruned three times to approximate targeted, orthogonally spaced, pruning dose levels. Targeted pruning dose levels were: 1) 15% foliage removed, 2) 30% foliage removed, and 3) 45% foliage removed. Within a pruning dose, each tree was subjected to a sequence of wind speeds. Four, equally spaced wind speed levels were targeted: 1) 15 mph, 2) 30 mph, 3) 45 mph, and 4) 60 mph. Data was collected on every tree, before it was pruned and at all targeted pruning dose levels, at ambient wind speeds and at all targeted wind speeds. Therefore, data was collected 20 different times on the same tree within a pruning type. The first four lion's tailed, raised, reduced, and thinned trees were blocked in time by tree within type forming a complete block design. The last three lion's tailed, raised, and reduced trees and all structurally pruned trees were added in no particular order.

Pruning Type

Pruning types are defined in the American National Standard for Tree Care Operations (ANSI 2001) and in <u>An Illustrated Guide to Pruning – Second Edition</u> (Gilman 2002). Five types evaluated here are common in practice or are recommended as a means to reduce wind damage to trees (Matheny and Clark 1994; Brown 1995; Gilman 2002; Harris, Clark et al. 2004). One person was chosen to execute all pruning to maintain treatment consistency. Prior to testing, trees similar to those selected for experimentation were pruned by a team of individuals and pruning types and doses discussed. During experimentation, parts of a canopy removed by pruning were collected and stored in paper bags for gravimetric analysis of actual pruning dose.

Lion's Tailing

Four trees were lion's tailed as part of the complete block design. Pruning consisted of removing primary and higher order branches smaller than 0.5 inches in diameter at their point of attachment to the trunk or parent stem. Branch diameter was determined using a digital caliper as average width measured in two perpendicular directions. Pruning dose levels were determined in the field from geometric dimensions of the canopy; all tissue removed was dried and weighed to calculate actual dose. The 15% pruning dose consisted of pruning within the lowest 15% of canopy height and the most interior 15% of canopy radius. The 30% and 45% pruning doses were applied in similar fashion. Canopy height and diameter measurements were taken on the day of testing following the procedure used for tree selection. Pruned volume was determined as follows. The canopy's main leader was marked at 15%, 30%, and 45% of total canopy height calculated as: canopy height × (0.15, 0.30, and 0.45 respectively) + min. height. Fifteen, thirty, and forty-five percent of canopy radius was calculated by multiplying 0.5 × canopy diameter by 0.15, 0.30 and 0.45 respectively. During pruning, canopy radius was measured with a common tape measure.

Foliage removed from the first four lion's tailed trees was inadequate at all dose levels. Therefore, three additional trees were included to better approximate targeted pruning dose levels. The three additional lion's tailed trees were blocked in time with each other but not with other pruning types. Pruning, canopy appearance, and canopy structure of the three additional lion's tailed trees was similar to the first four, but pruning dose in the field was determined as a visual estimate of live foliage removed. All tissue removed was dried and weighed to calculate actual dose. Examples of lion's tailing from an urban landscape and pruning of test trees at each dose are provided in Figures 3.1 to 3.3. Seven lion's tailed trees were included in the statistical analysis.

Raising

The first four raised trees were blocked in time with other pruning types. The first raised tree was the first of all trees tested. It was not included in the analysis because experimental procedure changed for all subsequent trees. Pruning dose levels for the first four raised trees were determined in the field from geometric dimensions of the canopy as follows. On the day of testing, canopy height was measured and the main leader was marked at 15%, 30%, and 45% of total canopy height following the procedure used for lion's tailing. The 15% pruning dose was applied by pruning from the base of the canopy up the main leader to the 15% mark. The 30% and 45% dose levels were applied in similar fashion. All tissue removed was dried and weighed to calculate actual dose. Pruning was conducted by removing all branches from the main leader at their point of attachment. Branches originating high in the canopy but drooping below the elevation of the mark on the main leader were also removed to that elevation so the entire canopy width was lifted. Foliage removed at each pruning dose for the first four raised trees exceeded targeted levels so three additional trees were included to better approximate targeted pruning doses.

The three additional raised trees were blocked in time with each other but not with other pruning types. Pruning dose for the additional raised trees was determined in the field as a visual estimate of live foliage removed; all tissue removed was dried and weighed to calculate actual dose. Pruning was carried out as before, but if removal of a large limb caused an excessive dose, it was treated as a second leader and raised as per the main leader. Examples of raising from an urban landscape and pruning of test trees are provided (Figures 3.4 to 3.6). Six of the seven raised trees were included in the statistical analysis.

Reduction

Reduction pruning involved making heading cuts (shearing) to reduce the geometric size of a canopy. Pruning did not involve ‘drop-crotch pruning’ or using reduction cuts as is commonly recommended for reducing the size of a tree or part of a tree in a landscape.

The first four reduced trees were blocked in time with other pruning types. Pruning dose for the first four reduced trees was determined in the field by geometric dimensions of a canopy. On the day of testing, canopy height and average canopy diameter were determined as before. The main leader was marked at 85%, 70%, and 55% of total canopy height calculated as: max height – canopy height × (0.85, 0.70, and 0.55 respectively). Pruning was accomplished by first removing the main leader at the designated mark followed by pruning the exterior of the remaining canopy to re-establish each trees original three dimensional shape, but in a smaller version. No foliage was removed from interior parts of a canopy. All tissue removed was dried and weighed to calculate actual dose. Foliage removed from all but the first dimensionally reduced tree exceeded targeted pruning doses at all levels. Therefore, three additional trees were reduced to better approximate targeted dose levels.

The three additional reduced trees were not blocked in time with each other or with other pruning types. Pruning was carried out in as per other reduced trees but dose was determined in the field as a visual estimate of live foliage removed – trunks were not marked prior to pruning. All tissue removed was dried and weighed to calculate actual dose. Examples of reduction from an urban landscape and pruning of test trees at each dose are provided (Figures 3.7 to 3.9). Seven reduced trees were included in the statistical analysis.

Structural

Three trees were structurally pruned. Structurally pruned trees were blocked in time with each other but were not blocked with other pruning types. They were all evaluated at the end of the data collection period. Structural pruning involved making reduction and removal cuts to shorten and slow growth of stems competing with the main trunk, and to develop scaffold branches. Little thought was given to canopy size, shape, or density. Pruning dose was determined in the field as a visual estimate of live foliage removed; all tissue removed was dried and weighed to calculate actual dose. Examples of structural pruning from an urban landscape and pruning of test trees at each dose are provided (Figures 3.10 and 3.11). Structurally pruned tree number 2 was left out of the statistical analysis because of an inadvertent change in procedure. Two structurally pruned trees were included in the statistical analysis.

Thinning

Four trees were thinned and all four were blocked in time with other pruning types. Thinning was conducted by making reduction and removal cuts throughout the entire canopy, especially at the outer edge of a canopy. Pruning dose was determined in the field as a visual estimate of live foliage removed. All tissue removed was dried and weighed to calculate actual dose. Thinning produced a uniformly dense canopy without changing the canopy's initial geometric dimensions. Examples of thinning from an urban landscape and pruning of test trees at each dose are provided (Figures 3.12 and 3.13). Four thinned trees were included in the statistical analysis.

Pruning Dose

Pruning dose is defined in Sections 5.5.3 and 5.5.4 of A300 (ANSI 2001) as a percentage of foliage removed. Pruning dose used in the statistical analyses was percentage of foliage dry weight removed. All parts of a canopy collected and stored during pruning were dried at 70ºC until they reached a constant weight. Foliage was then separated from stems and both foliage and stem weight were recorded separately for each treatment combination. The remaining canopy (clear trunk excluded) of 13 of the 27 trees tested was also cut into small sections, dried, and measured as per pruned cuttings to calculate an average canopy dry weight. Pruning dose was calculated as dry weight of an individual pruning dose (summed incrementally) ⁄ average canopy dry weight × 100. Pruning dose was also calculated from actual tree canopy dry weight for the 13 trees used to calculate the average canopy dry weight.

Wind Speed

High winds are not regularly experienced at the University of Florida Tree Unit. Winds were generated using an airboat (Figure 3.14) driven by a 1988 Chevy 350 engine, a 2-1-power reduction unit, and a 2-blade, Sensenich wide blade, 78-inch, left hand rotation, composite propeller (Sensenich Wood Propeller Co., Inc., Plant City, FL, USA). Airboat rudders were locked in an orientation perpendicular to the long axis of the propeller and the boat was set on two concrete piers. Piers were engineered to elevate the propeller's midpoint to the estimated center of pressure on an average unpruned, undisturbed canopy. This corresponded to one third average total canopy height, or an elevation of 10 ft. 2 in. The airboat was lifted into place with a crane and was fixed to the piers with 2 in. angle iron that ran across the hull and 0.75 in. diameter threaded rod secured into the concrete with epoxy.

A downwind profile of generated wind speed was used to determine the location for placement of trees during testing. Gill propeller anemometers (Model 27106R R.M. Young Company, Traverse City, MI, USA) and a proprietary data acquisition program were used to measure and record wind speeds. Orthogonal anemometers were mounted on a steel tower 16 ft. 5 in. and 33 ft. off the ground as well as 10 ft. 1 in. off the ground on an outrigger. The outrigger was located seven feet upwind of the tower.

On November 21, 2003 the first set of downwind profile tests were conducted with the outrigger located at distances of 18 ft. 5 in., 29 ft. 3 in., and 39 ft. 8 in. downwind from the airboat propeller. Wind speeds were recorded at 100 Hz for one minute at motor rpm starting at 1000 rpm and increasing to 4500 rpm in increments of 500 rpm. Data collected is summarized in Table 3-2. Before additional testing, the airboat stern was elevated eight inches. The airboat propeller was then centered at an elevation equal to 10 ft. 10 in. and the airboat hull sat at a five degree angle from horizontal. Tower anemometers were abandoned in subsequent testing.

Wind speeds were measured on December 3, 2003 to correlate wind speed to motor rpm (Table 3-3). Anemometers were located 17 ft. downwind from the propeller and wind speeds were collected at 100 Hz for approximately four minutes at motor rpm starting at 1000 rpm and increasing to 4500 rpm in increments of 500 rpm. Data is summarized in Table 3-3.

Two 3-cup anemometers with directional sensors (Met One 034B, Campbell Scientific, Inc., Logan, UT, USA) measured wind speeds during testing. These anemometers were mounted in split ring hangers welded to telescoping steel conduit so they could be elevated to vertical center of the tree canopy (calculated as: canopy height ⁄ 2 + min. height). One anemometer was located approximately 7 ft. upwind and the other approximately 14 ft. downwind of each tree during testing. Directional sensors were unstable in generated winds so vanes were removed and wind direction was not recorded during testing.

On April 19, 2004 wind speed was correlated to motor rpm using Campbell anemometers (Figure 3.15). Anemometers were located at 10 ft. 2 in. and 23 ft. 3 in. downwind from the airboat propeller and at an elevation of 9 ft. 6 in. with respect to the height of the propeller (this was equivalent to the height of Young anemometers when they were 17 ft. downwind of the propeller). Data was collected at 0.5 Hz for three minutes at each rpm starting at 1000 rpm and running up to 4000 rpm in increments of 500 rpm. Campbell anemometers recorded higher wind speeds than Young anemometers at the higher rpm (Figure 3.15).

Because there were discrepancies between wind speeds recorded by Young and Campbell anemometers, a road test was conducted to check the accuracy of the Campbell anemometers. On April 21, 2004 anemometers were held out the front passenger window of a Jeep Grand Cherokee as it was driven from 10 mph to 70 mph in increments of 10 mph. Wind speeds recorded at 0.5 Hz for two minutes at each velocity are summarized in Table 3-4. Wind speeds recorded by the West anemometer (its location relative to the tree during testing) were nearly identical to the speedometer reading. The East anemometer was more variable. It was uncertain if greater error was in the anemometer or the driver's ability to maintain a constant velocity. Measurements from the East anemometer were not used in the analysis.

The East anemometer was included as an aside. Coder suggested that canopy density can be determined by measuring wind speeds on windward and leeward sides of the canopy (Coder 2000). Wind speeds recorded by the East anemometer were erratic despite pruning dose so it was not included in the analysis.

Trunk Deflection

Tree response to wind loading was measured as trunk deflection below the canopy. Before testing, a trunk was marked at 18, 30, 42, and 54 in. above the first root and eight cable extension transducers (CET) (Celesco Transducer Products Inc., Chatsworth, CA, USA) were attached to the trunk in pairs at those elevations (Figures 3.14 and 3.16). The four lowest CETs were fixed with 10 in. cables (PT1A-10-UP-5K-M6-SG), followed a by a pair of 15 in. CETs (PT1A-15-UP-5K-M6-SG), and finally a pair of 25 in. CETs (PT1A-25-UP-5K-M6-SG). The 10 in. CETs were calibrated using a common 12 in. ruler, while 15 in. and 25 in. CETs were calibrated using a 10 ft. tape measure. Linear regression produced R^2 values of 1.0 for all CETs (Figures 3.17 and 3.18).

Transducers were bolted to two pieces of 3 in. × 2 in. angle iron such that each angle iron had two 10 in., one 15 in., and one 25 in. transducer spaced 1 ft. apart along its length. During testing, angle irons were clamped to 4 in. × 4 in. wooden posts located approximately 16 ft. from the tree and spaced approximately 23 ft. 5 in. apart (Figure 3-19). Elevation of an angle iron on a post was determined on day of testing using line levels that hung from nylon string stretched between lowest transducers and the 18 in. mark on a trunk. Piano wire (0.01 in. diameter) was used to create extensions between transducer cables and the trees. Piano wire extensions were attached to trees with plastic cable ties. Deflection of the trunk was calculated at each interval as described in Figure 3.20.

Longitudinal Young's modulus is the most significant factor affecting bending (Barnett and Bonham 2004) and it is known to vary among species and within species. Every effort was made to select and maintain trees so there would be a uniform longitudinal Young's modulus among trees tested. Genetic variation among trees was limited by using clonally propagated trees. Trees were young enough (5-6 years old) that they were likely composed entirely of juvenile wood with no heartwood. Because they were nursery grown, they likely had wide, uniform growth rings and little to no reaction wood. Wood in all trees likely had the same moisture content because trees were irrigated regularly up until the day they were tested. Still, because variation in the longitudinal Young's modulus among trees would confound results based on trunk movement, efforts were made to determine green and kiln dried values of longitudinal Young's modulus. Testing was conducted on coupons (1 in. × 1 in. × 18 in. sections) cut from trunks at different elevations, and on whole trunks, following standard test methods for small clear specimens of timber (Bailey 2000a) and static tests of wood poles (Bailey 2000b) respectively. Figure 3.21 shows testing apparatus used in both procedures. Young's modulus calculations were conducted by an undergraduate as an University Scholars' project and more procedural detail is given in that report (Trachet 2005).

Experimental Procedure

Testing began May 19, 2004. One tree was tested per day. Testing dates are included in Table 3-1. Trees remained irrigated and undisturbed until the day they were tested. One exception was structurally pruned tree number two, which was excluded from the analysis because it was moved a day early, and without irrigation, it was severely water stressed before testing was complete. On a day of testing, each tree was moved from the field to the testing site and its rootball and the base of its trunk were secured so the tree would remain upright. Figure 3.22 depicts the apparatus used to secure a rootball and the base of a trunk. Eight cable extension transducers (CETs) were connected to the trunk and the tree was tested at all wind speeds before any pruning was executed. Transducers were then disconnected and the tree was pruned to the lowest targeted pruning dose (15% foliage removed). After pruning, CETs were reconnected and the process was repeated. Each tree was tested four times – once before pruning and once at each of the three targeted pruning doses.

Motor rpm to wind speed correlations indicated that to achieve desired wind speeds, testing should proceed from ambient to 1500, to 3000, and finally 4500 rpm. However, when testing the first raised tree, significant defoliation occurred at and above 3000 rpm. Thus the protocol was changed to proceed from ambient to 1250, to 2000, to 2750, back to 1250 rpm, and finally at ambient once more. Data was collected for two minutes at ambient conditions and for four minutes at individual rpm. Changes in wind speed occurred consecutively but data collection was interrupted as rpm changed.

Measurements from CETs, anemometers, and from a thermistor temperature probe (Model 107 Campbell Scientific, Inc.) were taken at 0.5 Hertz. The temperature probe was suspended 1.5 ft above ground on site and was protected from direct sunlight. The data acquisition system (DAQ) consisted of a Campbell Scientific CR10X datalogger used in combination with a Campbell AM 416 multiplexer (Figure 3.23) and a program written in Loggernet 2.1 (Campbell Scientific, Inc.). The DAQ system was powered from a standard 120 VAC socket through a 12 VDC converter.

Statistical Analysis

Pruning types were compared using analysis of variance (ANOVA) followed by least squares means separations adjusted using Tukey's method. Pruning dose and wind speed were analyzed in similar fashion and by regressions using a complete two factor quadratic empirical model. Regressions on wind speed and pruning dose were used to develop response surfaces of trunk movement from which orthogonal levels of each parameter were extracted. Extracted values were used in a three way ANOVA to compare effects of pruning type, pruning dose, and wind speed on tree movement. The results and statistical analysis are covered in detail in chapter four. Data was analyzed using the SAS system for windows release 8.02 (© 1999-2001 SAS Institute Inc., Cary, NC, USA).

Table 3-1. Measurements used to determine physical similarity of trees tested.

Date tested	Pruning type[a]	Tree[b]	Mxch[c] (ft.)	Mnch[d] (ft.)	Tch[e] (ft.)	Cd[f] (ft.)	Taper[g]	Rd[h] (in.)	Tw[i] (lbs)	Hvcc[j] (ft.)	Area[k] ($ft.^2$)	Volume[l] ($ft.^3$)
19May04	RA01	4	20.00	5.04	14.96	6.65	-0.04	31.00	660	18.28	312.10	1038.21
24May04	LT01	3	19.30	4.88	14.43	6.30	-0.05	33.50	680	17.58	283.90	898.58
25May04	TH01	36	19.20	4.54	14.66	5.30	-0.03	29.75	530	17.31	233.19	646.24
26May04	RE01	28	22.10	5.29	16.81	5.70	-0.03	29.25	610	19.66	284.36	857.10
28May04	RA02	40	20.50	5.27	15.23	6.15	-0.04	32.75	680	18.30	287.40	904.03
01Jun04	LT02	24	20.40	4.65	15.75	6.00	-0.04	31.00	700	18.75	286.56	890.13
02Jun04	TH02	39	17.40	4.77	12.63	6.25	-0.04	30.50	680	15.75	254.80	774.27
03Jun04	RE02	30	21.40	4.71	16.69	6.30	-0.02	32.25	615	19.84	318.22	1039.77
04Jun04	RA03	27	19.20	4.75	14.45	5.80	-0.04	30.50	585	17.35	256.84	762.92
07Jun04	LT03	26	20.70	4.92	15.78	6.10	-0.04	30.75	625	18.83	292.73	921.76
08Jun04	TH03	5	19.70	4.56	15.14	5.95	-0.02	31.50	710	18.11	274.80	841.10
09Jun04	RE03	32	20.10	5.08	15.02	5.55	-0.03	29.75	630	17.79	251.19	725.97
10Jun04	RA04	41	19.00	5.04	13.96	6.15	-0.04	30.75	670	17.03	268.75	828.59
18Jun04	LT04	49	20.50	5.19	15.31	6.25	-0.04	30.75	645	18.44	294.36	938.78
21Jun04	TH04	1	20.60	4.58	16.02	5.85	-0.04	32.75	675	18.94	281.77	860.28
23Jun04	RE04	31	21.00	5.00	16.00	5.60	-0.03	31.00	595	18.80	267.38	787.51
28Jun04	RA05	42	19.90	4.60	15.30	6.20	-0.01	30.75	690	18.40	291.24	922.81
30Jun04	RA06	43	18.20	4.92	13.28	6.20	-0.04	30.75	630	16.38	261.63	801.40
01Jul04	RA07	37	20.80	4.71	16.09	6.30	-0.04	28.75	565	19.24	309.05	1002.40
31Aug04	RE05	22	19.80	5.13	14.68	6.40	-0.03	30.75	585	17.88	293.30	943.40
02Sep04	RE06	19	21.30	4.96	16.34	6.45	-0.05	31.00	640	19.57	321.87	1067.02
26Oct04	LT05	44	20.80	4.52	16.28	6.20	-0.03	31.25	617	19.38	305.98	982.14
30Oct04	LT06	21	20.90	5.00	15.90	5.90	-0.02	27.50	505	18.85	282.95	868.68
03Nov04	LT07	45	21.40	4.69	16.71	6.05	-0.03	30.50	622	19.74	303.56	960.09

Table 3-1. Continued.

Date tested	Pruning type[a]	Tree[b]	Mxch[c] (ft.)	Mnch[d] (ft.)	Tch[e] (ft.)	Cd[f] (ft.)	Taper[g]	Rd[h] (in.)	Tw[i] (lbs)	Hvcc[j] (ft.)	Area[k] ($ft.^2$)	Volume[l] ($ft.^3$)
04Nov04	ST01	29	21.10	4.90	16.20	5.70	-0.03	30.00	610	19.05	275.87	826.29
10Nov04	ST02	11	19.80	4.67	15.13	6.05	-0.03	31.75	650	18.16	280.34	869.37
11Nov04	ST03	9	18.90	4.71	14.19	6.15	-0.03	29.50	580	17.27	272.15	842.44
23Nov04	RE07	38	19.50	4.71	14.79	6.20	-0.02	30.25	600	17.89	283.75	892.40
		mean =	20.13	4.85	15.28	6.06	-0.03	30.73	628	18.31	283.22	881.92
		Std =	1.051	0.226	1.03	0.30	0.01	1.24	49.9	1.02	20.89	97.58

[a]Pruning type: Pruning treatment assigned (type and number within type). Pruning types are: LT= lion's tailing, RA = raising, RE = reduction, ST = structural, TH = thinning.

[b] Tree: Number of original 50 selected from the field.

[c] Mxch: Maximum canopy height = distance from the top of the rootball to the top of the canopy.

[d] Mnch: Minimum canopy height = distance from the top of the rootball to the origin of the lowest branch.

[e] Tch: Total canopy height. = Mxch - Mnch.

[f] Cd: Canopy diameter = widest point of the canopy measured in two perpendicular directions and averaged. The main outline of the canopy was used to determine diameter – single shoots extending beyond the main body of the canopy were neglected

[g] Taper: Trunk taper parameter = -(R-r)/R where R = radius at 6 in. above the top-most root, and r = radius at 54 in. above the top-most root.

[h] Rd: Rootball diameter = average width of the root ball measured at the surface in two perpendicular directions.

[i] Tw: Total weight of the tree and its rootball.

[j] Hvcc: Height to vertical center of the canopy = ((0.5 * Ch) + Mnch)

[k] Area: Canopy projected surface = 0.5 × the vertical surface area of a cone (whose dimensions are height = 0.667 × Ch and radius = 0.5 × Cd) + 0.25 × the surface area of an ellipsoid (whose dimensions are radius of the long axis = 0.333 × Ch and radius of the short axis = 0.5 × Csd.

[l] Volume: Canopy volume.= the volume of a cone (whose dimensions are height = 0.667 × Ch and radius = 0.5 × Cd) + 0.5 × the volume of an ellipsoid (whose dimensions are radius of the long axis = 0.333 × Ch and radius of the short axis = 0.5 × Cd).

Table 3-2. Downwind profile of wind speeds generated by an airboat. Wind speeds were recorded for one minute at 100 Hz using gill propeller anemometers (Model 27106R R.M. Young Company, Traverse City, MI, USA) and a proprietary data acquisition program.

	Wind speed (mph)											
	Test 1 (21Nov2003)				Test 2 (21Nov2003)				Test 3 (21Nov2003)			
Distance[a]	29 ft. 3 in.		36 ft. 3 in.		39 ft. 8 in.		46 ft. 8 in.		39 ft. 8 in.		46 ft. 8 in.	
Elevation[b]	10 ft. 1 in.		16 ft. 5 in.		10 ft. 1 in.		16 ft. 5 in.		10 ft. 1 in.		16 ft. 5 in.	
RPM	Mean	Max.[c]	Mean	Max.	Mean	Max.	Mean	Max.	Mean	Max.	Mean	Max.
1000	5	7	2	2	3	5	2	3	5	9	2	4
1500	10	15	2	3	9	15	3	5	10	15	4	9
2000	10	20	3	5	12	17	3	5	18	25	5	10
2500	12	32	5	10	20	25	4	9	21	25	5	12
3000	15	28	7	12	25	32	7	15	25	35	6	12
3500	28	28	3	3	26	34	7	10	18	30	3	18
4000	33	33	4	4	25	32	3	5	19	27	6	12
4500	37	37	5	5	25	38	4	7	25	35	10	20

	Wind speed (mph)			
	Test 4 (21Nov2003)			
Distance	18 ft. 5 in.		25 ft. 5 in.	
Elevation	10 ft. 1 in.		16 ft. 5 in.	
RPM	Mean	Max.	Mean	Max.
1000	15	25	2	4
1500	22	30	3	8
2000	33	38	6	10
2500	35	45	5	9
3000	44	52	8	10
3500	38	48	13	22
4000	33	45	4	6
4500	40	50	8	10

[a] Distance: Distance from the airboat propeller to the anemometer.
[b] Elevation: Elevation from the ground to the anemometer.
[c] Max.: Maximum wind speed recorded.

Table 3-3. Calibration of motor rpm to wind speed. Wind speeds were recorded for one minute at 100 Hz using gill propeller anemometers (Model 27106R R.M. Young Company, Traverse City, MI, USA) and a proprietary data acquisition program.

	Wind speed (mph)		
Distance[a]	17 ft. 0 in.		
Elevation[b]	10 ft. 1 in.		
RPM	Mean	Max.[c]	Std. dev.
ambient	2.6	5.7	0.9
1000	9.1	15.0	2.9
1500	17.4	23.2	2.0
2000	24.5	29.4	2.4
2500	32.4	39.9	2.7
3000	38.4	46.8	2.6
3500	44.7	56.5	3.3
4000	50.0	60.4	3.7
4500	58.7	70.9	3.9

[a] Distance: Distance from the airboat propeller to the anemometer.
[b] Elevation: Elevation from the ground to the anemometer.
[c] Max.: Maximum wind speed recorded.

Table 3-4. Wind speeds recorded during a road test. Data was collected for 2 min. at 0.5 Hz using two 3-cup anemometers (Met One 034B, Campbell Scientific, Inc., Logan, UT, USA).

	Wind speed (mph)					
	West[a] (21Apr2004)			East (21Apr2004)		
Speedometer	Mean	Peak	Std. dev.	Mean	Peak	Std. dev.
10	9.7	10.5	0.7	9.1	12.3	1.2
20	20.7	23.0	1.0	22.1	25.7	1.7
30	30.3	32.8	0.9	30.6	33.7	1.7
40	40.2	47.1	2.4	42.5	44.5	1.0
50	50.6	52.5	1.1	52.5	53.4	0.6
60	60.6	63.2	1.3	64.8	67.7	1.2
70	73.5	78.5	1.5	75.7	80.2	2.2

[a] West and East refer to the location of the anemometer with respect to the tree during testing.

Figure 3.1. Three examples of lion’s tail pruning taken from urban landscapes.

Figure 3.2. Example of geometrically defined lion's tail pruning (lion's tailed tree number 1). Progression of targeted pruning doses: A) no pruning; B) 15% pruning; C) 30% pruning; and D) 45% pruning.

A B C D

Figure 3.3. Example of visually defined lion's tail pruning (lion's tailed tree number 7). Progression of targeted pruning doses: A) no pruning; B) 15% pruning; C) 30% pruning; and D) 45% pruning.

Figure 3.4. Two examples of raising pruning type taken from urban landscapes.

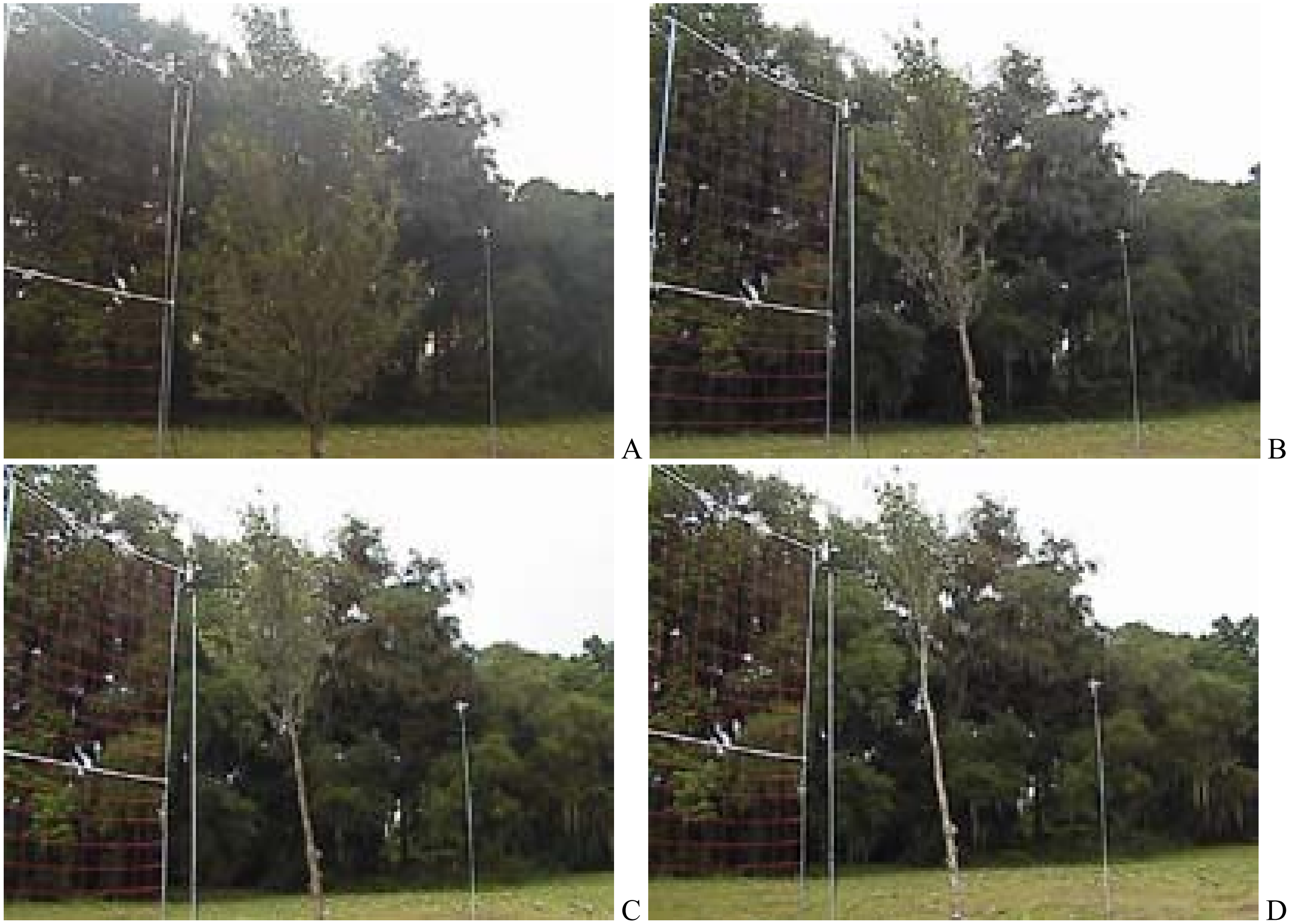


Figure 3.5. Example of geometrically defined raised pruning (raised tree number 3). Progression of targeted pruning doses: A) no pruning; B) 15% pruning; C) 30% pruning; and D) 45% pruning.

Figure 3.6. Example of visually defined raised pruning (raised tree number 7). Progression of targeted pruning doses: A) no pruning; B) 15% pruning; C) 30% pruning; and D) 45% pruning.

Figure 3.7. Two examples of reduction pruning type taken from urban landscapes.

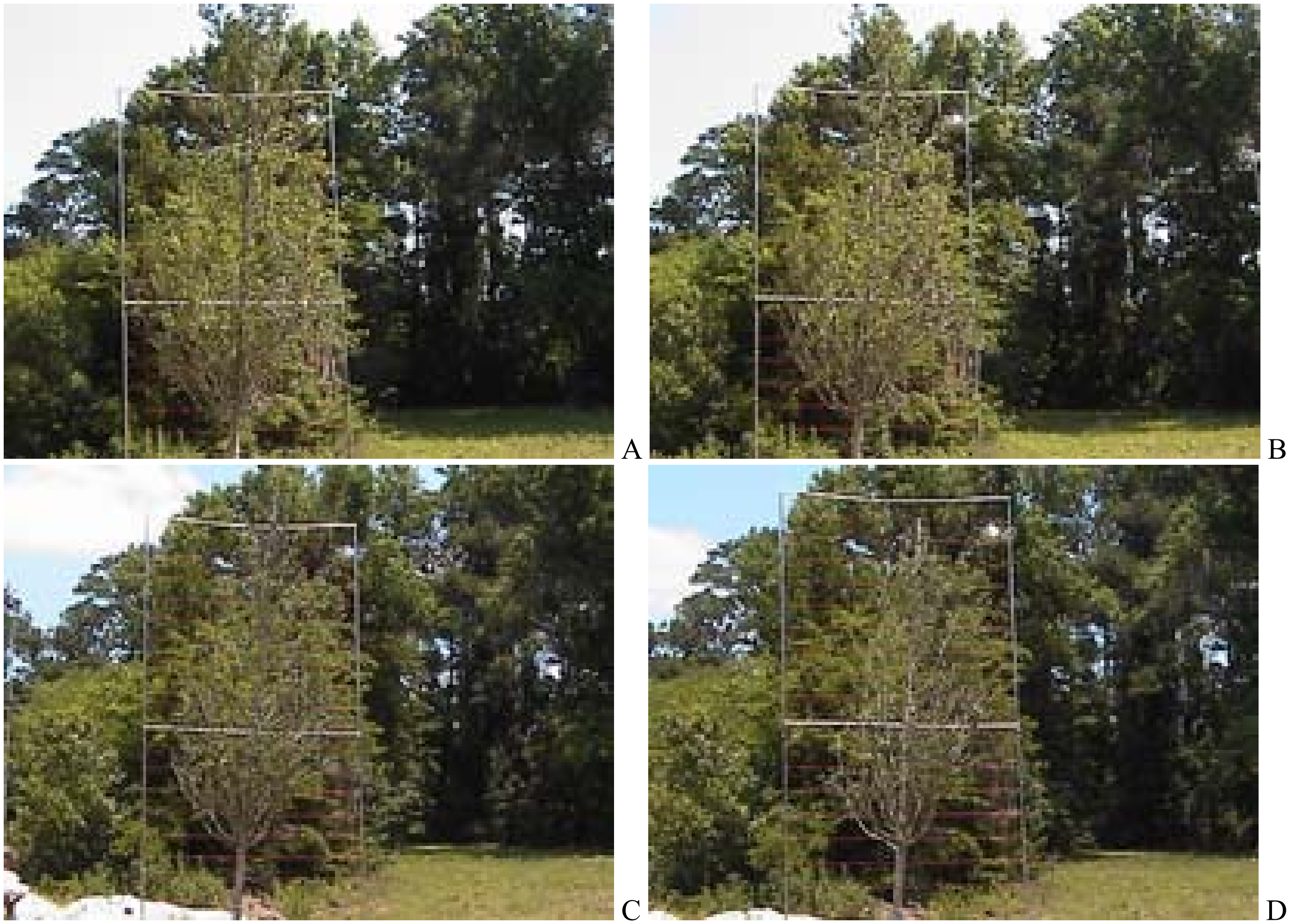


Figure 3.8. Example of geometrically defined reduction pruning (reduced tree number 1). Progression of targeted pruning doses: A) no pruning; B) 15% pruning; C) 30% pruning; and D) 45% pruning.

Figure 3.9. Example of visually defined reduction pruning (reduced tree number 7). Progression of targeted pruning doses: A) no pruning; B) 15% pruning; C) 30% pruning; and D) 45% pruning.

Figure 3.10. Two examples of structural pruning type taken from urban landscapes – before (A and C) and after (B and D) respectively.

A B C D

Figure 3.11. Examples of structural pruning (structurally pruned tree number 1). Progression of targeted pruning doses: A) no pruning; B) 15% pruning; C) 30% pruning; and D) 45% pruning.

A

B

Figure 3.12. Example of thinning taken from urban landscapes – before (A) and after (B).

Figure 3.13. Example of thinning (thinned tree number 4). Progression of targeted pruning doses: A) no pruning; B) 15% pruning; C) 30% pruning; and D) 45% pruning.

A

B

Figure 3.14. Airboat used to generate wind: A) side view and B) rear view.

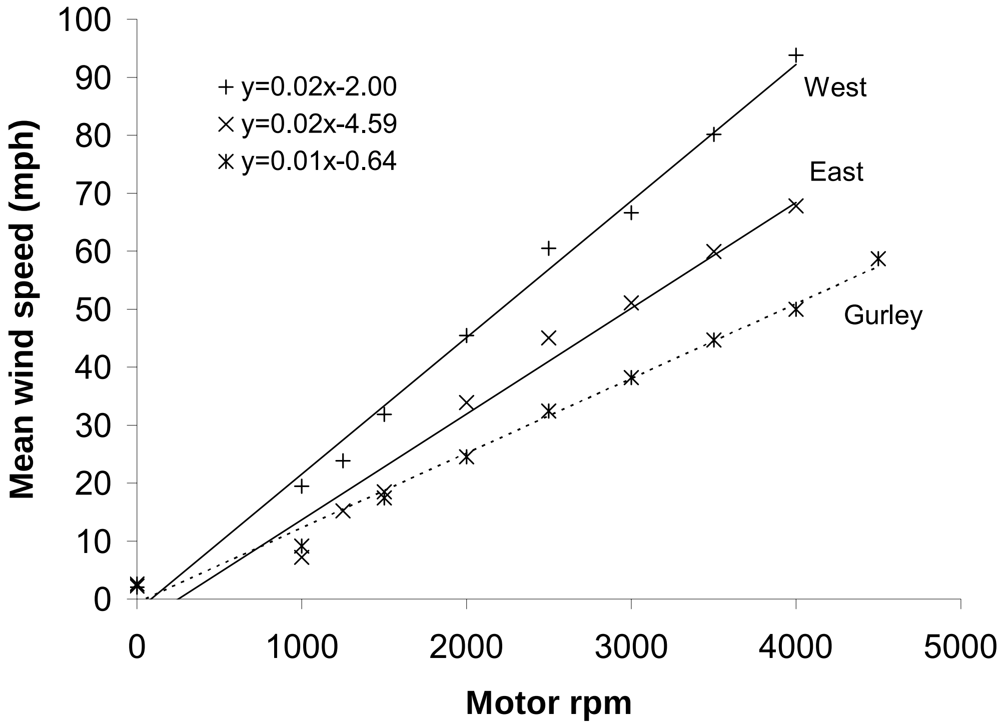


Figure 3.15. Calibration curves of the mean wind speeds as measured by Campbell (West and East) and Young (Gurley) anemometers. West anemometer was located 10 ft. 2 in. downwind; East anemometer 23 ft. 3 in. downwind; and Gurley anemometry located 17 ft. downwind.

Figure 3.16. The four South cable extension transducers (CET).

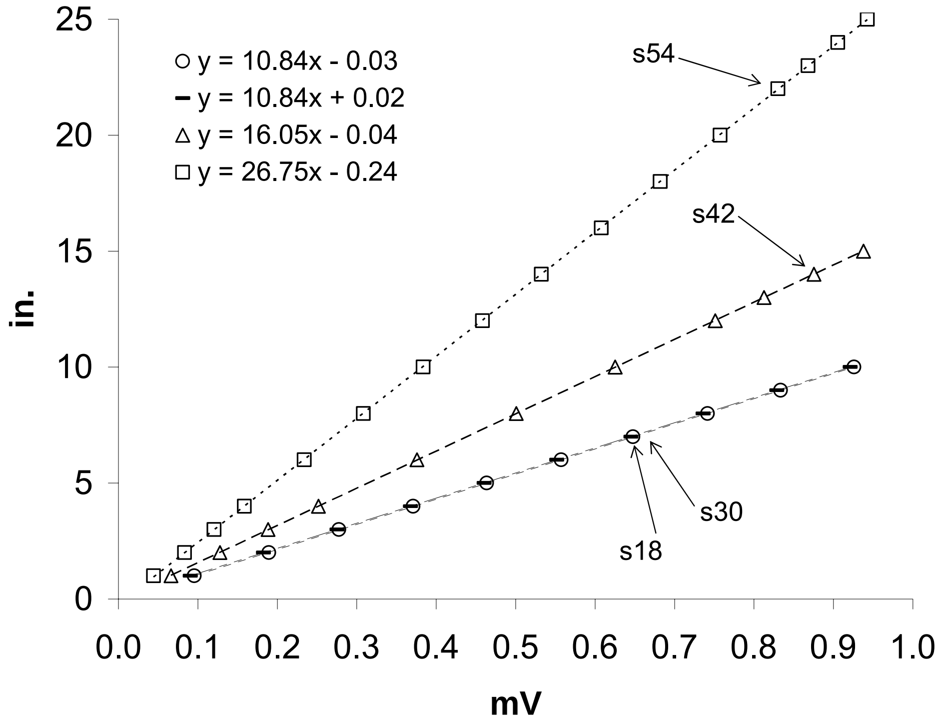


Figure 3.17. Southern cable extension transducer (CET) calibration curves. Labels indicate the location of the CET with respect to the tree and propeller and the elevation on the trunk during testing (e.g.: s18 = southern CET elevated to 18 inches). $R^2 = 1.0$ for all regressions. mV = millivolts; in. = inches

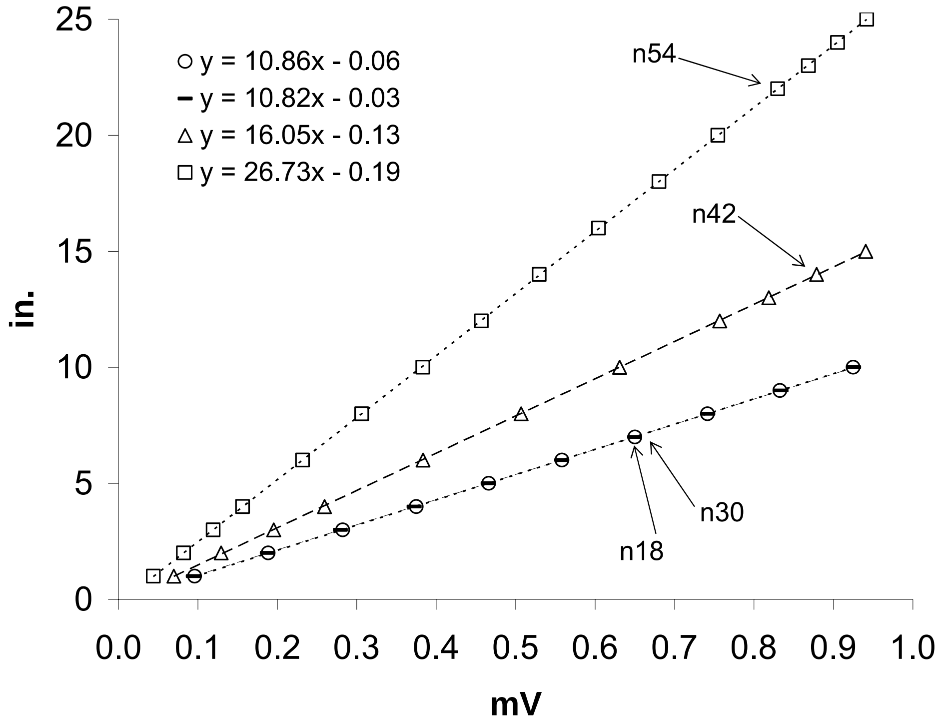


Figure 3.18. Northern cable extension transducer (CET) calibration curves. Labels indicate the location of the CET with respect to the tree and propeller and the elevation on the trunk during testing (e.g.: n18 = northern CET elevated to 18 inches). R^2 = 1.0 for all regressions. mV = millivolts; in. = inches

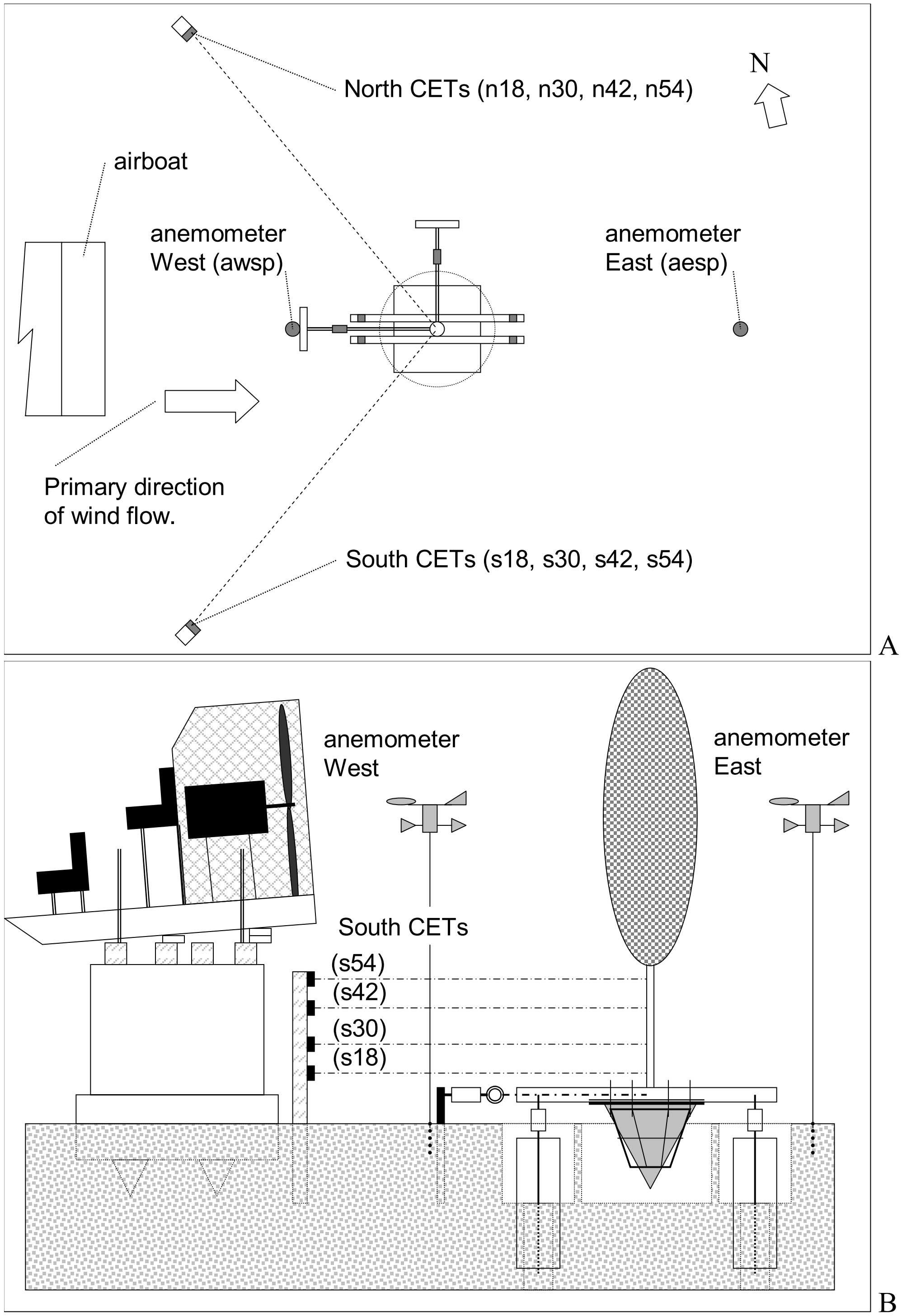
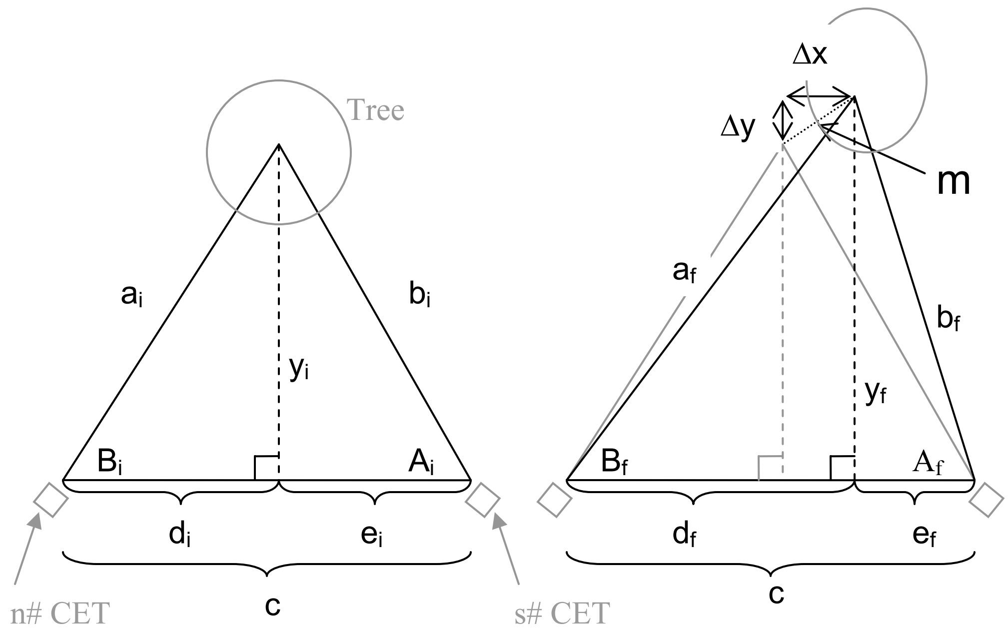


Figure 3.19. Schematics (bird's-eye (A) and profile (B) views of cable extension transducer (CET) and anemometer positions.

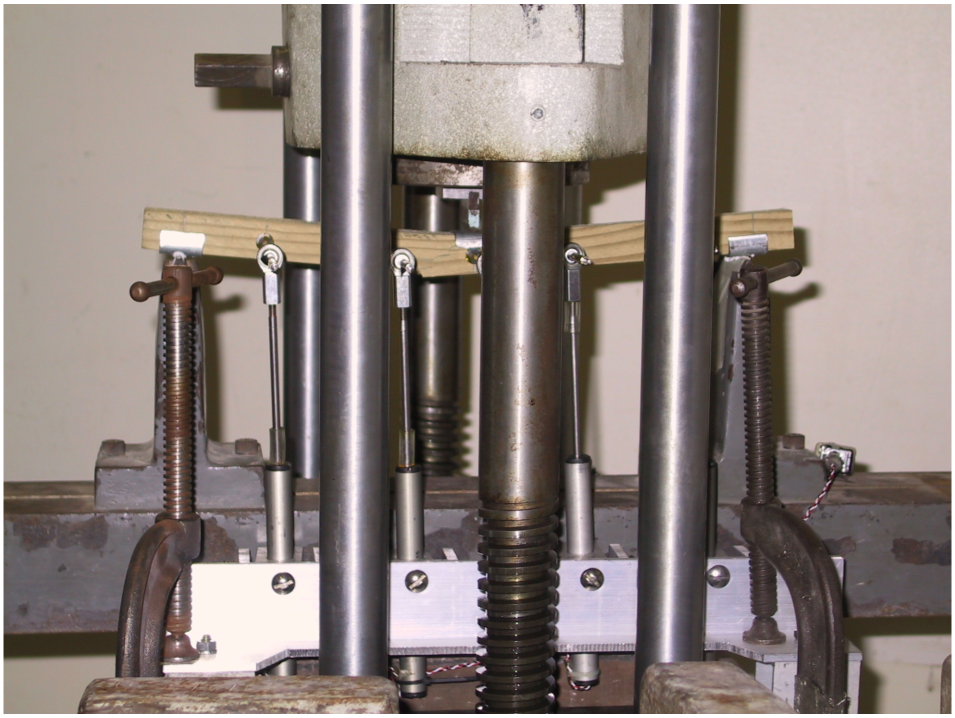


a_i	wire extension + average of n# CET readings at ambient by pruning dose
b_i	wire extension + average of s# CET readings at ambient by pruning dose
c	distance between n# and s# CETs measured manually at set-up
A_i	$= \text{Cos}^{-1}((b_i^2+c^2-a_i^2)/2b_ic)$
B_i	$= \text{Cos}^{-1}((a_i^2+c^2-b_i^2)/2a_ic)$
y_i	$= (b_i\text{Sin}A_i + a_i\text{Sin}B_i)/2$
d_i	$= y_i/\text{Tan}B_i$
e_i	$= y_i/\text{Tan}A_i$

a_f	wire extension + n# CET reading at designated time, rpm, and pruning dose
b_f	wire extension + s# CET reading at designated time, rpm, and pruning dose
c	distance between n# and s# CETs measured manually at set-up
A_f	$= \text{Cos}^{-1}((b_f^2+c^2-a_f^2)/2b_fc)$
B_f	$= \text{Cos}^{-1}((a_f^2+c^2-b_f^2)/2a_fc)$
y_f	$= (b_f\text{Sin}A_f + a_f\text{Sin}B_f)/2$
d_f	$= y_f/\text{Tan}B_f$
e_f	$= y_f/\text{Tan}A_f$

$\Delta x_\#$	$= d_i-d_f = e_i-e_f$
$\Delta y_\#$	$= y_i-y_f$
$m_\#$	$= \text{sqrt}(\Delta x^2+\Delta y^2)$ = displacement of the trunk

Figure 3.20. Cable extension transducer calculations (these are for one specific height represented in inches by subscript #).



A

B

Figure 3.21. Apparatus used to determine longitudinal Young's modulus: A) Coupon test, and B) trunk test.


A

B
Figure 3.22. Apparatus used to fix the trunk and rootball of trees during testing. A) Steel plate and basket used to fix the rootball. B) Tree fixed as it was during testing

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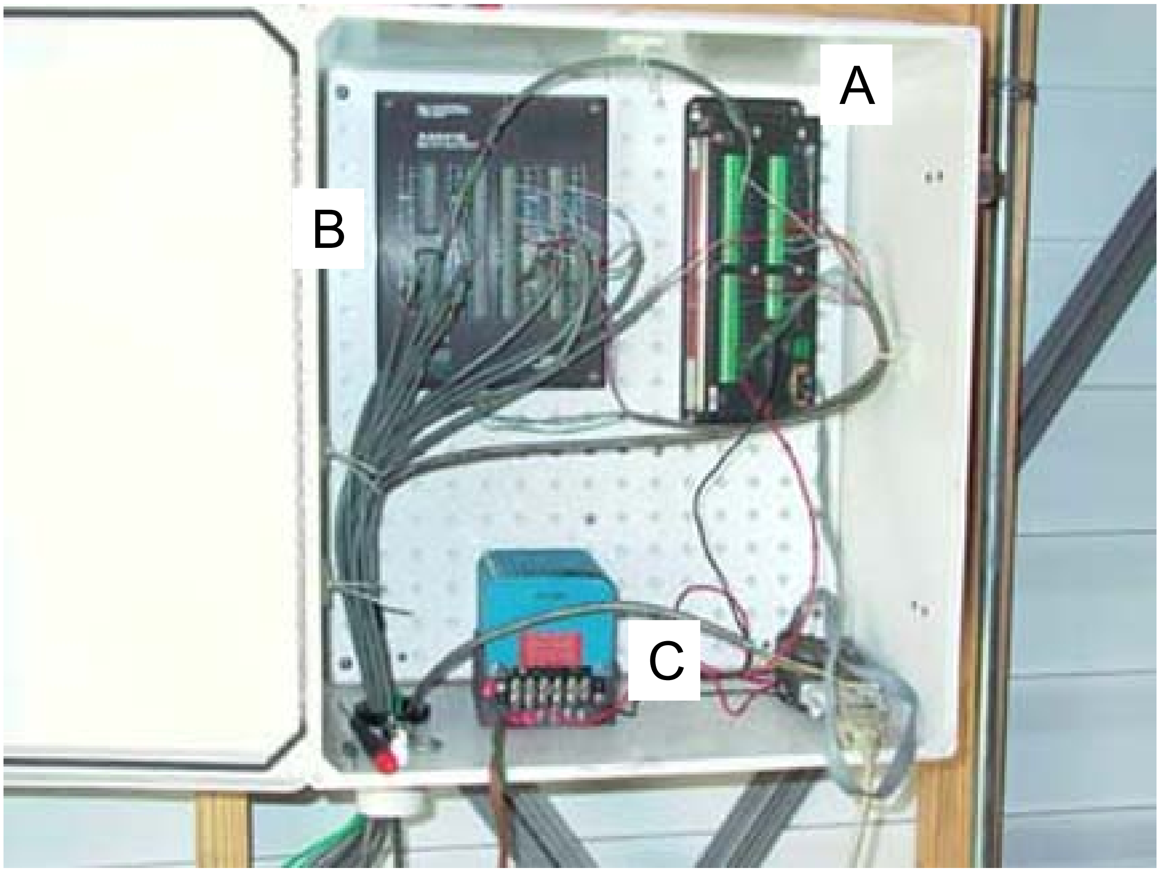


Figure 3.23. Data acquisition system used in the field: A) Campbell Scientific CR10X datalogger, B) AM 416 multiplexer and C) 12 VDC regulated power supply.

CHAPTER 4
RESULTS

Randomization

Trees were randomly assigned to a pruning type. Ten physical characteristics used to select trees were used to compare trees assigned to pruning types. There were no differences among pruning types with one exception. Elevation to the vertical center of the canopy was statistically (P = 0.039) lower (143 in.) for trees assigned to the thinned pruning type than for those assigned to the reduced pruning type (154 in.). Since this was the only difference among types, no adjustments were made in the assignment of trees to pruning types.

Pruning Dose

All pruning doses were calculated from an average canopy dry mass. Average canopy dry mass was calculated from 13 of the 27 trees tested. Table 4-1 shows foliage, stem, and total canopy dry mass for the 13 trees used to determine average canopy dry mass. Foliage, stem, and total canopy dry mass for all trees were within three standard deviations of the mean for each category. Thus none of the 13 trees used to determine average canopy dry mass were obvious outliers as defined by the Empirical Rule in statistics (Ott and Longnecker 2001).

Pruning doses were calculated as percentage of dry mass removed from the average tree and from the actual tree where possible (Table 4-2). Table 4-2 also shows targeted pruning dose and foliage, stem, and total dry mass removed at each pruning. As expected, pruning doses calculated from average canopy dry mass were different than those calculated from actual canopy dry mass for the 13 trees used to determine the average. Difference in calculated dose was most apparent in the percent foliage dry mass removed – 3.5% on average with the greatest difference 13% for structurally pruned tree number 3 at the 45% targeted dose level. To keep dose consistent in the analysis, dose was calculated using the average canopy dry mass. Percent foliage dry mass was chosen for use in the statistical analyses because ANSI (2001) defines pruning dose as a percentage of foliage removed. Percent stem dry mass and percent total dry mass removed from the canopy correlated well to percent foliage dry mass (R^2 = 0.76 and 0.85 respectively). Figure 4.1 shows the similarity between pruning doses calculated from foliage dry mass and those calculated from total dry mass.

Dose levels were more variable than expected. This was significant since comparisons among pruning types depended on consistent dose levels among types. Efforts to determine pruning dose using canopy dimensions were futile. Figure 4.1A shows that foliage removed from lion's tailed trees one through three at all dose levels was considerably less than the targeted dose levels. On the other hand, excess foliage was removed from raised and reduced trees two through four at all dose levels. Lion's tailed trees four through seven, and raised and reduced trees five through seven were added to better approximate targeted pruning dose levels. Pruning dose levels for those additional ten trees were determined in the field as a visual estimate of the foliage removed. Dose levels for structurally pruned trees one through three and thinned trees one through four were also determined visually and they were well distributed about the targeted levels (Figure 4.1A). No additional trees were tested for structural or thinned pruning types.

Wind Speed

Vertical wind profile was measured once before and twice after testing all 27 trees. Vertical wind profile was calculated as an average of 120 measurements taken per elevation per day on the three days it was evaluated (Figure 4.2A). Generated winds did not disperse vertically. As motor rpm increased, vertical profile became more concentrated (conical). One three cup anemometer was used to measure all elevations in the vertical wind profile sequentially. The same three cup anemometer was used to measure wind speeds at the vertical center of each tree canopy during testing. Figure 4.2B shows mean wind speeds recorded for all 27 trees at 2750 rpm on test dates as well as average vertical wind profile measured prior to and post testing. Wind speeds recorded on testing dates did not correspond with values in the average vertical wind profile (Figure 4.2B). It should be noted that because generated winds did not disperse vertically, upper and lower portions of tree canopies were subjected to lower wind speeds than the center of a canopy.

An experiment-wise comparison of generated wind speeds showed that selected motor rpm produced desired steps in wind speed (Table 4-3). The statistical difference between wind speeds generated at 1250 motor rpm before and after higher rpm was attributed to a large number of measurements used in comparisons. This statistical difference had no substantial effect since the two means at 1250 rpm differed by less than three miles per hour, while means between separate rpm differed by nearly 15 miles per hour.

Wind speeds were compared among pruning types by motor rpm. Raised trees generally experienced the highest generated wind speeds while lion's tailed and structurally pruned trees experienced lower wind speeds at every rpm (Table 4-4). Least squares means adjusted with Tukey's method indicated that at the highest motor rpm, wind speeds were statistically different among all pruning types except among thinned and reduced types (Table 4-4). Average wind speed recorded for lion's tailed trees differed from that recorded for reduced trees by 11.47 mph. This variation in generated wind speeds was corrected for in the analysis.

Wind speeds were compared among trees and pruning dose levels by rpm. Time series plots show that recorded wind speeds were not consistent between trees (Figure 4.3A and B). Wind speeds were fairly consistent within an rpm on some days (Figure 4.3A and B) but showed tremendous variation within an rpm on others (Figure 4.3C and D). Table 4-5 shows wind speeds recorded for each tree at the highest motor rpm.

Response

Two variables were considered to represent tree response to wind loading. The first was trunk movement at an elevation 54 inches above the topmost root (m54 – Figure 4.4A). The second was the area below the deflected trunk in the plane of primary wind flow (dya – Figure 4.5A). Trunk movement (m54) and deflected area (dya) were perfectly correlated with each other (R^2 = 1.0 at highest motor rpm and no foliage removed) and both were comparably correlated with wind speed (R^2 = 0.26 and 0.27 respectively at highest motor rpm and no foliage removed). Both measures showed that trunk movement tracked changes in wind speeds relatively well within a tree (Figures 4.4B and 4.5B). Both also showed there were differences in trunk movement among trees independent of wind speed. Mean wind speed at the highest rpm (Table 4-5) was decidedly greater for lion's tailed tree number 2 (LT02) than it was for lion's tailed tree number 1 (LT01), but m54 and dya were both lower for LT02 than for LT01. Deflected area appeared more responsive to changes in wind speeds but it was also more variable than m54 and it provided a measure of trunk movement in only one horizontal direction, that parallel to the primary wind flow. Trunk movement (m54) provided a measure of deflection in both horizontal directions, parallel and perpendicular to the primary wind flow and it was most responsive of all individual measurements. Therefore, m54 was chosen for use in the analysis and dya was considered redundant.

Trunk movement (m54) proved to be an effective measure of tree response regardless of quality of the corresponding wind speed profile. Time series plots of m54 (Figure 4.6) showed better resolution of individual rpm than time series plots of wind speed (Figure 4.3). They also showed effect of pruning dose as reduced movement with each repeated sequence of motor rpm (Figure 4.6).

Tree testing date was expected to influence trunk movement. Trees were tested from May 2004 to November 2004 so there was ample time for growth and development of trunks. Trees tested early were blocked in time by type but additional lion's tailed (numbers 4-7), raised (numbers 5-7), and reduced (numbers 5-7) trees and all structurally pruned trees were not blocked in time. Figure 4.7 shows that trunk movement (m54), at the highest motor rpm and no foliage removed, appeared to decrease with time from May through November while wind speeds did not ($R^2 = 0.53$). However, comparison of lion's tailed trees tested early in the year with those tested later showed no differences ($P = 0.664$) in m54 attributable to date tested. There was not enough evidence to conclude that tree growth had a significant impact on trunk movement over the dates tested.

Longitudinal Young's modulus was expected to influence trunk movement as well. Results from efforts to determine Young's modulus of whole trunks and coupons were inconclusive (Trachet 2005), so efforts were abandoned and Young's modulus was assumed to be uniform within and among trees tested. Structurally pruned tree number two suffered significant water stress which provided reason to believe its Young's modulus differed from that of other trees. It was left out of the analysis and there were no other anomalies that knowingly might have caused variation in Young's modulus among trees. As a result, the assumption of material homogeneity seems appropriate for the trees tested.

Analytical Approach

A principal goal of this experimental study was to compare effects of pruning type on tree response to wind load. Because pruning dose and wind speed were not recorded at set levels, orthogonal levels of both were sought to simplify comparisons between pruning types. Trunk movement (m54) was regressed against wind speeds (Wind) and pruning doses (Dose) measured for each tree (Tables 4-6 and 4-7). A complete two factor quadratic empirical model was used for all regressions as given in Equation 4.1, where $b_0 - b_5$ are constants generated as the regression coefficients.

$$m54 = b_0 + b_1 Wind + b_2 Dose + b_3 Wind^2 + b_4 Dose^2 + b_5 Wind \times Dose \qquad (4.1)$$

A quadratic model was chosen because wind speed is accounted for in the standard equation used to calculate drag by the fluid velocity term (which is squared) and pruning dose results in a reduction in surface area (also a squared term). Two regressions were conducted: one using all measurements of wind speed and m54 (Table 4-6), and one using measurements of wind speed and m54 averaged within pruning type, tree, pruning dose and rpm (Table 4-7). Figure 4.8 shows a graphical representation of all m54 measurements and average m54 measurements for raised tree number 5. Regressions using averaged m54 had higher R^2 values than those using all measurements and they were simpler since pruning dose coefficients were almost entirely insignificant. All regressions using averages of wind speed and m54 had R^2 values in excess of 0.94.

Regression equations were used to predict trunk movement (pm54) for all trees at orthogonal levels of pruning dose and wind speed. For some trees predicted values were interpolated between large gaps in the data (Figure 4.9A). For others predicted values were extrapolated some distance from the data (Figure 4.9B and C). Figure 4.10 gives a graphical summary of the procedure used to generate predicted average m54 (pm54) values for an individual tree.

The pm54 values were used to compare pruning type, pruning dose and wind speed in a three-way analysis of variance (ANOVA). Table 4-8 shows that there was essentially no difference between ANOVA results using pm54 values predicted from equations using all measurements of m54 and wind speed, and those using the averages m54 and wind speed. Similarly, there was little difference between ANOVAs using m54 versus those using deflected area (dya). Table 4-8 confirms that average m54 was as good a measure of tree response as m54, deflected area (dya), or average dya. Average trunk movement (m54) was used to complete the analysis.

The three-way ANOVA using predicted trunk movement (pm54) (Table 4-9) showed that interaction between pruning type, pruning dose, and wind speed, and interaction between pruning type and pruning dose were statistically insignificant (P = 1.00 and P = 0.74 respectively). However, interactions between pruning type and wind speed (Figure 4.11) and between pruning dose and wind speed (Figure 4.12) were significant (P < 0.0001 for both). Throwing out early lion’s tailed, raised and reduced trees that had extreme dose levels (Figure 4.1A) did not affect the results. Further analysis was conducted to quantify the significance of the interactions.

Predicted trunk movement (pm54) was used to compare pruning types at each wind speed averaged across pruning dose. Table 4-9 shows least squares means, adjusted with Tukey's method, ordered by pruning type at each targeted wind speed. Predicted trunk movement of thinned trees was statistically greater than the pm54 of structurally pruned, raised, and lion's tailed trees at 45 mph and greater than all other trees at 60 mph. There were no statistical differences between pruning types at lower wind speeds. These results are seen clearly in the pruning type × wind speed interaction profile plot (Figure 4.11). Thinning was the least effective pruning type for reducing wind load and there were no differences between the other four types.

Predicted trunk movement (pm54) was then used to compare wind speeds within each pruning type averaged across pruning dose. Table 4-10 shows least squares means, adjusted with Tukey's method, ordered by pruning dose at each targeted wind speed. Predicted trunk movement increased for all pruning types as wind speeds increased. The increase in movement was statistically significant ($P < 0.05$) at all wind speeds for all pruning types except structural pruning. In structurally pruned trees, pm54 was only statistically different between 15 and 60 mph wind speeds. There was no statistical difference in movement between 15 to 45 mph or between 30 to 60 mph wind speeds Overall, increases in wind speed resulted in increased trunk movement. Regression models (Table 4-7) also show this as coefficients for wind and wind^2 terms were almost always significant and positive.

The pruning dose × wind speed interaction (Table 4-11) was analyzed in the same fashion as pruning type × wind speed. At 30 mph predicted trunk movement was only reduced with a 60% pruning dose compared to no pruning. At the two highest wind speeds, the 30% dose was similar to both unpruned an the 60% pruning dose, with only pruning doses of 45% or greater predicting less trunk movement than no pruning. At both highest wind speeds, 60% pruning dose reduced predicted trunk movement about 50% compared to no pruning. This is represented graphically in Figure 4.12. Therefore, pruning dose affected tree response to wind load but the effect was not statistically significant at the low wind speeds and it was only statistically significant at the highest wind speeds once the 45% targeted pruning dose level was reached.

Separations of pm54 among wind speeds at each pruning dose level (averaged across pruning type) showed a similar effect. Least squares means, adjusted with Tukey's method, ordered by wind speed at each targeted pruning dose are shown in Table 4-12. The effect of pruning dose is first seen at the 30% targeted dose level as pm54 at 15 mph was not statistically different than pm54 at 30 mph. At the highest targeted dose level pm54 at 30 mph was not statistically different than pm54 at 15 or 45 mph – indicating that pruning dose increasingly offset the effect of wind speed. Prediction models showed this as well (Table 4-7). Although the dose and dose^2 coefficients are mostly insignificant, the dose*wind coefficients are almost all significant and negative. It is significant that pruning dose did not reduce trunk movement until 30% of the foliage was removed, and that further reduction in pm54 required a doubling of that dose (60% foliage dry mass removed). Both of these doses exceed current recommended pruning dose levels (ANSI 2001).

Table 4-1. Foliage and stem weight for 13 trees harvested to quantify pruning dose.

Pruning type[a]	Tree no.[b]	Remaining foliage[c] (lbs)	Pruned foliage[d] (lbs)	Sum foliage[e] (lbs)	Remaining stem[f] (lbs)	Pruned stem[g] (lbs)	Sum stem[h] (lbs)	Sum total[i] (lbs)
LT	4	2.568	2.171	4.739	26.780	5.147	31.927	36.666
LT	5	2.789	2.150	4.939	36.792	5.706	42.498	47.436
LT	6	3.098	1.857	4.955	35.255	5.035	40.290	45.246
LT	7	1.773	2.140	3.913	31.058	5.277	36.335	40.248
RA	3	1.202	3.425	4.627	14.627	12.730	27.357	31.984
RA	4	0.808	4.233	5.041	14.140	16.426	30.566	35.608
RA	6	2.116	2.837	4.952	19.387	11.562	30.949	35.901
RA	7	2.207	2.189	4.396	23.709	8.621	32.329	36.725
RE	5	2.114	2.011	4.125	29.844	3.086	32.930	37.055
RE	6	2.410	1.860	4.270	33.096	3.520	36.616	40.885
RE	7	1.564	2.262	3.827	31.056	4.047	35.102	38.929
ST	1	2.162	2.356	4.519	30.900	8.637	39.536	44.055
ST	3	0.975	2.683	3.658	26.632	8.930	35.562	39.220
			mean =	4.458		mean =	34.769	39.227
			std. err.[j] =	0.131		std. err =	1.199	1.201

[a] Pruning types: LT = lion's tailing, RA = raising, RE = reduction, ST = structural, TH = thinning.
[b] Tree no.: Number assigned to a tree within a pruning type (LT 4 was the fourth tree lion's tailed).
[c] Remaining foliage: Foliage dry mass remaining on the tree after the heaviest pruning dose.
[d] Pruned foliage: Foliage dry mass removed with all pruning doses.
[e] Sum foliage: Sum of remaining and pruned foliage.
[f] Remaining stem: Stem dry mass remaining on the tree after the heaviest pruning dose.
[g] Pruned stem: Stem dry mass removed with all pruning doses.
[h] Sum stem: Sum of remaining and pruned stem.
[i] Sum total: Sum foliage plus sum stem.
[j] Std. err.: Standard error of 1 standard deviation.

Table 4-2. Percent foliage dry weight, stem dry weight, and total dry weight removed with each pruning dose.

			Foliage dry mass removed			Stem dry mass removed			Total dry mass removed		
Pruning type[a]	Tree no.[b]	targeted dose[c] (%)	Sum[d] (lb_m)	Average dose[e] (%)	Actual dose[f] (%)	Sum (lb_m)	Average dose (%)	Actual dose (%)	Sum (lb_m)	Average dose (%)	Actual dose (%)
LT	1	15	0.532	12	—	1.598	5	—	2.130	5	—
LT	1	30	0.759	17	—	2.496	7	—	3.255	8	—
LT	1	45	1.328	30	—	3.933	11	—	5.261	13	—
LT	2	15	0.202	5	—	0.476	1	—	0.678	2	—
LT	2	30	0.817	18	—	2.465	7	—	3.282	8	—
LT	2	45	1.336	30	—	4.051	12	—	5.386	14	—
LT	3	15	0.505	11	—	1.544	4	—	2.049	5	—
LT	3	30	0.895	20	—	2.624	8	—	3.519	9	—
LT	3	45	1.448	32	—	3.625	10	—	5.074	13	—
LT	4	15	0.459	10	10	1.231	4	4	1.690	4	5
LT	4	30	1.073	24	23	2.844	8	9	3.918	10	11
LT	4	45	2.171	49	46	5.147	15	16	7.318	19	20
LT	5	15	0.572	13	12	1.878	5	4	2.450	6	5
LT	5	30	1.320	30	27	4.117	12	10	5.437	14	11
LT	5	45	2.150	48	44	5.706	16	13	7.856	20	17
LT	6	15	0.560	13	11	1.975	6	5	2.536	6	6
LT	6	30	1.215	27	25	3.740	11	9	4.955	13	11
LT	6	45	1.857	42	37	5.035	14	12	6.893	18	15
LT	7	15	0.635	14	16	1.902	5	5	2.537	6	6
LT	7	30	1.273	29	33	3.579	10	10	4.852	12	12
LT	7	45	2.140	48	55	5.277	15	15	7.417	19	18

Table 4-2. Continued

Pruning type[a]	Tree no.[b]	Targeted dose[c] (%)	Foliage dry mass removed: Sum[d] (lb_m)	Foliage dry mass removed: Average dose[e] (%)	Foliage dry mass removed: Actual dose[f] (%)	Stem dry mass removed: Sum (lb_m)	Stem dry mass removed: Average dose (%)	Stem dry mass removed: Actual dose (%)	Total dry mass removed: Sum (lb_m)	Total dry mass removed: Average dose (%)	Total dry mass removed: Actual dose (%)
RA	1	45	3.720	83	—	16.800	48	—	20.520	52	—
RA	2	15	2.583	58	—	10.291	30	—	12.875	33	—
RA	2	30	3.450	77	—	13.743	40	—	17.194	44	—
RA	2	45	3.786	85	—	14.724	42	—	18.510	47	—
RA	3	15	2.153	48	47	9.615	28	35	11.768	30	37
RA	3	30	2.564	58	55	10.744	31	39	13.309	34	42
RA	3	45	3.425	77	74	12.730	37	47	16.155	41	51
RA	4	15	1.858	42	37	6.632	19	22	8.489	22	24
RA	4	30	3.571	80	71	14.203	41	46	17.774	45	50
RA	4	45	4.233	95	84	16.426	47	54	20.659	53	58
RA	5	15	1.070	24	—	3.549	10	—	4.619	12	—
RA	5	30	1.839	41	—	6.320	18	—	8.159	21	—
RA	5	45	2.810	63	—	11.940	34	—	14.751	38	—
RA	6	15	1.101	25	22	3.782	11	12	4.882	12	14
RA	6	30	2.071	46	42	7.365	21	24	9.436	24	26
RA	6	45	2.837	64	57	11.562	33	37	14.399	37	40
RA	7	15	0.735	16	17	2.459	7	8	3.194	8	9
RA	7	30	1.527	34	35	5.819	17	18	7.346	19	20
RA	7	45	2.189	49	50	8.621	25	27	10.809	28	29

Table 4-2. Continued

Pruning type[a]	Tree no.[b]	Targeted dose[c] (%)	Foliage dry mass removed: Sum[d] (lb_m)	Foliage dry mass removed: Average dose[e] (%)	Foliage dry mass removed: Actual dose[f] (%)	Stem dry mass removed: Sum (lb_m)	Stem dry mass removed: Average dose (%)	Stem dry mass removed: Actual dose (%)	Total dry mass removed: Sum (lb_m)	Total dry mass removed: Average dose (%)	Total dry mass removed: Actual dose (%)
RE	1	15	1.159	26	—	0.939	3	—	2.099	5	—
RE	1	30	1.757	39	—	2.225	6	—	3.983	10	—
RE	1	45	2.239	50	—	4.717	14	—	6.956	18	—
RE	2	15	1.834	41	—	1.948	6	—	3.782	10	—
RE	2	30	2.992	67	—	4.830	14	—	7.822	20	—
RE	2	45	3.651	82	—	8.808	25	—	12.458	32	—
RE	3	15	1.326	30	—	1.052	3	—	2.378	6	—
RE	3	30	2.472	55	—	3.034	9	—	5.506	14	—
RE	3	45	3.252	73	—	6.440	19	—	9.692	25	—
RE	4	15	1.665	37	—	1.347	4	—	3.012	8	—
RE	4	30	2.808	63	—	3.514	10	—	6.322	16	—
RE	4	45	3.789	85	—	7.826	23	—	11.615	30	—
RE	5	15	0.648	15	16	0.641	2	2	1.289	3	3
RE	5	30	1.333	30	32	1.595	5	5	2.929	7	8
RE	5	45	2.011	45	49	3.086	9	9	5.097	13	14
RE	6	15	0.603	14	14	0.659	2	2	1.261	3	3
RE	6	30	1.410	32	33	2.197	6	6	3.607	9	9
RE	6	45	1.860	42	44	3.520	10	10	5.380	14	13
RE	7	15	0.802	18	21	0.929	3	3	1.731	4	4
RE	7	30	1.531	34	40	2.235	6	6	3.766	10	10
RE	7	45	2.262	51	59	4.047	12	12	6.309	16	16

Table 4-2. Continued

Pruning type[a]	Tree no.[b]	Targeted dose[c] (%)	Foliage dry mass removed: Sum[d] (lb_m)	Foliage dry mass removed: Average dose[e] (%)	Foliage dry mass removed: Actual dose[f] (%)	Stem dry mass removed: Sum (lb_m)	Stem dry mass removed: Average dose (%)	Stem dry mass removed: Actual dose (%)	Total dry mass removed: Sum (lb_m)	Total dry mass removed: Average dose (%)	Total dry mass removed: Actual dose (%)
ST	1	15	0.864	19	19	2.408	7	6	3.272	8	7
ST	1	30	1.691	38	37	4.931	14	12	6.621	17	15
ST	1	45	2.356	53	52	8.637	25	22	10.993	28	25
ST	2	15	0.873	20	—	3.564	10	—	4.437	11	—
ST	2	30	1.539	35	—	7.501	22	—	9.041	23	—
ST	2	45	1.976	44	—	9.972	29	—	11.948	30	—
ST	3	15	0.869	19	24	2.825	8	8	3.693	9	9
ST	3	30	1.860	42	51	5.706	16	16	7.566	19	19
ST	3	45	2.683	60	73	8.930	26	25	11.612	30	30
TH	1	15	0.907	20	—	1.365	4	—	2.272	6	—
TH	1	30	1.781	40	—	3.046	9	—	4.827	12	—
TH	1	45	2.381	53	—	4.203	12	—	6.584	17	—
TH	2	15	0.786	18	—	0.969	3	—	1.754	4	—
TH	2	30	1.578	35	—	2.171	6	—	3.749	10	—
TH	2	45	2.570	58	—	4.213	12	—	6.783	17	—
TH	3	15	0.735	16	—	1.504	4	—	2.238	6	—
TH	3	30	1.639	37	—	2.715	8	—	4.355	11	—
TH	3	45	2.607	58	—	4.843	14	—	7.451	19	—
TH	4	15	1.007	23	—	1.796	5	—	2.803	7	—
TH	4	30	1.970	44	—	3.943	11	—	5.913	15	—
TH	4	45	2.994	67	—	7.256	21	—	10.250	26	—

[a] Pruning types: LT = lion's tailing, RA = raising, RE = reduction, ST = structural, TH = thinning.
[b] Tree no.: Number assigned to a tree within a pruning type (i.e. LT 4 is the fourth tree lion's tailed).
[c] Targeted dose: Percentage of foliage dry mass intended to be removed by pruning.
[d] Sum: Total dry mass removed at specified pruning dose (foliage, stem, and total respectively). Dry mass was summed incrementally within a tree (i.e. sum at targeted dose 45 = sum of the dry mass removed at 15, 30 and 45 % levels).
[e] Average dose: Dose calculated from an average tree canopy dry mass [foliage (4.458 lb_m), stem (34.769 lb_m), and total (39.227 lb_m) respectively]
[f] Actual dose: A value in this column indicates that dose was calculated from the actual tree canopy dry mass (foliage, stem, and total respectively). A dash indicates the entire tree was not weighed.

Table 4-3. Wind speeds (mph) recorded during testing and least squares means (P = 0.05) adjusted with Tukey's method.

	Motor rpm[a]					
	1	1251	2000	2750	1252	2
n	6480	12956	12929	12960	12960	6463
Mean[b]	2.70 a[c]	23.26 b	38.05 c	52.51 d	20.99 e	2.93 a
Std. err.	0.02	0.06	0.09	0.12	0.06	0.02
Max	10.47	34.62	53.40	75.77	32.83	12.26

a Motor rpm 1 and 2 are ambient conditions and 1251 and 1252 are 1250 rpm before and after the higher rpm respectively.

b Mean is an average of all measurements within an rpm across pruning type, tree, and pruning dose.

c Means with the same letter within rows are not significantly different ($P < 0.05$) based on LS mean separations adjusted using Tukey's method

Table 4-4. Wind speed (mph) by pruning type and motor rpm.

Pruning type[b]	1[a] Mean[c]	1[a] Max.[d]	Pruning type	2750 Mean	2750 Max
LT	2.72 ± 0.03	10.47	LT	47.25 ± 0.27 a[e]	75.77
RA	2.16 ± 0.04	9.57	RA	58.72 ± 0.19 b	73.08
RE	2.43 ± 0.03	6.89	RE	52.71 ± 0.24 c	72.19
ST	4.03 ± 0.06	9.57	ST	50.37 ± 0.41 d	72.19
TH	2.93 ± 0.05	8.68	TH	53.64 ± 0.19 c	72.19

Pruning type	1251 Mean	1251 Max	Pruning type	1252 Mean	1252 Max
LT	21.27 ± 0.13	34.62	LT	18.54 ± 0.12	32.83
RA	25.93 ± 0.10	33.73	RA	24.55 ± 0.08	31.04
RE	23.80 ± 0.11	33.73	RE	21.45 ± 0.11	31.94
ST	19.10 ± 0.20	32.83	ST	17.44 ± 0.18	31.04
TH	24.91 ± 0.10	33.73	TH	21.81 ± 0.12	31.94

Pruning type	2000 Mean	2000 Max	Pruning type	2 Mean	2 Max
LT	34.92 ± 0.19	53.40	LT	3.02 ± 0.04	12.26
RA	42.22 ± 0.15	52.51	RA	2.42 ± 0.04	10.47
RE	37.58 ± 0.17	53.40	RE	2.68 ± 0.03	9.57
ST	34.80 ± 0.29	50.72	ST	4.06 ± 0.05	7.79
TH	40.53 ± 0.15	52.51	TH	3.16 ± 0.05	9.57

[a] Motor rpm 1 and 2 are ambient conditions and 1251 and 1252 are 1250 rpm before and after the higher rpm respectively.

[b] Pruning types: LT = lion's tailing, RA = raising, RE = reduction, ST = structural, TH = thinning.

[c] Mean: Mean ± standard error of one standard deviation with n from 720 to 3360 per pruning type.

[d] Max: Maximum value recorded.

[e] Means with the same letter within columns are not significantly different ($P < 0.05$) based on LS mean separations adjusted using Tukey's method

Table 4-5. Wind speed, trunk movement (m54), and deflected area (dya) at 0 pruning dose and 2750 rpm.

		Wind speed (mph)			m54 (in.)			dya (in.^{2})		
Pruning type[a]	Tree no.[b]	Mean[c]	Std. err.[d]	Max[e]	Mean	Std. err.	Max	Mean	Std. err.	Max
LT	1	47.50	0.50	60.56	3.05	0.03	4.19	106.73	1.22	145.91
LT	2	66.59	0.54	73.98	2.96	0.04	4.05	102.27	1.26	137.73
LT	3	36.74	0.57	50.72	2.48	0.02	3.15	87.50	0.69	111.86
LT	4	33.63	0.91	54.30	2.76	0.02	3.33	95.81	0.66	118.30
LT	5	28.63	0.76	58.77	1.46	0.02	2.16	51.37	0.54	75.40
LT	6	41.00	0.93	63.24	1.39	0.01	1.75	48.89	0.37	61.93
LT	7	51.50	0.46	60.56	1.87	0.02	2.51	66.01	0.84	90.24
RA	2	62.69	0.32	69.51	4.08	0.03	4.74	150.95	1.10	177.49
RA	3	61.42	0.50	70.40	2.29	0.01	2.67	80.84	0.48	95.89
RA	4	63.68	0.61	72.19	4.57	0.02	5.14	157.42	0.80	177.72
RA	5	65.06	0.25	71.29	3.62	0.02	4.04	127.52	0.62	144.44
RA	6	58.96	0.79	70.40	2.36	0.01	2.76	85.08	0.53	99.33
RA	7	66.00	0.41	71.29	2.81	0.02	3.23	99.81	0.60	116.27
RE	1	52.74	0.91	66.82	2.76	0.03	3.45	97.76	1.13	122.59
RE	2	65.11	0.35	70.40	4.13	0.02	4.54	145.99	0.62	161.65
RE	3	48.62	1.03	70.40	3.56	0.03	4.65	124.42	1.10	162.83
RE	4	61.14	0.32	67.72	2.98	0.01	3.30	106.51	0.52	117.54
RE	5	56.49	0.55	65.93	2.17	0.02	2.69	76.33	0.89	94.85
RE	6	39.01	1.18	61.46	1.91	0.01	2.23	67.90	0.40	81.81
RE	7	63.01	0.28	70.40	2.57	0.02	3.05	91.18	0.69	107.84
ST	1	65.97	0.20	69.51	2.21	0.01	2.50	77.85	0.53	88.33
ST	2	32.59	0.87	56.98	1.21	0.01	1.42	42.44	0.37	50.20
ST	3	42.74	0.93	62.35	2.11	0.04	2.87	72.53	1.27	99.75
TH	1	55.33	0.21	63.24	4.23	0.03	5.28	146.49	1.19	184.15
TH	2	52.13	0.35	60.56	3.21	0.02	3.85	111.81	0.71	137.40
TH	3	40.28	0.31	48.93	3.00	0.02	3.67	104.18	0.75	129.55
TH	4	61.73	0.77	72.19	3.60	0.02	4.09	126.35	0.87	143.72

[a] Pruning types: LT = lion's tailing, RA = raising, RE = reduction, ST = structural, TH = thinning.
[b] Tree no.: Number assigned to a tree within a pruning type (i.e. LT 4 is the fourth tree lion's tailed).
[c] Mean: Average of 120 measurements.
[d] Std err: Standard error of one standard deviation.
[e] Max: Maximum value recorded.

Table 4-6. Regression coefficients and R^2 values generated using all measurements of trunk movement (m54) and wind speed (Wind) within a pruning type, tree, pruning dose (Dose), and rpm treatment combination in a complete two factor quadratic empirical model. R^2 values for regressions of deflected area (dya) are given for comparison.

Pruning type[a]	Tree no.[b]	Intercept	Wind	Dose	$Wind^2$	$Dose^2$	Wind*Dose	R^2 (m54)[c]	R^2 (dya)[d]
LT	1	NS[e]	0.0394638	0.0047193	0.0004759	-0.0002174	-0.0010233	0.925	0.924
LT	2	0.0521557	0.0283154	-0.0159439	0.0001968	0.0005834	-0.0004388	0.911	0.917
LT	3	NS	0.0590989	-0.0065756	-0.0001017	0.0001145	-0.0007349	0.805	0.805
LT	4	0.0678023	0.0590676	-0.0098421	0.0000748	0.0001746	-0.0007114	0.818	0.818
LT	5	-0.1399732	0.0564957	-0.0026469	-0.0003689	0.0000586	-0.0003598	0.761	0.759
LT	6	0.0562677	0.0228512	-0.0085027	0.0001034	0.0001678	-0.0003292	0.883	0.884
LT	7	NS	0.0351883	-0.0065309	-0.0000014	0.0001463	-0.0006956	0.836	0.834
RA	2	NS	0.0478202	NS	0.0002678	0.0000184	-0.0006647	0.952	0.949
RA	3	-0.0642992	0.0296015	0.0017010	0.0000995	0.0000141	-0.0004418	0.955	0.950
RA	4	0.1265204	0.0482748	NS	0.0003028	-0.0000210	-0.0005730	0.961	0.962
RA	5	NS	0.0345920	0.0021254	0.0003331	-0.0000616	-0.0003397	0.975	0.974
RA	6	-0.0916750	0.0293212	0.0049636	0.0001484	-0.0000387	-0.0004692	0.909	0.909
RA	7	NS	0.0311609	0.0024453	0.0001711	-0.0000527	-0.0003323	0.953	0.951
RE	1	0.0473252	0.0432073	0.0051511	0.0001259	-0.0001726	-0.0005428	0.909	0.905
RE	2	-0.0933176	0.0357488	0.0054225	0.0004122	-0.0000259	-0.0004044	0.895	0.894
RE	3	NS	0.0596352	NS	0.0001248	-0.0000479	-0.0004766	0.904	0.901
RE	4	NS	0.0333231	0.0051231	0.0002828	-0.0000796	-0.0003062	0.966	0.962
RE	5	0.0489778	0.0269396	-0.0044869	0.0001827	0.0000754	-0.0002095	0.926	0.924
RE	6	NS	0.0530362	NS	-0.0002288	NS	-0.0002129	0.747	0.747
RE	7	0.0492041	0.0508709	NS	0.0003363	-0.0001186	-0.0000891	0.958	0.956

Table 4-6. Continued.

Pruning type[a]	Tree no.[b]	Intercept	Wind	Dose	Wind^2	Dose^2	Wind*Dose	R^2 (m54)[c]	R^2 (dya)[d]
ST	1	-0.1543650	0.0288068	0.0037946	0.0001217	-0.0000384	-0.0003226	0.959	0.957
ST	2	NS	0.0405986	-0.0057574	-0.0002261	0.0000806	-0.0004180	0.751	0.744
ST	3	-0.0680923	0.0411714	NS	0.0001394	NS	-0.0004593	0.870	0.865
TH	1	0.0695847	0.0402283	-0.0091875	0.0005953	0.0001810	-0.0006801	0.935	0.932
TH	2	-0.0586411	0.0366951	NS	0.0004529	0.0000266	-0.0004189	0.956	0.952
TH	3	NS	0.0468575	NS	0.0003885	0.0000353	-0.0005330	0.897	0.897
TH	4	-0.1534129	0.0405974	0.0035574	0.0002915	NS	-0.0004013	0.933	0.935

[a] Pruning types: LT = lion's tailing, RA = raising, RE = reduction, ST = structural, TH = thinning.
[b] Tree no.: Number assigned to a tree within a pruning type (LT 4 was the fourth tree lion's tailed).
[c] R^2 (m54): regressions using all wind speed and m54 measurements within pruning type, tree, pruning dose, and rpm.
[d] R^2 (dya): regressions using all wind speed and dya measurements within pruning type, tree, pruning dose, and rpm.
[e] NS: Not statistically significant at P = 0.05.

Table 4-7. Regression coefficients and R^2 values generated using averages of trunk movement (avm54) and wind speed (Wind) within a pruning type, tree, pruning dose (Dose), and rpm treatment combination in a complete two factor quadratic empirical model. R^2 values for regressions of average deflected area (avdya) are given for comparison.

Pruning type[a]	Tree no.[b]	Intercept	Wind	Dose[c]	$Wind^2$	$Dose^2$	Wind*Dose	R^2 (avm54)[d]	R^2 (avdya)[e]
LT	1	NS[f]	0.0346330	NS	0.0006744	NS	-0.0012533	0.991	0.991
LT	2	NS	0.0249140	NS	0.0002559	NS	-0.0004317	0.986	0.989
LT	3	NS	0.0496499	NS	NS	NS	-0.0011734	0.949	0.950
LT	4	NS	0.0588409	NS	NS	NS	-0.0008994	0.951	0.952
LT	5	NS	0.0203197	NS	0.0010574	NS	-0.0004278	0.994	0.994
LT	6	NS	0.0206290	NS	0.0002513	0.0001765	-0.0005026	0.980	0.981
LT	7	NS	0.0326324	NS	NS	NS	-0.0004130	0.983	0.983
RA	2	NS	0.0460744	NS	0.0002787	NS	-0.0006488	0.980	0.978
RA	3	NS	0.0272470	NS	0.0001357	NS	-0.0004305	0.979	0.976
RA	4	NS	0.0467960	NS	0.0003508	NS	-0.0005782	0.976	0.979
RA	5	NS	0.0300226	NS	0.0004070	NS	-0.0003064	0.995	0.995
RA	6	NS	0.0247701	NS	0.0002553	NS	-0.0004774	0.979	0.979
RA	7	NS	0.0232733	NS	0.0003050	NS	-0.0002541	0.994	0.994
RE	1	NS	0.0441449	NS	0.0002051	NS	-0.0006638	0.975	0.975
RE	2	NS	0.0251932	NS	0.0005598	NS	-0.0002876	0.948	0.949
RE	3	NS	0.0463334	NS	0.0004676	NS	-0.0004837	0.990	0.990
RE	4	NS	0.0326210	NS	0.0003099	-0.0000629	-0.0003246	0.989	0.989
RE	5	NS	0.0200714	NS	0.0003093	NS	NS	0.983	0.984
RE	6	NS	0.0363065	NS	0.0004618	NS	-0.0003410	0.947	0.947
RE	7	NS	0.0200764	NS	0.0003667	NS	-0.0001350	0.986	0.986

Table 4-7. Continued.

Pruning type[a]	Tree no.[b]	Intercept	Wind	Dose[c]	$Wind^2$	$Dose^2$	Wind*Dose	R^2 (avm54[d])	R^2 (avdya[e])
ST	1	NS	0.0266158	NS	0.0001453	NS	-0.0003157	0.985	0.986
ST	2	NS	0.0345746	NS	NS	NS	-0.0006789	0.968	0.969
ST	3	NS	0.0275358	NS	0.0005033	NS	-0.0004889	0.988	0.988
TH	1	NS	0.0365198	NS	0.0006660	NS	-0.0006502	0.988	0.989
TH	2	NS	0.0337152	NS	0.0005155	NS	-0.0004285	0.993	0.993
TH	3	NS	0.0313188	NS	0.0008477	NS	-0.0006126	0.982	0.983
TH	4	NS	0.0299773	NS	0.0005137	NS	-0.0004197	0.986	0.986

[a] Pruning types: LT = lion's tailing, RA = raising, RE = reduction, ST = structural, TH = thinning.
[b] Tree no.: Number assigned to a tree within a pruning type (LT 4 is the fourth tree lion's tailed).
[c] Dose: Percentage of foliage dry mass removed from the tree with pruning.
[d] avm54: Wind speed and m54 measurements averaged within pruning type, tree, pruning dose, and rpm.
[e] avdya: Wind speed and dya measurements averaged within pruning type, tree, pruning dose, and rpm.
[f] NS: Not statistically significant at $P = 0.05$.

Table 4-8. ANOVA of predicted trunk movement (p_avm54) and predicted deflected area (p_avdya).

Source of variation	p_m54[a] (in.)		p_avm54[b] (in.)		p_dya[c] ($in.^2$)		p_avdya[d] ($in.^2$)	
	F	*P > F*	*F*	*P > F*	*F*	*P > F*	*F*	*P > F*
Pruning type[e]	41.49	< 0.001	21.94	< 0.001	42.16	< 0.001	21.98	< 0.001
Pruning dose[f]	83.49	< 0.001	66.18	< 0.001	84.22	< 0.001	67.11	< 0.001
Pruning type * pruning dose	0.58	0.898	0.75	0.739	0.62	0.870	0.78	0.708
Wind speed[g]	395.29	< 0.001	399.48	< 0.001	396.02	< 0.001	402.90	< 0.001
Pruning type * wind speed	7.37	< 0.001	3.69	< 0.001	7.26	< 0.001	3.54	< 0.001
Pruning dose * wind speed	5.96	< 0.001	5.02	< 0.001	5.93	< 0.001	5.05	< 0.001
Pruning type * pruning dose * wind speed	0.07	1.000	0.12	1.000	0.07	1.000	0.12	1.000

[a] p_m54: predicted trunk movement based on all measurements within pruning type, tree, pruning dose and motor rpm.
[b] p_avm54: predicted trunk movement based on measurements averaged within pruning type, tree, pruning dose and motor rpm.
[c] p_dya: predicted trunk deflected area based on all measurements within pruning type, tree, pruning dose and motor rpm.
[d] p_avdya: predicted trunk deflected area based on measurements averaged within pruning type, tree, pruning dose and motor rpm.
[e] Pruning types: LT = lion's tailing, RA = raising, RE = reduction, ST = structural, TH = thinning.
[f] Pruning dose (percentage of foliage dry mass removed) levels at which average trunk movement was predicted from regression models.
[g] Wind: wind speed (mph) levels at which average trunk movement was predicted from regression models.

Table 4-9. Least squares means of predicted average trunk movement (p_avm54) due to interaction of pruning type and wind speed – type by wind speed.

Type[b]	p_avm54[a] (in.)			
	15 (mph)[c]	30 (mph)	45 (mph)	60 (mph)
ST	NS[d]	NS	1.31a[e]	2.05a
RA	NS	NS	1.50a	2.25a
LT	NS	NS	1.51a	2.39a
RE	NS	NS	1.77ab	2.70a
TH	NS	NS	2.07b	3.32b

[a] p_avm54: Average trunk movement predicted from regression models.
[b] Pruning types: LT = lion's tailing, RA = raising, RE = reduction, ST = structural, TH = thinning.
[c] Wind speed (mph) levels at which average trunk movement was predicted from regression models.
[d] NS: Not statistically significant at $P = 0.05$.
[e] Means with the same letter within columns are not significantly different ($P < 0.05$) based on LS mean separations adjusted using Tukey's method.

Table 4-10. Least squares means of predicted average trunk movement (p_avm54) due to interaction of pruning type and wind speed – wind speed by type.

Wind[b]	p_avm54[a] (in.)				
	Lion's tailing	Raising	Reduction	Structural	Thinning
15	0.34a[c]	0.40a	0.41a	0.28ab	0.41a
30	0.82b	0.89b	1.00b	0.72abc	1.10b
45	1.51c	1.50c	1.77c	1.31bcd	2.07c
60	2.39d	2.25d	2.70d	2.05cd	3.32d

[a] p_avm54: Average trunk movement predicted from regression models.
[b] Wind speed (mph) levels at which average trunk movement was predicted from regression models.
[c] Means with the same letter within columns are not significantly different ($P < 0.05$) based on LS mean separations adjusted using Tukey's method.

Table 4-11. Least squares means of predicted average trunk movement (p_avm54) due to interaction of pruning dose and wind speed – dose by wind speed.

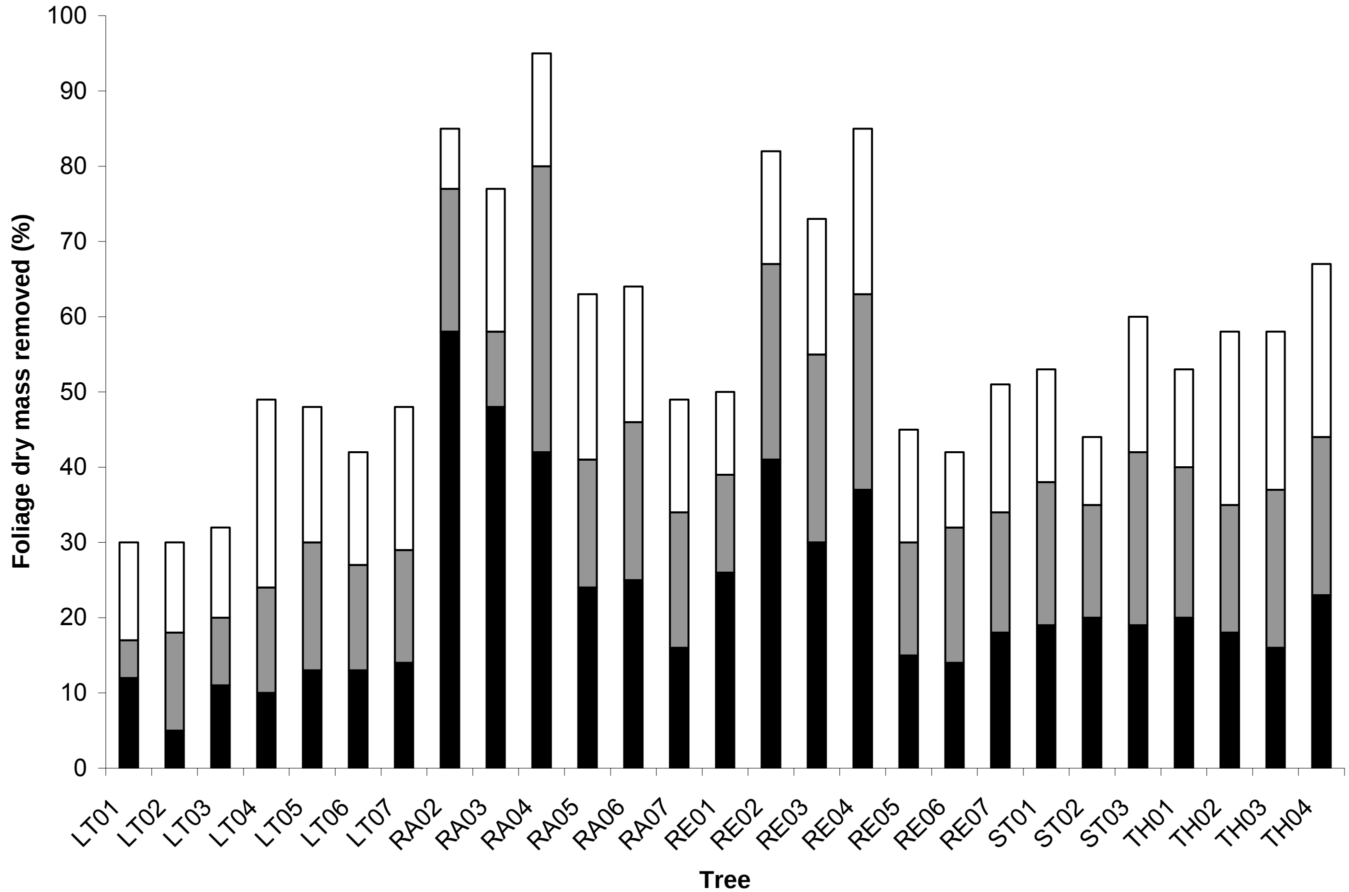
Dose[b]	p_avm54[a] (in.)			
	15 (mph)[c]	30 (mph)	45 (mph)	60 (mph)
60	NS[d]	0.51ab[e]	1.01ab	1.71ab
45	NS	0.70abc	1.31abc	2.11abc
30	NS	0.90abcd	1.62bcd	2.53bcd
15	NS	1.11bcd	1.94cde	2.96cde
0	NS	1.32cd	2.27de	3.40de

[a] p_avm54: Average trunk movement predicted from regression models.
[b] Dose: Pruning dose (percentage of foliage dry mass removed) levels at which average trunk movement was predicted from regression models.
[c] Wind speed levels at which average trunk movement was predicted from regression models.
[d] NS: Not statistically significant at $P = 0.05$.
[e] Means with the same letter within columns are not significantly different ($P < 0.05$) based on LS mean separations adjusted using Tukey's method.

Table 4-12. Least squares means of predicted average trunk movement (p_avm54) due to interaction of pruning dose and wind speed – wind speed by dose.

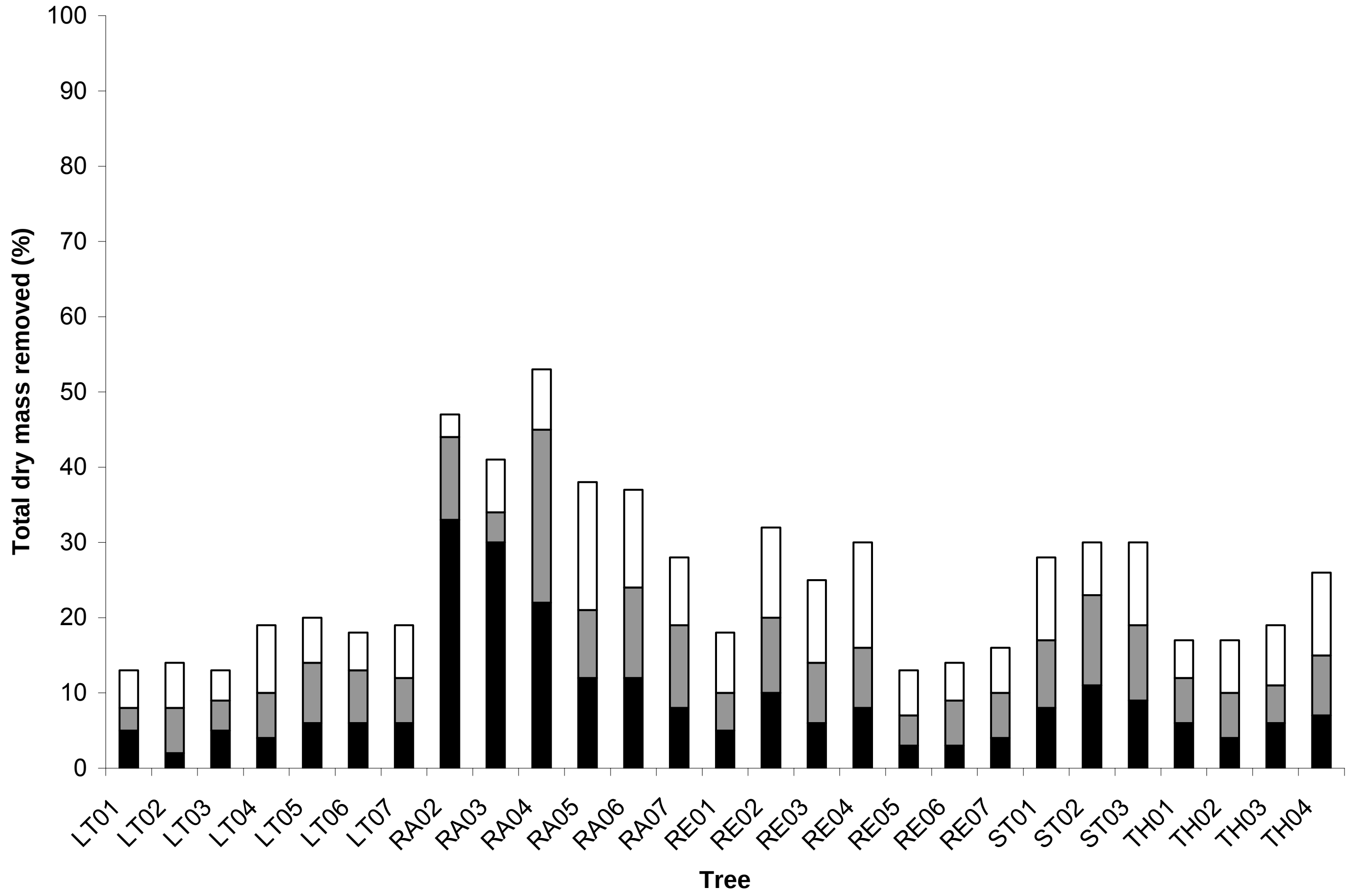
Wind[b]	p_avm54[a] (in.)				
	No foliage dry mass removed[c]	15 % foliage dry mass removed	30 % foliage dry mass removed	45 % foliage dry mass removed	60 % foliage dry mass removed
15	0.56a[d]	0.46a	0.36a	0.27a	0.19a
30	1.32b	1.11b	0.90a	0.70a	0.51ab
45	2.27c	1.94c	1.62b	1.31b	1.01b
60	3.40d	2.96d	2.53c	2.11c	1.71c

[a] p_avm54: Average trunk movement predicted from regression models.
[b] Wind speed (mph) levels at which average trunk movement was predicted from regression models.
[c] Pruning dose (percentage of foliage dry mass removed) levels at which average trunk movement was predicted from regression models.
[d] Means with the same letter within columns are not significantly different ($P < 0.05$) based on LS mean separations adjusted using Tukey's method.



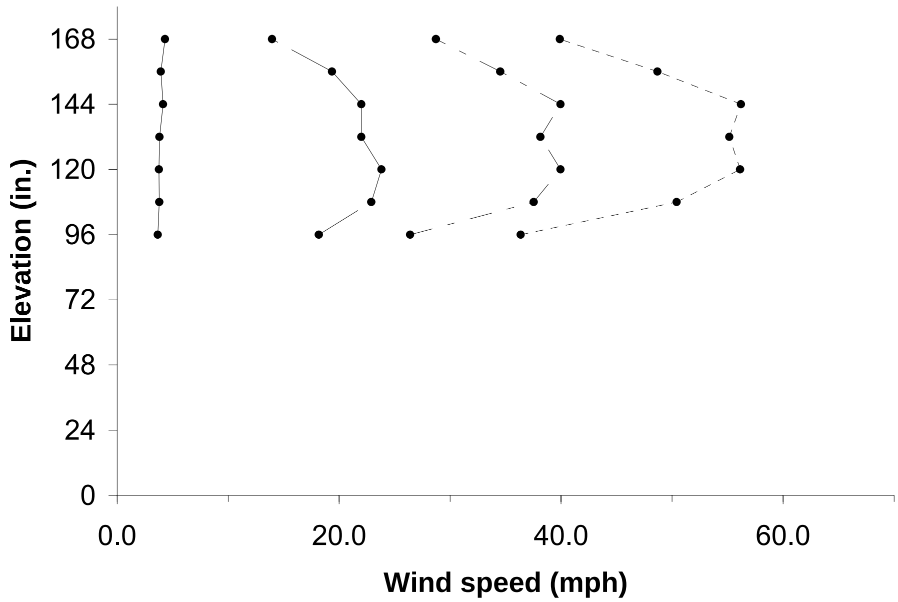
A

Figure 4.1. Pruning dose represented as percentage of foliage dry mass removed (A) and percentage of total dry mass removed (B) with respect to an average tree canopy mass. Black bar = 15%, gray bar = 30%, and white bar = 45% targeted pruning dose levels. LT = lion's tailing, RA = raising, RE = reduction, ST = structural, TH = thinning pruning types. Number represents a tree assigned to the specific pruning type (27 trees total).

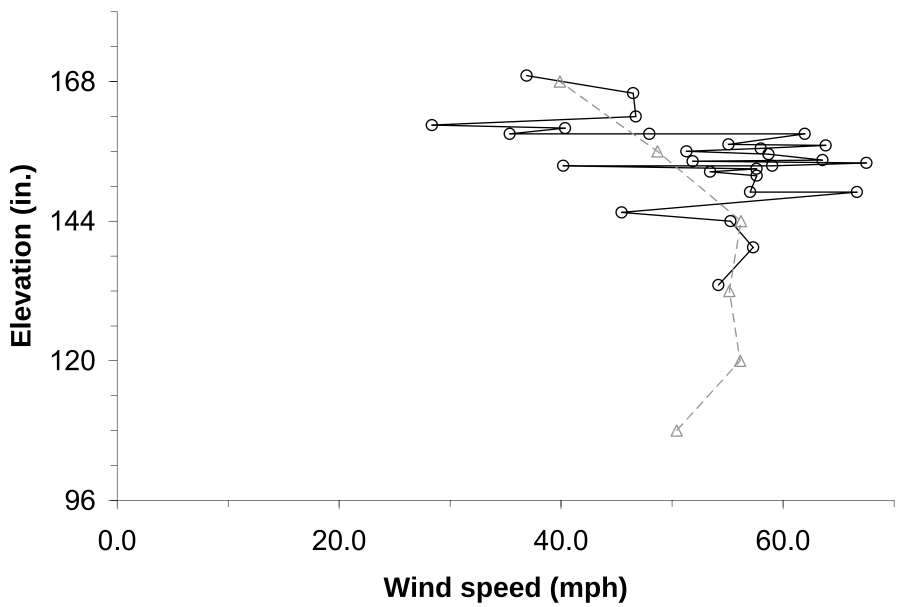


B

Figure 4.1. Continued.



A



B

Figure 4.2. Vertical profile of average generated wind speeds. A) Measured before and after testing on three different days (27May2004, 9Mar2005, and 15Mar2005). Profiles represent ambient (solid line), 1250 (dash line), 2000 (dash dot line), and 2750 (dot line) motor rpm. Wind speeds were recorded at 0.5 Hz for 4 minutes at each elevation and averaged across days within an elevation (solid circles). B) Measured during testing – 27 trees at 2750 rpm. Circles and solid line represent average wind speeds for 27 trees while triangles and dash line represent the equivalent portion of the 2750 motor rpm profile measured before and after testing.

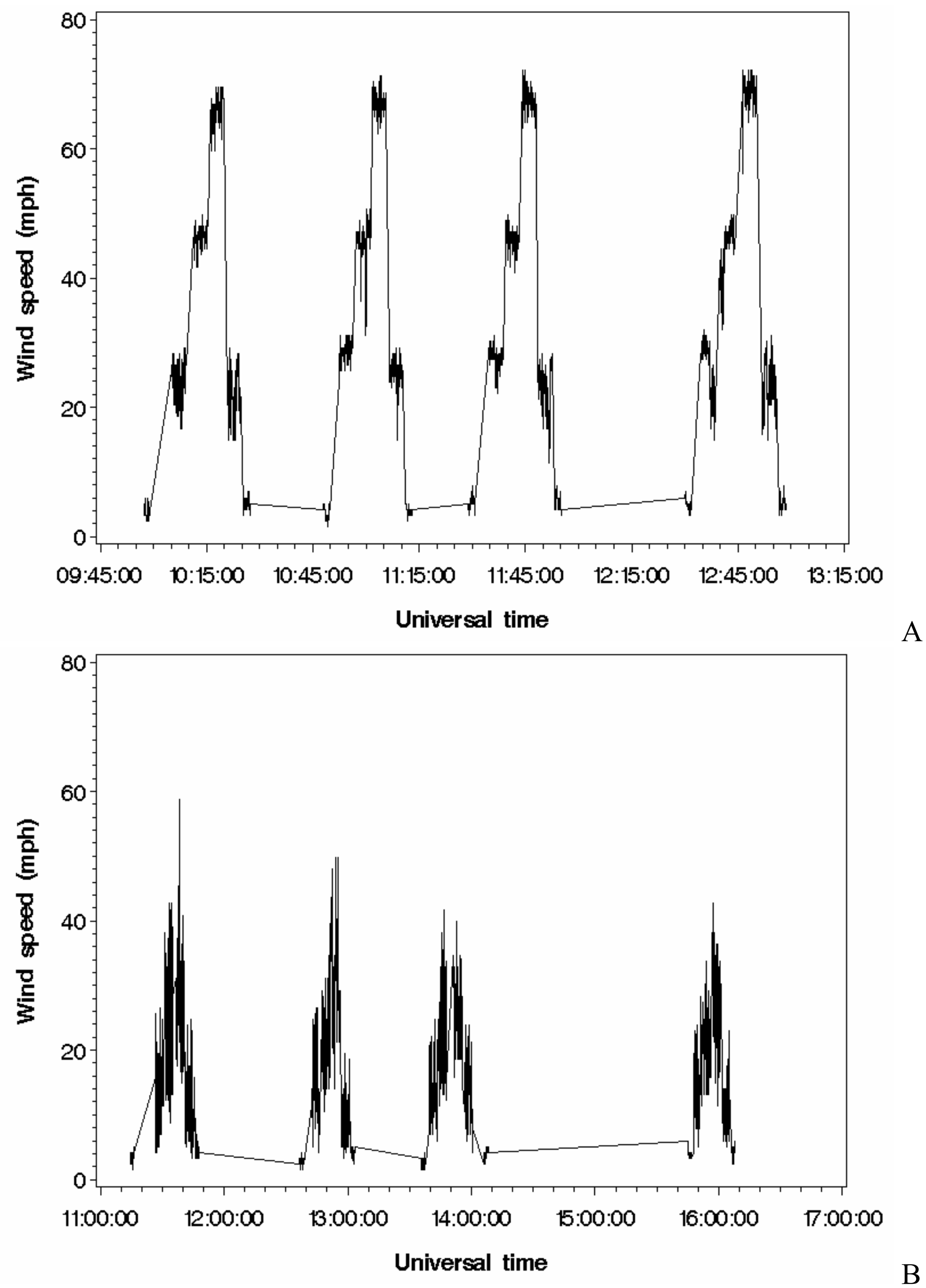
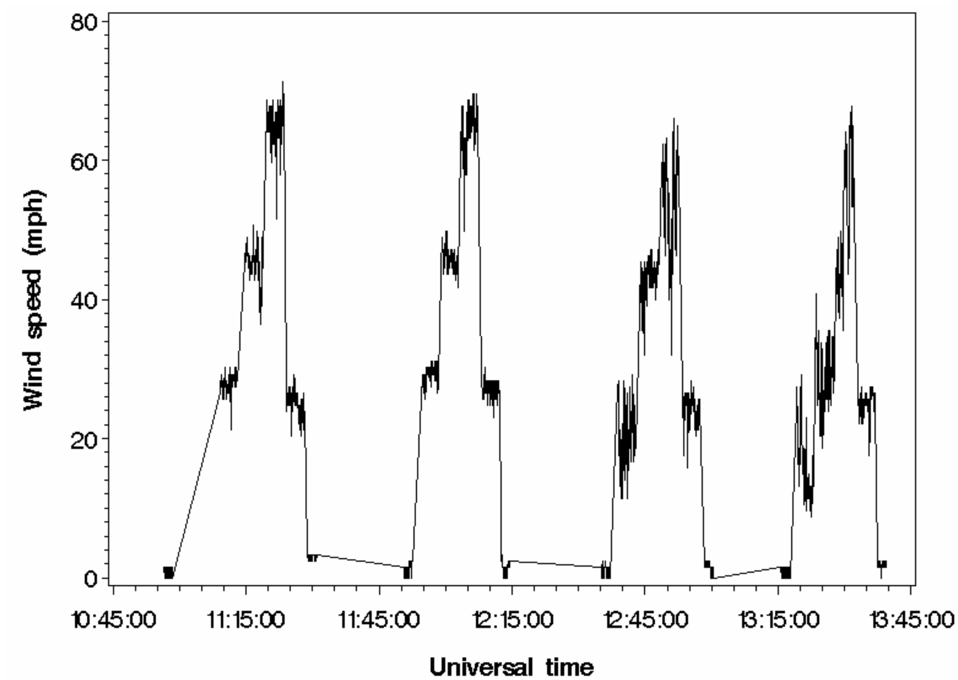
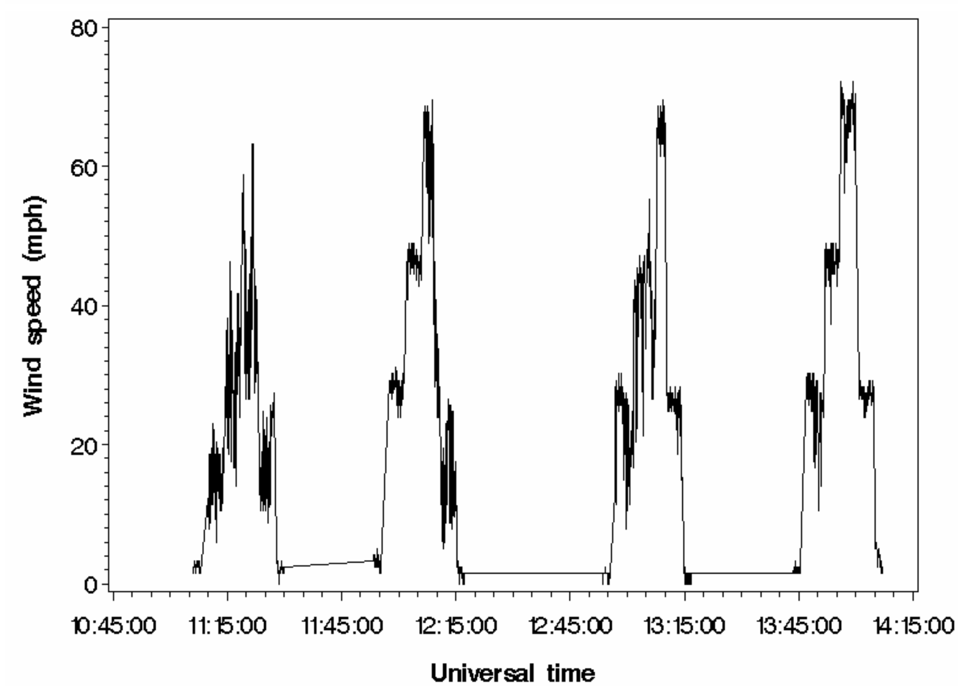


Figure 4.3. Four profiles of wind speeds generated by the airboat during testing (measured at 0.5 Hz). A) A desirable profile (structural pruned tree number 1), B) an undesirable profile (lion's tailed tree number 5), C) a profile that progresses from good to poor (raised tree number 5), and D) a profile that progresses from poor to good (lion's tailed tree number 6). Each profile was recorded on a different day of the year. Peaks represent a sequence of rpm repeated four times.



C



D

Figure 4.3. Continued.

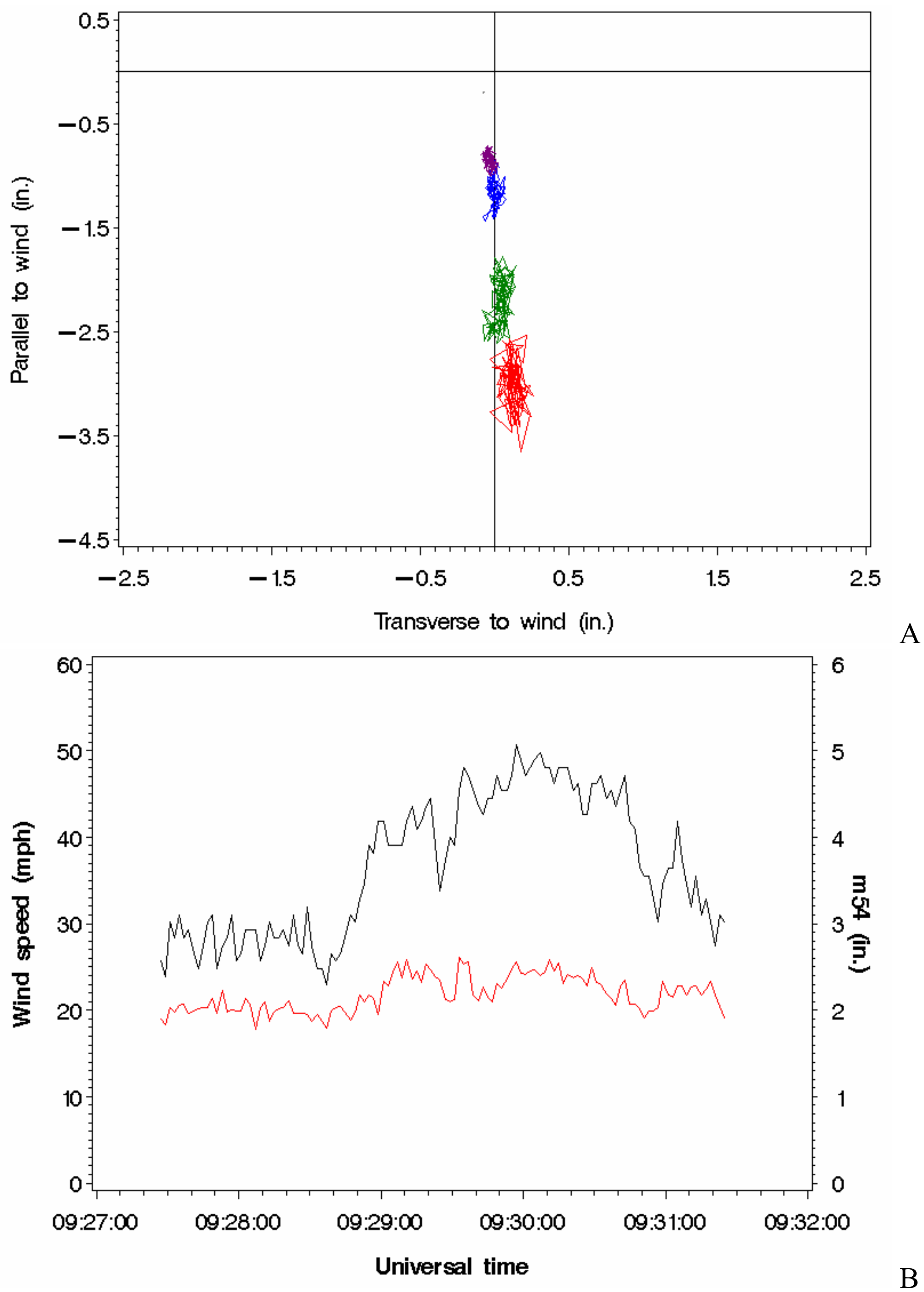


Figure 4.4. Trunk movement measured at an elevation 54 inches above topmost root (m54 – thinned tree number 3 before any pruning). A) Bird's eye, plan view of m54 in winds generated at all motor rpm (black – 1, grey – 2, blue – 1251, purple – 1252, green – 2000, red – 2750 rpm). Trunk position starts at the origin and was recorded at 0.5 Hz. Primary direction of wind flow is from top to bottom of the page. B) Time series of wind speed (black) and m54 (red) at 2000 rpm.

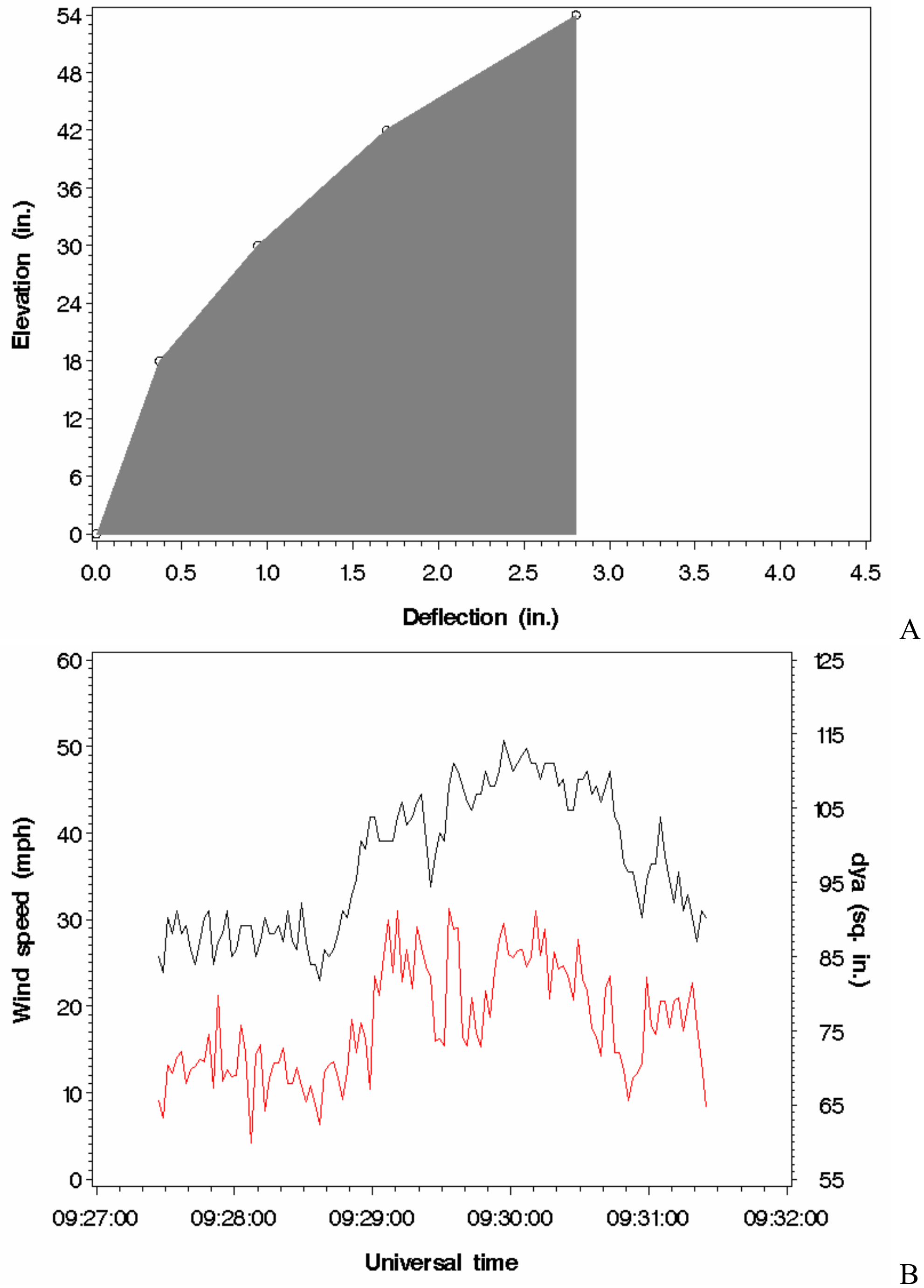
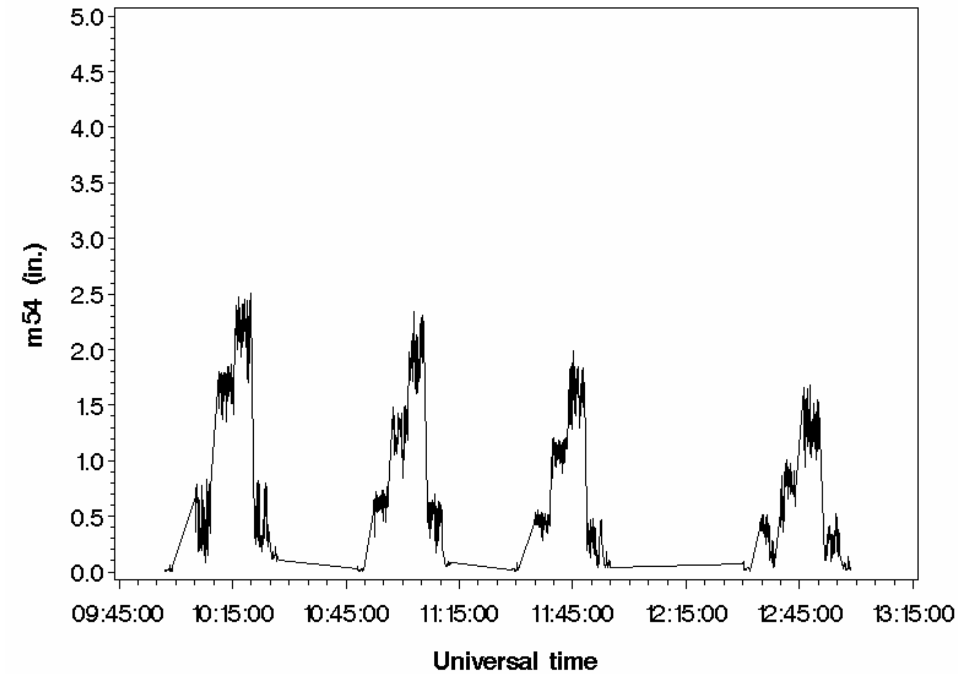
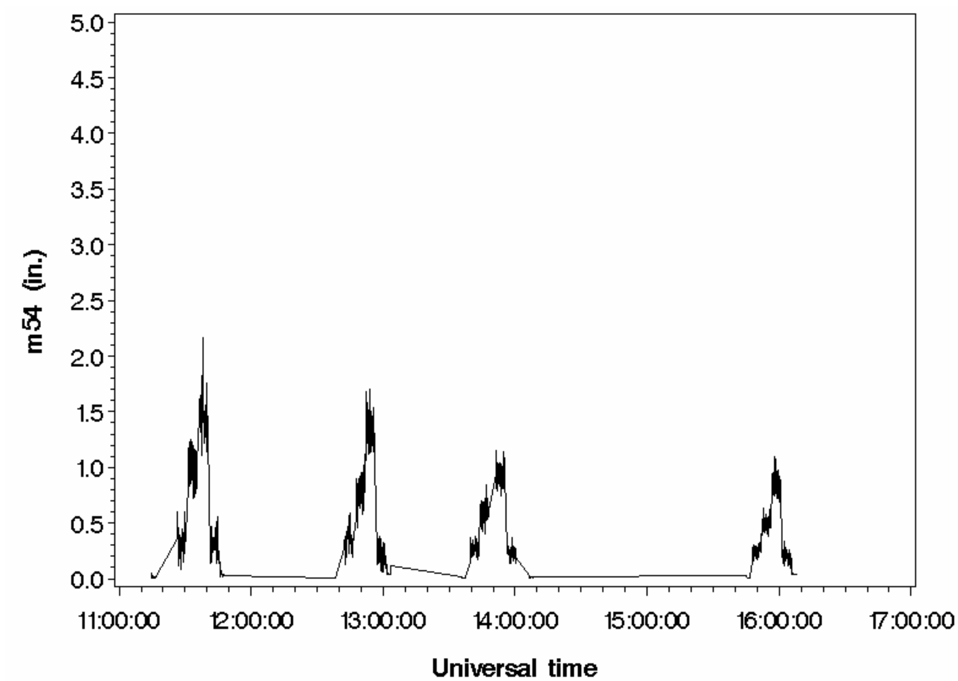


Figure 4.5. Trunk movement measured as an area of deflection (dya – thinned tree number 3 before pruning). A) Transverse view of dya (x-axis is exaggerated for illustration). Cable extension transducers were located at 18, 30, 42, and 54 inches along the trunk (circles). Primary direction of wind flow was from left to right across the page. B) Time series of wind speed (black) and dya (red) at 2000 rpm recorded at 0.5 Hz.

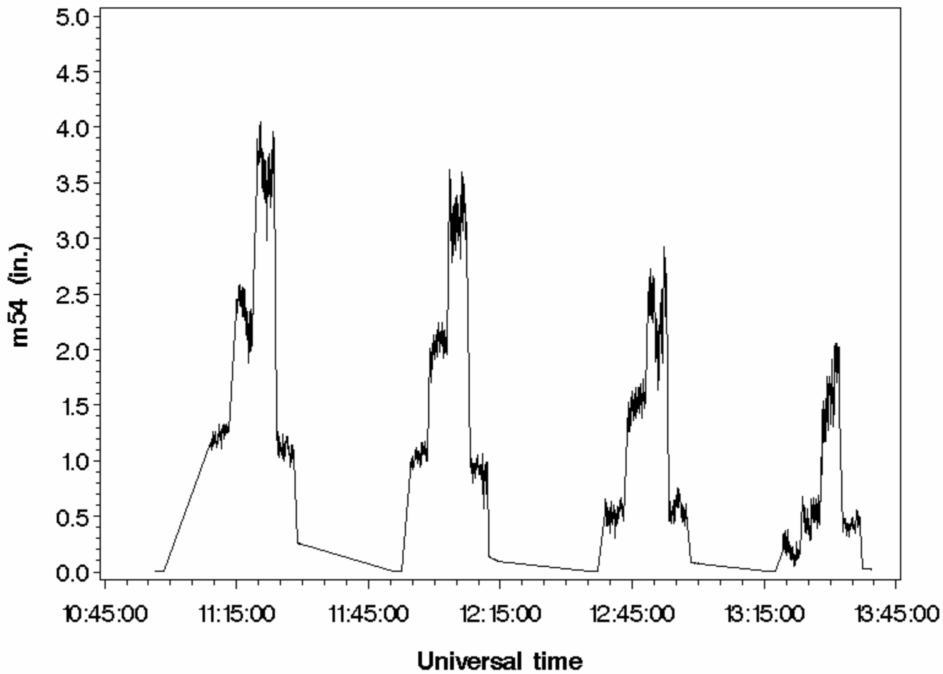


A

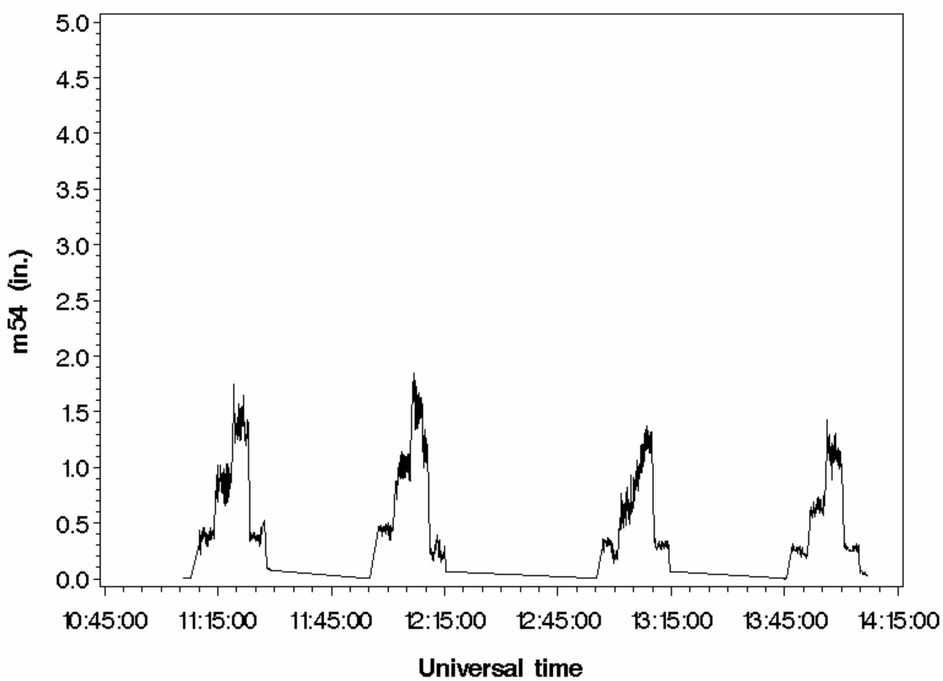


B

Figure 4.6. Four time series profiles of trunk movement at an elevation 54 inches above topmost root (m54 – recorded at 0.5 Hz). A) A desirable wind profile (structural pruned tree number 1), B) an undesirable wind profile (lion's tailed tree number 5), C) a wind profile that progresses from good to poor (raised tree number 5), and D) a wind profile that progresses from poor to good (lion tailed tree number 6). Peaks represent a sequence of motor rpm used to generate wind speeds that was repeated for each pruning dose. Pruning dose increases in severity from left to right across the page.

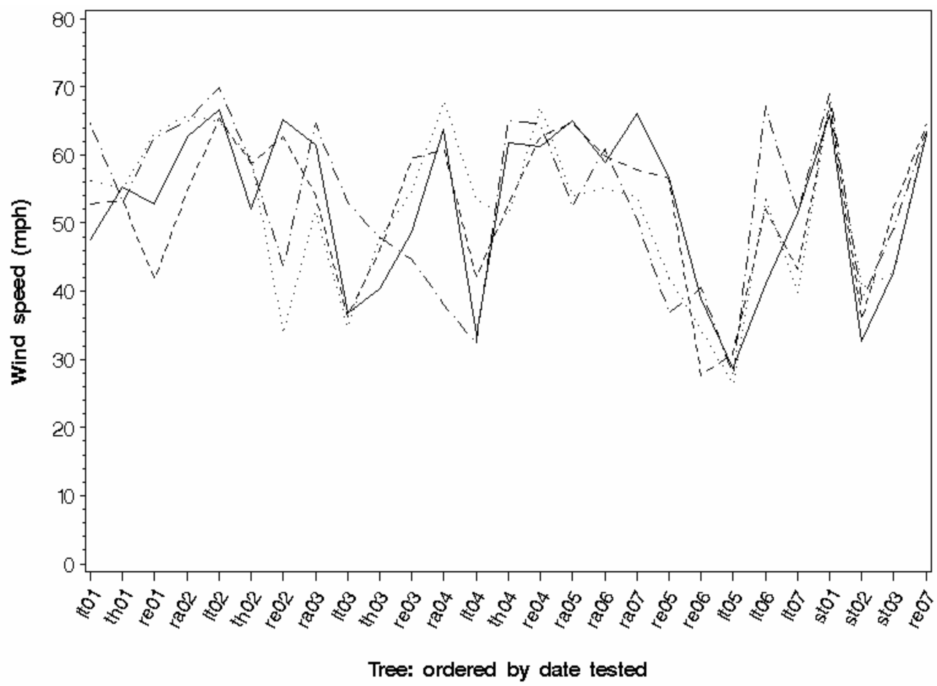


C

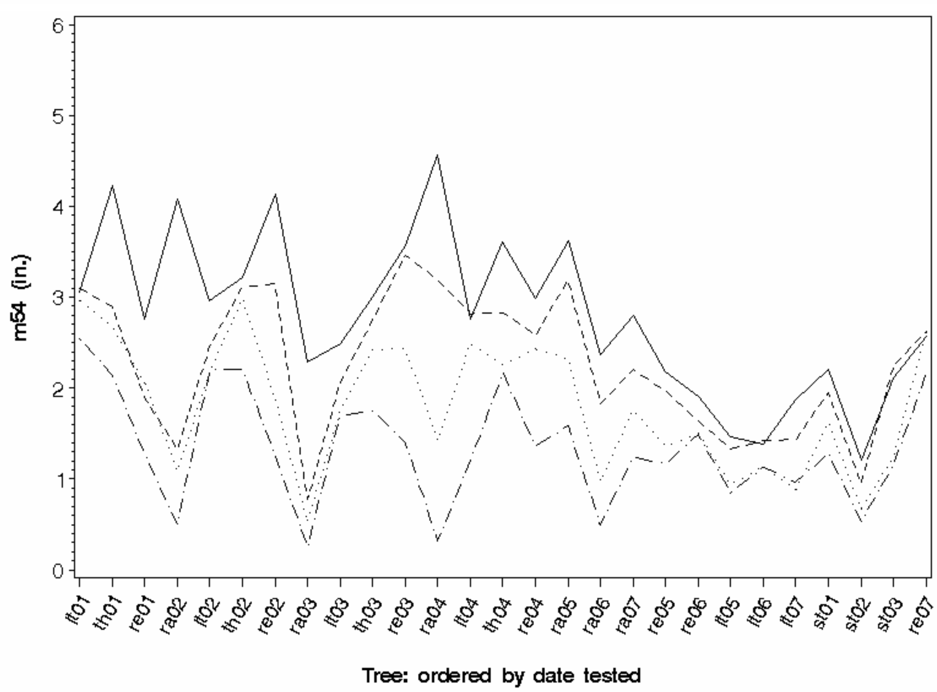


D

Table 4.6. Continued.

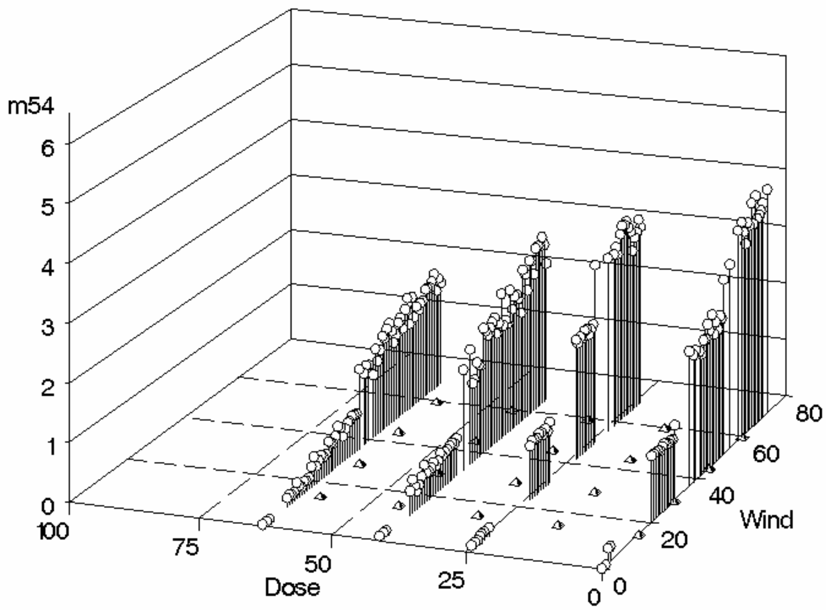


A

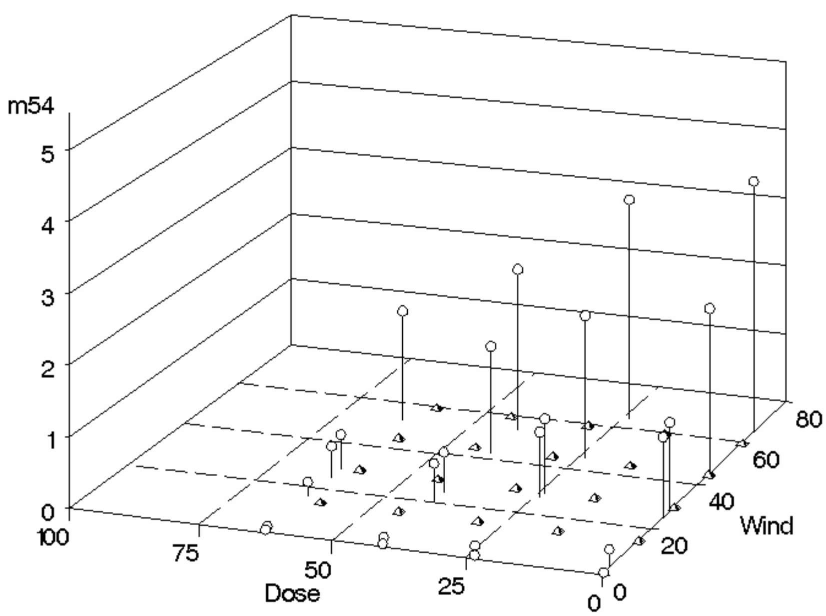


B

Figure 4.7. Wind speed (A) trunk movement (m54) (B) at all pruning doses by date tested. Solid line is no foliage dry mass removed. Dash line is 15%, dot line is 30%, and dash-dot line is 45% targeted dose level. Tree label is a combination of pruning type and tree within the pruning type. Pruning types are: lt = lion's tailing, ra = raising, re = reduction, st = structural, and th = thinning (lt01 represents the first tree that was lion's tailed).

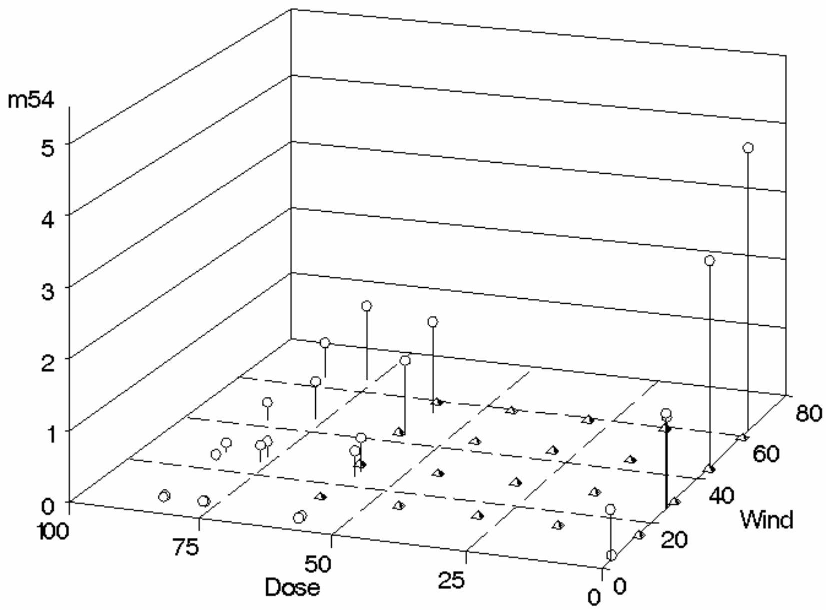


A

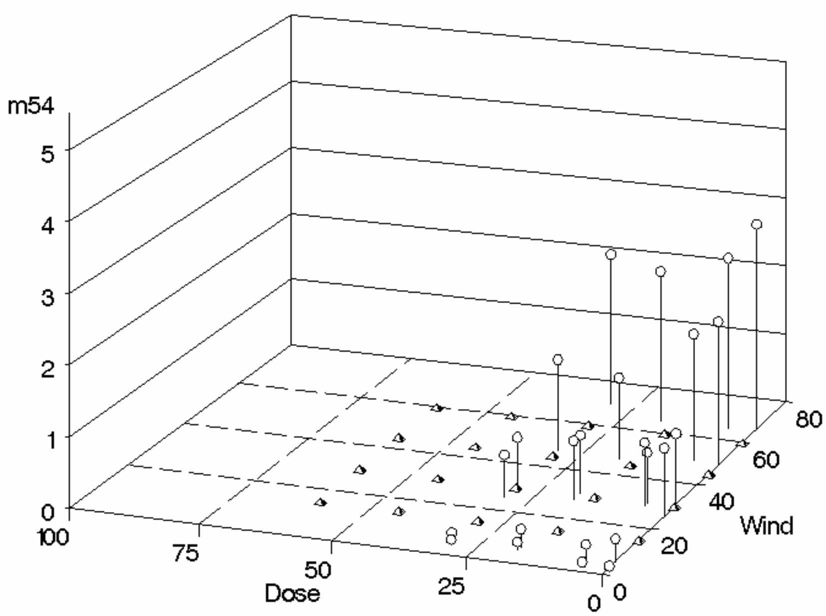


B

Figure 4.8. Three dimensional scatterplots of trunk movement at an elevation 54 inches above topmost root: A) all measurements within a pruning type and tree – raised tree number 5, B) trunk movement and wind speed averaged within a motor rpm. Plots show one of the better distributions of wind speed and pruning dose. Pyramids represent orthogonal levels of wind speed and pruning dose targeted to simplify statistical analysis.

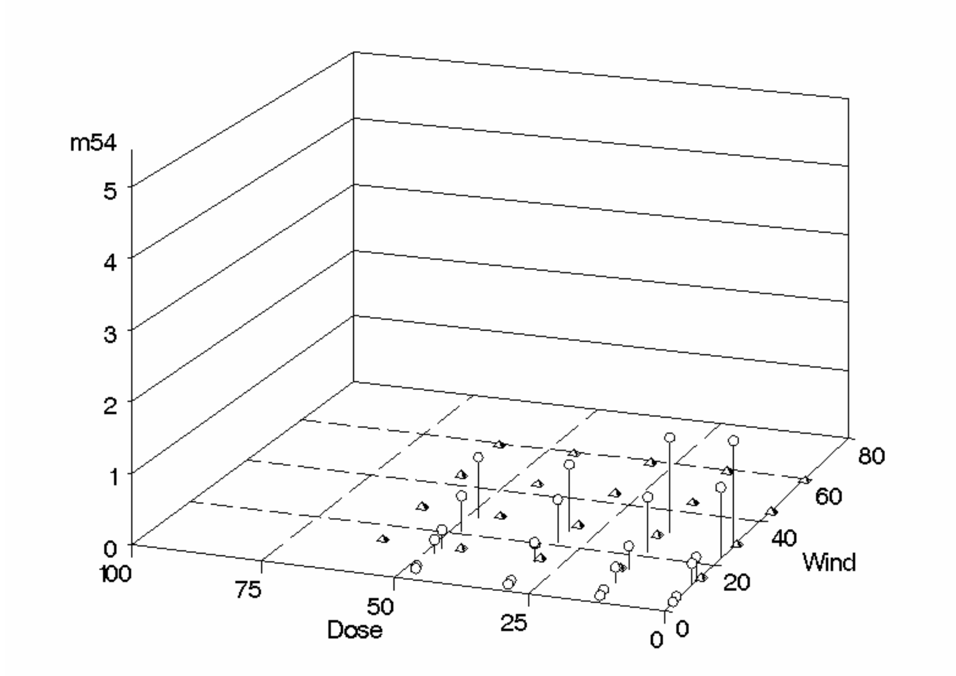


A



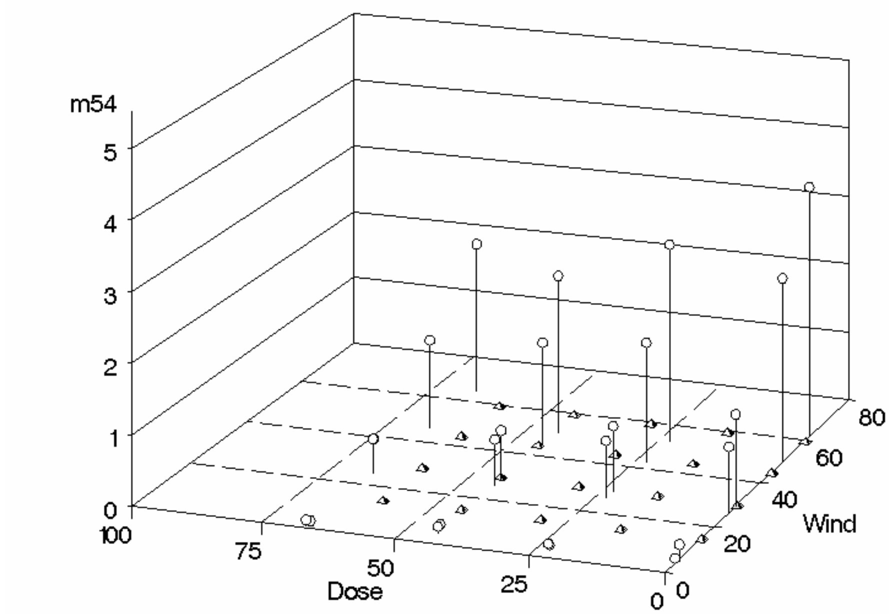
B

Figure 4.9. Three less desirable distributions of wind speed and pruning dose (% foliage dry mass removed): A) A good distribution of wind speed but nothing in the low end of pruning dose – raised tree number 2, B) a good distribution of wind speed but nothing in the high end of pruning dose – lion tail tree number 2, C) a poor distribution of both wind speed and pruning dose – lion tail tree number 5. Pyramids represent orthogonal levels of wind speed and pruning dose targeted to simplify statistical analysis.



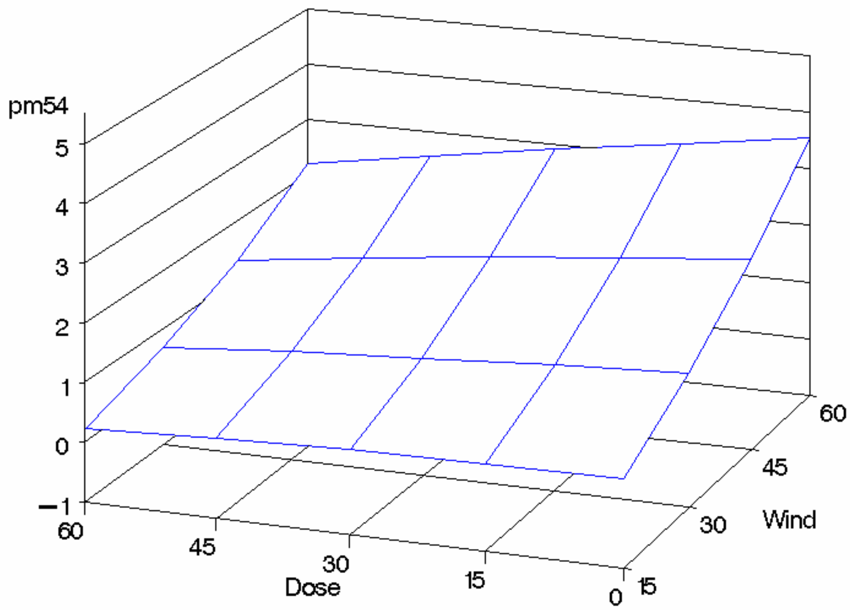
C

Figure 4.9. Continued.

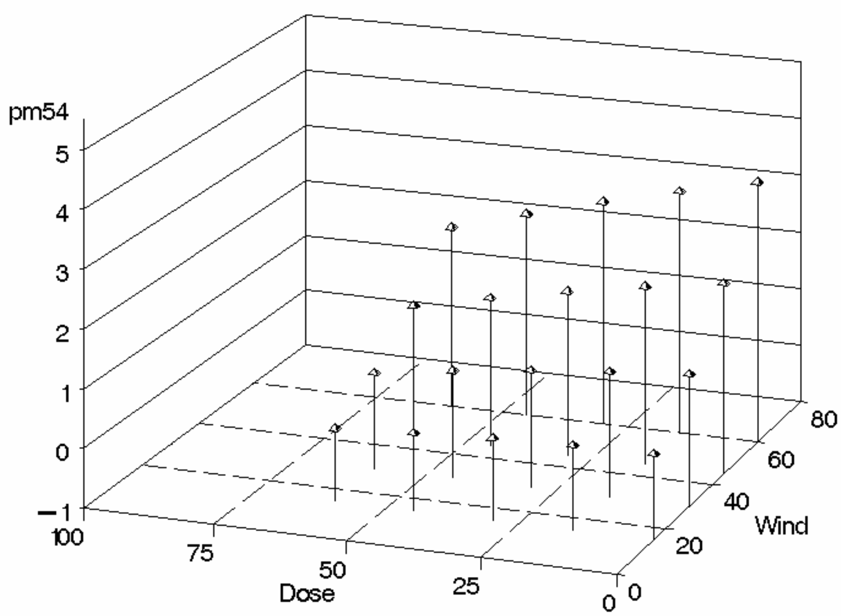


A

Figure 4.10. A graphical summary of the procedure used to generate predicted response values (thinned tree number 4): A) Trunk movement measured 54 inches above topmost root (m54 – averaged within motor rpm) plotted against wind speed (averaged within motor rpm) and pruning dose (percent of foliage dry mass removed). Pyramids represent orthogonal levels of pruning dose and wind speed targeted to simplify statistical analysis. B) Response surface representing predicted m54 ($m54 = 0.02998 * wind + 0.0005 * wind^2 - 0.0004 * wind * dose$, $R^2 = 0.986$). C) Predicted levels of m54 (pm54) at orthogonal levels of pruning dose and wind speed. Predicted levels in C were used in the statistical analysis.



B



C

Figure 4.10. Continued.

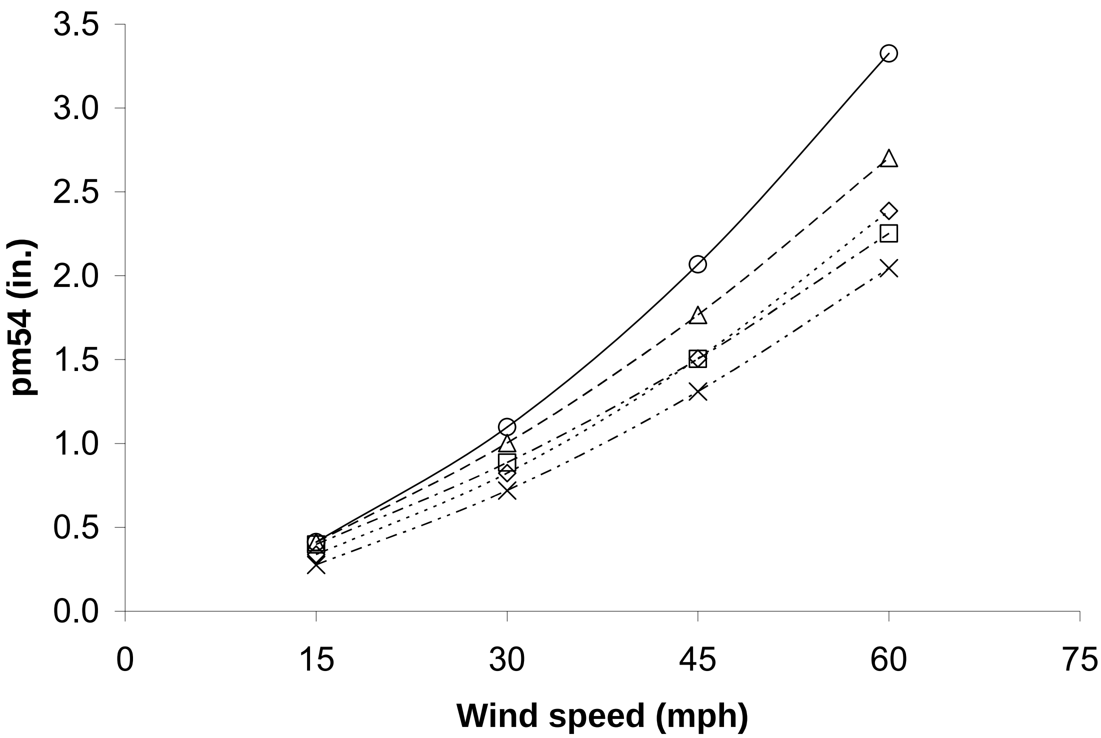


Figure 4.11. Interaction between pruning type and wind speed ($p<0.0001$) resulting from predicted average trunk movement at an elevation 54 inches above topmost root (pm54). Vertical axis is the least square means of pm54 adjusted using Tukey's method. Lines represent pruning types. Circles and solid line = thinned, triangles and dash line = reduced, squares and dash dot line = raised, diamonds and dot line = lion tailed, and Xs and dash dot dot line = structural.

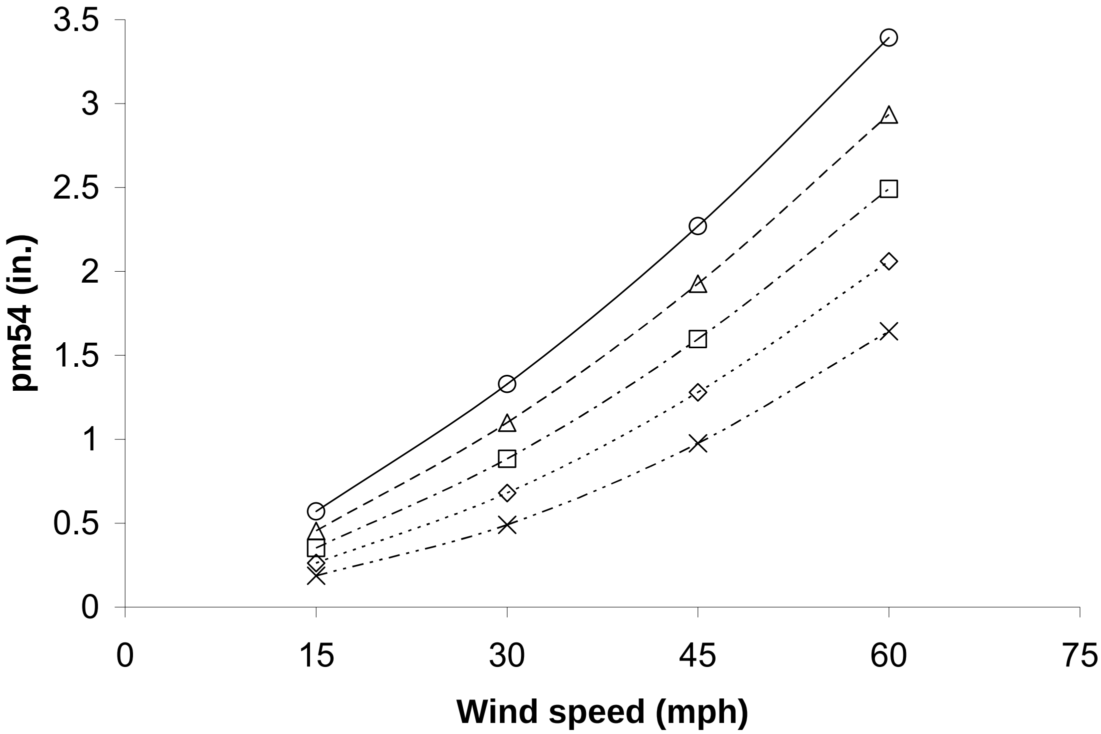


Figure 4.12. Interaction between pruning dose and wind speed ($p<0.0001$) resulting from predicted average trunk movement at an elevation 54 inches above topmost root (pm54). Vertical axis is the least square means of pm54 adjusted using Tukey's method. Lines represent pruning dose levels. Circles and solid line = 0% foliage dry mass removed, triangles and dash line = 15%, squares and dash dot line = 30%, diamonds and dot line = 45%, and Xs and dash dot dot line = 60%.

CHAPTER 5
DISCUSSION AND CONCLUSIONS

Live oak trees were an appropriate specimen for aeromechanical investigation. Live oak leaves are stiff with acute bases and short petioles. Vogel (1989) demonstrated that leaves with similar construction had high individual leaf drag coefficients that increased with increasing wind speeds. Highrise® oak leaves presumably have high individual drag coefficients, exemplified by the defoliation seen on raised tree number one in winds generated above 3000 motor rpm (> 50 mph). Whether results of pruning type and pruning dose would be more or less pronounced among trees where foliage had a low individual leaf drag coefficient; or where foliage reconfigured to reduce leaf drag is uncertain. However, effects of pruning type and pruning dose were only apparent at high wind speeds. Vogel (1989) demonstrated that at such wind speeds, drag coefficients declined for all leaves (except those that were stiff with acute bases and short petioles), and especially for leaves that reconfigured, since leaves that reconfigured did so more effectively at high wind speeds. Drag coefficients for clusters of leaves decreased for all leaf types, but less for stiff leaves with acute bases and short petioles than for other types. Thus, the effects of pruning type and pruning dose reported here would likely be less pronounced in other species based on the type of foliage alone.

In addition to leaf characteristics, live oak foliage was well distributed throughout the canopy. Hoag et al. (1971) showed that distribution of foliage is a good measure of the location of the resultant drag force (location of the load if it were applied as a point load) acting on a limb. Pruning types differed in how they affected foliage distribution throughout the canopy. Therefore differences in trunk movement between pruning types might be attributed to differences in the location of the resultant drag force. Elevation of the resultant drag force was very different between raised and reduced trees, particularly at the highest pruning dose, yet trunk movement was statistically similar for both types at all wind speeds and all pruning doses. Raising and lion's tailing likely elevated the location of the resultant drag force while reduction and structural likely lowered it. Thinning should have had the least effect on location of the resultant drag force since the goal of thinning was to create an even distribution of foliage throughout the canopy without changing canopy dimensions. However, thinning was the only pruning type that was statistically different; trunk movement was greatest at the highest predicted wind speeds for thinned trees. This was likely because canopy dimensions did not change for thinned trees while they did for other pruning types.

It was fortunate that thinning was the one pruning type that differed from all others. The only significant difference in physical characteristics among unpruned trees assigned to pruning types (difference in elevation to vertical center of canopy) was between thinned and reduced trees. Elevation to vertical center of canopy defined the length of the lever arm over which the force of wind acted. Thus it also affected location of the resultant drag force and could have been confounded with pruning type. Elevation to vertical center of canopy was lower for unpruned thinned trees than for unpruned reduced trees. Despite the shorter lever arm, trunk movement was greater for unpruned thinned trees than for unpruned reduced trees. Therefore, the only significant difference in physical characteristics among unpruned trees likely did not alter the effect of pruning type, assuming trunk elasticity was uniform among pruning types. Additionally, because the interaction between pruning type and pruning dose was not statistically significant, differences between unpruned thinned and unpruned reduced trees did not likely alter effects of pruning dose either.

Pruning dose primarily affected surface area projected into the wind and was applied as a measured decrease in percent foliage dry weight. Dose was calculated as a percent of foliage dry weight because foliage is the crux of ANSI (2001) definitions. However, others have reported that foliage is the most appropriate estimate of area in calculations involving aerodynamic drag of trees. Hoag et al. (1971) went so far as to say: "When there are leaves on the branches, the leaf area is the only significant area." Vollsinger et al. (2005) reported that leaves had more drag per unit frontal area than stems and trunk. Moore and Maguire (2004) and Roodbaraky et al. (1994) also agreed that aerodynamic drag of foliage was the most significant factor affecting external damping of tree sway. Foliage dry weight is highly correlated to foliage surface area (Ohara and Valappil 1995; Meadows and Hodges 2002) so percent foliage dry weight was a good measure of projected surface area. Also, percent foliage dry weight was an effective way to measure the effect of pruning dose.

Pruning dose levels were extremely variable among trees. For many trees, the highest predicted pruning dose levels were extrapolated from actual data. For example, no lion's tailed tree had 60% of its foliage removed during pruning. As a result, caution should be used when viewing comparisons at the higher pruning dose levels. However, all but the lowest predicted pruning dose levels are beyond biologically acceptable limits, so these extrapolations are not dangerously precarious. The same is not true for wind speed.

Wind speeds generated by the airboat were extremely variable among trees, especially for winds generated at the highest motor rpm. For many trees, the highest predicted wind speeds were also extrapolated from actual data, but that was not the case for every tree in any comparison. While these results are credible, caution should be used when viewing comparisons at high wind speeds.

We have no reasonable explanations for the variability in generated wind speeds. Differences in elevation of the anemometer are the most likely explanation. Vertical wind profiles were not laminar and the anemometer was not located at the same elevation for all trees. While some differences between wind speeds were seemingly explained by elevation of the anemometer, others were not. Elevation of the anemometer was not clearly responsible for variation in wind speeds.

Other possible explanations for variation in wind speeds proved similarly inconclusive. There were no recognizable patterns within pruning type or day of year tested. There were also no noticeable patterns attributable to time of day or a motor condition (e.g. a need to warm the motor up or a temporary motor fatigue). Correlations between generated wind speeds and temperature, time of day, and day of year were low (R^2 = 0.06, 0.03, and 0.08 respectively for the highest rpm). Barometric pressure and relative humidity are known to affect motor performance but neither was measured on site. Inconsistencies in wind speeds could have been due to operator error. This would likely be minimal because there were large increments between rpm used, and the motor was controlled primarily by one operator. The tachometer could have malfunctioned since it was connected to the motor via a 75 foot cable. But this was unlikely since tachometer and wiring were all new at the start of the experimental study and there were no noticeable inconsistencies in gauge output or in sound of the motor. Inconsistencies in wind speeds could also have been due to variation in performance of an old motor.

Wind fields generated by the airboat were smaller than tree canopies because winds did not dissipate much radially. The airboat was elevated so the entire width and lower half of a canopy were in the primary wind flow. However, the upper half of a canopy was likely outside the primary wind flow and the effects this had on results can not be known with certainty. Effects of a small wind field should have been most conspicuous on raised trees, but trunk movement of raised trees was not significantly different than movement of lion's tailed, reduced, or structurally pruned trees at any wind speed. Therefore, limited size of the wind field likely did not affect comparisons among pruning types or doses.

Researchers using wind tunnels and trucks to generate winds have met similar complications. Mayhead (1973) noted that leading shoots of several trees he tested were outside the primary wind flow. Vollsinger et al. (2005) and Rudnicki et al. (2004) trimmed foliage so trees fit in their wind tunnel, and only the upper portion of the main leader was harvested for testing. Trees have been harvested for all wind tunnel studies using real plant tissue, and by Hoag et al. (1971) when a limb was mounted to a truck. An advantage of using the airboat is that trees did not have to be harvested for testing. Harvesting affects water relations in the tree; moisture content affects wood material properties (Ellis and Steiner 2002); therefore moisture content affects trunk movement.

Comparisons among pruning type, pruning dose, and wind speed were based on trunk movement measured by displacement transducers. Milne (1991) and Roodbaraky et al. (1994) used displacement transducers to analyze natural sway frequency and damping of trees. Gardiner (1995) used displacement transducers to correlate tree movement and wind loading. Gardiner preferred strain gauges to displacement transducers because strain gauges had greater resolution of small displacements. Resolution of our transducers decreased proportional to trunk movement so separations among pruning types and pruning doses at low wind speeds might have emerged if the displacement transducers had a higher resolution. Milne and Gardiner both recorded trunk movement at 10 Hz, and Roodbaraky el al. recorded at 4 Hz while our data acquisition system was only capable of recording at 0.5 Hz, which explains the sharp lines in our bird's eye plot compared to those in Gardiner's plots (see Gardiner 1995 Fig 2.1). James (personal communication) found that 40 Hz is optimal for recording measurements of tree movement using strain gauges. Sampling rate likely did not affect these results since wind speed and trunk movement was averaged over a four minute time interval.

Trunk movement provided a good representation of the effects of pruning and wind speed on these trees. According to elastic beam theory, trunk movement is directly proportional to aerodynamic drag times the cube of the height to the point of loading, and inversely proportional to three times the second moment of area times the longitudinal Young's modulus. Height to the point of loading was the same for almost all unpruned trees. Though there were statistical differences between elevations to vertical center of the canopy for unpruned reduced and unpruned thinned trees, means only varied by 14.95 inches, 8.2 % of total canopy height. The second moment of area was assumed to be circular and constant for all trees even though trunk caliper was not measured on the day of testing. Longitudinal Young's modulus was also assumed to be constant among trees tested. Efforts were made during tree selection to account for factors known to cause differences in longitudinal Young's modulus, and trunks were assumed to possess similar material properties based on selection criteria. Unfortunately, efforts to determine longitudinal Young's modulus using coupons and whole trunks were inconclusive. By combining terms, trunk movement was therefore directly proportional to aerodynamic drag times a constant. If pruning type, pruning dose, or wind speed affected aerodynamic drag, the effect would be manifest in trunk movement.

Of the affects tested, wind speed had the most significant effect on trunk movement, as was evident in individual tree regressions. This could have been anticipated since aerodynamic drag does not scale linearly with wind speed, as it does with surface area or drag coefficient, in the classical drag equation. Wind speed × pruning type and wind speed × pruning dose interactions were also significant. This too could have been anticipated since pruning affects both surface area and the drag coefficient, and past research has indicated that both surface area and the drag coefficient scale proportionally to some power of wind speed. Mayhead (1973) reported drag coefficients that decreased with increasing wind speed. Hoag et al. (1971) suggested that decreases in drag coefficients could be attributed instead to decreases in surface area. Vollsinger et al. (2005) and Rudnicki et al. (2004) separated changes in surface area from changes in drag coefficients by using wind speed specific frontal areas to calculate drag coefficients. Drag coefficients still decreased inverse to wind speed but not as sharply since decreases in frontal area were accounted for. Remaining decreases in drag coefficients might be accounted for by changes in skin friction but wind speed specific skin friction would be very difficult to measure on a flexible porous structure. Both studies reported that drag per unit frontal area increased proportionally to wind speed for all species tested. They also presented regressions that illustrated a squared wind speed term gave better coefficients of determination than a linear wind speed term when using wind speed specific frontal area. Thus, even though changes in surface area and the drag coefficient affected aerodynamic drag on their trees, changes in wind speed had a greater affect than either of the two. It seems reasonable then that pruning had limited effect on tree response relative to increasing wind speed.

Interaction of pruning type and wind speed was seen in two ways. First, trunk movement increased significantly at each wind speed for all pruning types, averaged across pruning dose, except for structurally pruned trees. With this exception, no pruning type effectively reduced predicted aerodynamic drag, even at wind speeds up to 60 mph. Thus changes in tree aerodynamic drag do not justify use of one pruning type over another. We have no explanation for the response of structurally pruned trees except possibly small sample size. Two structurally pruned trees were included in the analysis. Additional trees would have increased the sample size resulting in more powerful statistical tests.

Interaction of pruning type and wind speed was also seen among wind speeds. At high wind speeds trunk movement of thinned trees was greater than that of trees assigned to other pruning types. This might be explained by the affect of pruning type on crown dimensions. The geometric dimensions of thinned trees did not change with pruning as they did with all other pruning types. Since wind does not pass through a tree canopy in significant measure (Zhu, Matsuzaki et al. 2000), thinned trees likely presented the largest surface area to wind flow. Another explanation could be a difference in whole canopy skin friction. Thinning increases canopy porosity and since wind does not pass through a tree canopy, a more porous canopy might translate into a rougher canopy surface increasing whole canopy skin friction. Both explanations are plausible and either would increase tree aerodynamic drag.

Dimensions of lion's tailed tree canopies also changed very little with pruning. However, trunk movement of lion's tailed trees was not different than trunk movement of raised, reduced or structural trees. The combination of a small wind profile centered on a canopy where pruning removed all but the largest branches may have allowed more wind through the canopy of lion's tailed trees. Another explanation is that branches may have become more flexible with lion's tailing, increasing canopy streamlining which translated into less trunk movement. The former explanation is more plausible since only the acute effects of pruning were evaluated. There was not enough time between pruning and testing for additional growth to alter branch taper or branch wood material properties. Effects of structural pruning may not have been expressly manifest here since all trees were structurally pruned for years prior to testing. Other studies that evaluated pruning have not compared pruning types only pruning doses (Rudnicki, Mitchell et al. 2004; Moore and Maguire 2005; Vollsinger, Mitchell et al. 2005).

Interaction of pruning dose and wind speed was manifest only after 30% of foliage was removed from a canopy. Vollsinger et al. (2005) indicated that pruning experiments supported their proposal that a strong relationship exists between branch mass and drag, but they could not evaluate the effect of dose on streamlining because branches on the trees they used acted independently. Rudnicki et al. (2004) reported that effect of pruning dose was species specific. For red cedar, drag per unit branch mass decreased with increasing pruning dose and wind speed. With hemlock drag per unit branch mass increased with increasing pruning dose up to wind speeds close to 25 mph then it decreased with increasing wind speeds. For lodgepole pine, drag per unit branch mass increased with increasing pruning dose and wind speed. In both studies, trees were raised by removing first 30% then 60% of total branch mass. Changes in drag per unit branch mass were only significant for the lodgepole pine at 60% branch mass removed and 40 mph wind speeds. Moore and Maguire (2005) reported that raising did not influence natural frequency of trees until 80% of branch mass was removed. In all three reports and in this study, pruning dose was not effective until pruning dose exceeded biologically acceptable limits. Biologically acceptable limits are defined by pruning effects on biological functions like light harvesting and carbon assimilation, water transport, and reception and transduction of environmental signals. Removing excess foliage affects partitioning of tree growth among foliage, fruit, stems, and roots which can have negative affects on tree health as well as tree structure (Zeng 2003). American National Standards Institute (Accredited Standards Committee A300 2001) recommends no more than 25% of foliage be removed with any one pruning.

Additional results from this study were procedural in nature. Dose was most efficiently and effectively determined as a visual estimate of foliage removed. Using anemometry to estimate density of the canopy was ineffective. A single measurement of trunk movement at the base of the canopy was as effective as multiple measurements along the clear trunk. Small differences in the height of the lever arm (elevation to the vertical center of the canopy) were insignificant. Wind speeds were not reproduced consistently by calibrating wind speed to motor rpm. While none of this was the primary goal of this research, all of it is useful for future work on similar sized landscape trees.

An important caveat is that this study provides no information on the aerodynamic drag experienced by individual branches. It would be foolish to extrapolate these results to larger trees using the trees tested here to represent branches or parts of a larger structure. Further testing is required to determine effects of pruning on the aeromechanical behavior of individual branches when they are coupled as a continuous dynamic structure. It should also be noted that all studies to date have evaluated relatively straight line winds applied perpendicular to tree growth.

Here we used whole canopy aerodynamic drag, measured as the magnitude of trunk deflection, to make comparisons between pruning type, pruning dose, and wind speed. Wind speed was the most significant factor influencing trunk movement at all wind speeds. Pruning reduced trunk movement at all wind speeds and the effect of pruning increased with increasing wind speed. However, pruning did not have a significant effect on trunk movement until the amount of foliage removed exceeded biologically acceptable limits. Thinning did not reduce trunk movement at high wind speeds ($\geq$ 45 mph) as well as the other pruning types evaluated, while raising, reduction, lion's tailing, and structural pruning all reduced trunk movement equally well at all wind speeds.

CHAPTER 6
FUTURE WORK

It is impossible to study the way a tree's mechanical structure responds to wind without wind. This experimental study showed that an airboat was a viable option for generating wind outdoors. Since inception of this project, colleagues of Dr. Kurt Gurley at Florida International University have built a portable wind machine that generates a larger wind field and higher wind speeds. The machine is composed of two modular sub-units that could be repeated to create a larger wall of wind. Both subunits are mounted on a single trailer with a standard hitch so the wind can be taken to a tree in the landscape, rather than taking a tree to the wind by placing it in a wind tunnel or on a truck. Inconsistencies seen in wind generated by the airboat are minimized by controlling motor rpm with feedback from anemometry. Opportunities created by such a machine are vast and it would be inappropriate to attempt their enumeration here. However, one opportunity is to repeat the research described herein on similar sized or larger trees. With an improved wind field it would be possible to determine what, if any effect the narrow wind field had on these results.

There are multiple ways to approach the relationship between trees and wind. The approach evaluated here was to reduce canopy drag by reducing surface area projected into the wind through pruning. While no pruning type or pruning dose manifest an immediate benefit here, pruning was only evaluated for its acute effects on canopy drag. Pruning clearly effects tree growth in a predictable manner, therefore the chronic effects of pruning need to be considered as well. Apart from its short term effect on canopy drag, the enduring effects of pruning on tree structure need to be evaluated. Some information has been reported (Zeng 2003). However, more research should be designed to evaluate long term effects pruning types and pruning doses have on tree form and construction.

Tree construction is defined by the composition of individual tree parts and how those parts are joined together. Altering tree construction, strengthening the structure, is another approach to the relationship between trees and wind. It has been shown that trees respond to external mechanical stimuli by producing reaction wood (Kwon, Bedgar et al. 2001) and wound wood (Kane and Ryan 2003) which are both stronger than normal wood. However, while anatomical features of the stronger wood are clearly defined (Barnett and Bonham 2004), signal reception and transduction pathways that control its growth are not (Blancaflor 2002). Further research in this area will be facilitated by sequencing of the poplar genome (Brunner, Busov et al. 2004). There is less information defining how individual tree parts are joined together, although there is some (Gilman 2003). More work will be done in this area as individuals attempt to define how energy is dissipated through a tree (James 2003). Still, more information is needed to develop cultural practices that promote stronger tree structure.

This study was designed to provide practical information to tree care professionals. Apart from efforts to understand trees and wind, more work needs to be conducted to evaluate current cultural practices and hypothetical solutions to reduce wind damage in trees. There is far too much speculation by practitioners and not enough information to muffle opinion.

Tree biomechanics is still a budding field. Current research on relationships between wind and trees is spread among various disciplines and it is becoming increasingly complex. Hopefully, future research will take a structured course so that great strides will be made in a very short time.

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BIOGRAPHICAL SKETCH

Scott Alan Jones is the second in a family of eleven children. He was born May 10, 1972, to Phillip R. Jones and Gwen Stephenson Jones. Scott spent most of his formative years in southern Idaho working on farms and playing outdoors, which led him to pursue a career in horticulture. An undergraduate advisor at the University of Idaho, Dr. Robert R. Tripepi, and the director of the University of Idaho Arboretum, Dr. Richard J. Naskali, were jointly responsible for Scott's interest in arboriculture. After graduating from the University of Idaho in May 2000 with a Bachelor of Science in plant science, Scott went to work for Ryan Lawn and Tree (RLT) in Overland Park, KS. With RLT he was trained as a climber, crew chief, and department coordinator; and became acquainted with many of the day to day issues arborists face. Scott met Dr. Edward F. Gilman at the annual conference of the Kansas Arborist Association in 2002 and after exchanging a few e-mails, he accepted a position as a graduate research assistant at the University of Florida in the Department of Environmental Horticulture. After graduation, Scott will work as an arborist representative for The F. A. Bartlett Tree Expert Company in Cincinnati, OH.