The Effects of Pruning on Wind Resistance of Shade Trees

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Abstract

Three tree species, Freeman maple (*Acer x. freemanii*), swamp white oak (*Quercus bicolor* (Willd.)) and shingle oak (*Quercus imbricaria* (Michx.)) were tested before and after pruning to determine the effectiveness of pruning on reducing drag and bending moment. Pruning methods were thin, reduce and raise and meet the requirements set by the American National Standard Institute A300 standards for *Tree Care Operations Trees, Shrub, and Other Woody Plant Maintenance – Standard Practices (Pruning)*. Trees were tested up to speeds of 22.4m*s^{-1} over 1.6km by driving them in the bed of a truck. Drag, based on a centroid of the crown, and a bending moment was calculated. Drag and bending moment were also normalized by tree mass and crown area. Reduction pruning worked more effectively for Freeman maple and raise pruning for swamp white oak at reducing drag. Simple to measure tree characteristics were analyzed to determine the best predictors of drag and bending moment in the field. Tree mass frequently was the best predictor of drag and bending moment. Information should be used with caution due to the fact that the trees tested were small stature and a limited number of trees were tested.

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Introduction

Problem Statement

Trees play a vital role in urban and suburban ecosystems, providing many environmental and sociological benefits. For example, trees beautify landscapes and consequently can increase the likelihood of a property being leased (Maco & McPherson, 2003). Trees can reduce the need for cooling and heating in urban landscapes by up to 25% (Akbari, 2002). Individual trees can provide more than $100 worth of environmental and property values benefits depending on the species (Simpson & McPherson, 1998; McPherson, 2003). Trees also reduce air pollution and sequester and store carbon. In Chicago, urban trees were estimated to remove 5,575 metric tons of pollutants and sequester more than 300,000 metric tons of carbon per year. Pollution reduction due to trees in Chicago was estimated to save the city $9.2 million in air pollution reduction measures (McPherson et al., 1997). Trees also reduce runoff from precipitation events and provide wildlife habitat. Studies have also shown that trees can be beneficial to community stability (Austin, 2002) and can help reduce crime (Austin, 2002; Kuo, 2003). However, in order for trees to provide such benefits they must be properly planted and maintained (Dwyer et al., 1992).

Trees that are not properly maintained can become liabilities and are no longer assets to a community or property. In particular, trees that become structurally unsound may become hazards that can damage property or injure people (Harris et al., 2004). Damage from trees that break apart can increase the costs to property owners through cleanup, insurance, and repairs fees.

Even without breaking apart, trees that are not properly maintained can be dangerous by blocking views of motorists, interfering with utility wires, and damaging sidewalks so that tripping hazards are created (Miller, 1997). It is essential for the urban foresters and arborists who manage shade trees to understand how to properly maintain trees so that they remain assets. This is increasingly important since there is a large projected increase in urban growth (Nowak & Walton, 2005).

Pruning is a common treatment that arborists use with the intention of reducing the likelihood of trees becoming liabilities. Pruning has been recommended as a way to reduce resistance to wind (wind load) on shade trees, thereby reducing the likelihood of tree failure during high winds (Lilly, 2001; Gilman, 2002; Gilman & Lilly, 2002; Harris et al., 2004), but little actual data are available as to the effectiveness of this practice.

Literature Review

There has been much work on how wind affects trees on an individual or stand level. For example, the effects of wind on individual tree growth has been reported (Telewski, 1990; Telewski, 1995; Stokes et al., 1997; Coutts et al., 1999; Burgert & Eckstein, 2001; Moore & Maguire, 2001; Tamasi et al., 2005) as well as how silvicultural techniques can be used to reduce the risk of tree damage on the stand level (Rowan et al., 2003).

Wind loads can play a vital role in tree growth, and trees growing in chronically windy environments should be considered separately from the effects of rare wind effects such as hurricanes or storms (Ennos, 1997).

At the individual tree level, the effects of wind on different parts of the tree have been studied. Since roots serve as a support system and anchor for the entire plant, much work has investigated how wind affects tree roots. The tap root of English oak (*Quercus robur* L.) is shortened and there is an increase in lateral roots for trees exposed to greater wind loading (Tamasi et al., 2005). Coutts et al. (1999) showed that conifers exposed to repeated wind loading in one plane produced roots that resembled I- or T-beams, an optimal design to resist bending. This is similar to what Stokes et al. (1997) observed in sitka spruce (*Picea sitchensis* (Bong.) Carr.) exposed to repeated flexing. Repeated flexing also caused an increase in coarse root mass and coarse root to fine root ratio (Stokes et al., 1997). Such responses are believed to improve the anchorage of the trees subjected to wind movement (Stokes et al., 1997). Increases in root mass have also been documented to increase the effectiveness of the anchor in the plant (Stokes et al., 1997; Niklas & Spatz, 2000; Niklas, 2002).

Wind-induced changes are also evident in tree trunks. Trees loaded by the wind develop thicker wood rings in the prevailing wind direction (for example, the north-south plane) than in the direction perpendicular to the prevailing wind (James 2003). In maritime pine (*Pinus pinaster* Ait.) a development of larger ring size in the heartwood was more proportional to the leeward side of the tree in comparison to the windward side (Stokes et al., 2001). In general, trees growing in windy conditions show an increase in diameter growth (Telewski, 1995; Stokes et al., 1997; Harris et al., 2004). These observations have been supported by empirical evidence. Mechanical shaking to simulate wind load on loblolly pine (*Pinus taeda* L.) increased trunk diameter, as well as wood density and ethylene production (Telewski, 1990).

As trees mature and increase in diameter, the wood properties change. Mature wood and juvenile wood differ from each other in fiber and tracheid length, chemical composition of the cell walls, specific gravity and tensile strength (Panshin & Zeeuw, 1980). As trees increase in diameter, they become less flexible and are more susceptible to breakage from disastrous winds (King, 1986). As a tree adds diameter growth, it increases its rigidity and is less likely to break when exposed to stress. The increase in rigidity is due primarily to the increase in diameter, which increases the second moment of area or moment of inertia (I) of the stem cross-section; I is proportional to diameter raised to the fourth power, so small increases in diameter equal large increases in I and therefore much greater resistance to bending (Kane et al., 2001). Increases in Young's modulus or the modulus of elasticity (*E*) as the tree matures also contribute to stiffer stems (Cannell & Morgan, 1987). Flexibility helps trees dampen the sway associated with a load or wind force.

Even though wind can affect the rate of tree growth, the effect of growth rate on risk of failure is not clear. Slow growth in tropical trees is usually associated with higher density (and thus stronger) wood which improves wind resistance (Putz et al., 1983). This would not necessarily be true of ring-porous angiosperms, for which fast growth increases wood density and strength properties (Panshin & Zeeuw, 1980). However, neither Hauer et al.(1993), nor Asner et al. (1997) found evidence that wood properties, that is to say wood specific gravity, and likelihood of failure are correlated.

Wind loading also induces a physiological response in trees. Trees growing under windy conditions alter their process of transpiration by closing their stomata, which affects photosynthesis. This can create smaller leaves, more flexible petioles, and overall stunted growth (Ennos, 1997) which reduces drag on the tree.

Importantly, wind causes drag on trees. Drag can be defined as the rate of removal of momentum from a moving fluid (Vogel, 1994). Drag is the result of the slowing of fluid particles against a surface creating a stress across the surface of the object (Vogel, 1994; Munson et al., 2002). Drag is calculated as follows (Smith et al., 1987; Vogel, 1989, , 1994; Hedden et al., 1995; Munson et al., 2002):

$$D=0.5*\rho*C_d*A*U^2 \quad [1]$$

where ρ is the density of air,

C_d is the drag coefficient,

A is the surface area

U is the velocity of the fluid

Studies that have calculated drag and drag coefficients for trees have mostly been conducted in wind tunnels. Mayhead (1973) used a variety of commercially important British forest species trees to determine drag coefficients at various wind speeds. More recently, Rudnicki et al. (2004) and Vollsinger et al. (2005) have shown that a reduction in crown frontal area (between 36% and 54% for conifers and 20% and 37% for hardwoods at 20 $m*s^{-1}$) was largely responsible for the reduction in drag coefficients of conifers and hardwoods as wind speed increased. Trees used in wind tunnel tests, however, have mostly been small, about 2m in height, (Rudnicki et al., 2004; Vollsinger et al., 2005); and do not accurately reflect larger, less flexible trees. In addition, tests conducted in wind tunnels have used a laminar flow (Mayhead, 1973; Rudnicki et al., 2004; Vollsinger et al., 2005); when in reality, flow is turbulent.

Models have been created to predict wind speeds that will cause tree failure in forest stands. Trees in a forest interact with each other, and the collisions between them dampen the effects of wind (Milne, 1991). A silvicultural treatment like thinning compromises this damping effect. A model from Gardiner and Quine (2000) shows that spacing, site preparation and thinning are most influential for determining the critical wind speed at which failure occurs. The probability of failure increase from 0.876 to 0.001 for wind speeds that range from 17.6 $m*s^{-1}$ to 29.8 $m*s^{-1}$ at age 50 for Sitka Spruce in a gley soil. A study from Gardiner et al. (2000) compares two models for predicting critical wind speed and turning moment (torque) needed to break stems in conifers against field data. One of the models tested, GALES was developed to deal with wind damage in the interior of unthinned or lightly thinned British commercial conifer stands (Gardiner et al., 2000). The other model, HWIND was developed to predict wind damage to Finnish forests at the stand edge following the creation of new edge and after thinning (Peltola et al., 1999) Gardiner et al. (2000) show that the models closely predicted critical wind speeds compared to field data from forest edge trees. Peltola et al. (1999) produced similar findings when comparing their model results to measured critical wind speed and turning moments.

Trees mitigate the drag caused by wind in various ways. Some tree species produce leaves that are more streamlined under windy conditions; a longer petiole and a wide leaf blade base are examples of this and can be found on *Acer* and *Platanus* (Harris et al., 2004). The leaf blades may also roll into cone shapes, creating a smaller surface area thus reducing drag (Vogel, 1989, , 1994; Harris et al., 2004). The type of foliage on the tree can affect the drag; if a tree has leaves with acute bases and short petioles it will have a higher drag than those of lobed bases and long petioles (Vogel, 1989). Smaller branches and twigs are flexible enough to deflect under wind load, reducing drag and the center of pressure height (Vogel, 1989, , 1994; Ennos, 1999). After a hurricane in Puerto Rico, the most flexible trees were the least damaged (Francis, 2000). In addition, there is a tendency for low wood-specific gravity species to shed their leaves more easily reducing drag (Francis, 2000). Trees can also reduce wind-induced sway motion through contact with other trees (Milne, 1991), aerodynamic drag on foliage, adsorption of the sway by the stem (Milne, 1991; James, 2003) and the interaction of side branches with the main stem (James, 2003). On broadleaf trees, leaves are an important damping mechanism. The natural frequency of a plane (*Platanus*) tree was 0.80Hz without leaves and 0.42Hz with leaves (Roodbaraky et al., 1994). Trees can also shed smaller, peripheral branches to reduce drag and preserve the bulk of the tree’s structure (Niklas & Spatz, 2000; Niklas, 2002).

Plants also grow in such a way to provide a safety factor against extreme wind loading events (Spatz & Bruechert, 2000). The safety factor enables a tree to survive unusually high wind events, not extreme events (Niklas & Spatz, 2000; Spatz & Bruechert, 2000; Niklas, 2002).

During severe wind events, trees fail, in spite of the mechanisms to reduce drag described above. Forest trees fail either by snapping of the trunk or by uprooting (windthrow). A tree will uproot when the total turning moment (drag multiplied by center of pressure height) exceeds the support from the root-soil plate. Stem failure will occur when the breaking stress exceeds a critical value of the modulus of rupture (Peltola et al., 1999); the modulus of rupture is the maximum surface stress instantly at failure. The turning of trees (calculated as a bending moment) is generated by an extreme wind speed or by repeated gusts of lower wind speeds. In the former case, bending stress (turning moment) exceeds the tree's wood strength (resisting moment). In the latter case, repeated wind gusts cause the tree to sway near its natural frequency of movement, building up greater and greater sways until the bending stress (resisting moment) exceeded the capacity of the tree to resist breaking (Cannell & Coutts, 1988).

Drag is calculated by equation [1]; however, studies have found that trees do not fit the equation well. Some studies suggest that drag is proportional to velocity squared (Roodbaraky et al., 1994); however other studies of conifers show that tree drag is proportional to velocity rather than velocity squared (Mayhead, 1973; Rudnicki et al., 2004). Other studies found that drag is proportional to the product of the mass and wind speed and to the product of wind velocity squared and frontal area (Rudnicki et al., 2004; Vollsinger et al., 2005). Rudnicki et al.(2004), however, showed that drag on trees is closer to the equation [1] than had been previously shown because they used speed-specific crown areas instead of just using the still-air crown frontal area that Mayhead (1973) and Mayhead et al. (1975) used.

Forest Trees and Shade Trees

Most of the work on wind and trees has related to forest trees. Shade trees are trees that devote more resource to foliage production and are not competing with adjacent vegetation as intensely as forest trees. Forest trees tend to grow tall, with relatively small crowns, small lateral branches, and a relatively non tapered trunk (Kozlowski & Pallardy, 1997). There are two main reasons for this growth habit, 1) forest trees compete for light and so must grow tall to avoid being shaded out by their competitors (Kozlowski & Pallardy, 1997; Smith et al., 1997); 2) aside from trees on the edge of a stand, forest trees are protected from the wind by their competitors, reducing the need for an individual tree to grow large in diameter relative to height (Smith et al., 1987; Milne, 1991; James, 2003). Shade trees, on the other hand, because of the lack of competition, tend to grow broad, rounded crowns, maximizing leaf area for photosynthesis (Harlow et al., 1996; Harris et al., 2004). Shade trees also tend to have more tapered and stout trunks because they are entirely exposed to the wind (Telewski, 1995).

Winds influencing forest and shade trees have different patterns of flow that affect the trees differently. Forest trees experience most of the force of the wind of the edge, and on the top of the canopy (Kruijt et al., 1995). Edge trees have common characteristics of shade trees and forest trees; they generally have more branching and a more pronounced taper (Smith et al., 1997). This facilitates damping to reduce tree sway and protects the forest from the wind forces (Gardiner, 1995). The shear force at the top of the canopy has little effect on the trees (Vogel, 1994; Finnigan & Brunet, 1995) because that is where the velocity of wind is at its slowest due to the velocity profile of moving air (Vogel, 1994; Munson et al., 2002). These conditions allow the forest trees to escape maximum wind forces, but shade trees do not have these luxuries. A shade tree endures the full force of the wind and must therefore rely on the stoutness of the trunk (Telewski, 1995; Stokes et al., 1997; Harris et al., 2004) and the reconfiguration of the leaves (Vogel, 1989) to reduce drag.

Little research has been conducted to examine the effects of wind on shade trees in comparison to forest trees. Many studies have been *ex post facto* surveys of damaged trees after major storms (Duryea et al., 1996; Francis, 2000). Other research examined the sway damping abilities of shade trees (Roodbaraky et al., 1994; James, 2003).

Pruning

Forest trees are sometimes pruned to improve timber quality (Smith et al., 1997), while shade trees are pruned for aesthetic and safety reasons (Miller, 1997; Harris et al., 2004). Removal of dead wood in a forest stand can improve the quality of wood harvested; however, this practice is expensive and is generally used only on high value species that will yield a high return on the investment at harvest (Emmingham & Fitzgerald, 1995; Smith et al., 1997). Other research examining the cost-benefit ratio of tree pruning in forest stands found that pruning is a financial risk. Due to its expensive nature, pruning in a forest stand should only be conducted after careful consideration (Holley et al., 2005). Research has also been conducted to look at the effects of pruning trees on an edge to reduce the possibilities of wind throw in forest trees. Comparisons of common tree pruning methods (top-pruning, topping and edge feathering treatments) were tested to determine their effect on the reduction of wind damage to newly exposed cutblock boundaries. Rowan et al. (2003) found that topping and pruning trees at newly exposed forest edges, such as that created when a clear-cut is prescribed, can reduce windthrow and stem breakage by 40%.

Arborists prune trees when they are young to help establish the tree's form. Older trees are pruned to help maintain the health of the tree. Pruning can control the plant's size, as well as influence flowering, fruiting and vigor. Pruning can also be used to compensate for root loss from trenching (Watson, 1998), invigorate stagnating plants and increase the value of conifers (Harris et al., 2004). Urban foresters create pruning schedules to maintain public safety on right-of-ways; these schedules can include pruning of street trees that block signs and limit traffic sights (Miller, 1997). Municipalities also prune trees to reduce safety hazards, prune for plant structure and prune to provide clearance for walk ways or street traffic (Miller, 1997). Pruning trees in cities generally consists of preventive maintenance and structural pruning (Miller, 1997). Pruning trees can also decrease damage from storms (Sisinni et al., 1995).

Pruning and wind effects

Pruning has been researched to investigate its effectiveness for stress and failure reduction. With leaves considered the main contributor to wind drag in trees (Vogel, 1994), removal of branches will help reduce drag on the tree. A study examining wind gusts and associated damage showed that when foliage remained on the trees, branch failures were more common in comparison to when leaves were not on the branches (Luley et al., 2001). A survey conducted after a major hurricane found that pruned trees had better survival then unpruned trees (Duryea et al., 1996).

According to Gilman and Lilly (2002), crown thinning, crown reduction, and pollarding can be prescribed to reduce the tree's resistance to wind, but these recommendations are not based on empirical evidence. Matthews (1988), found that thinned trees along streets and in the open remained standing after a hurricane, while the unthinned trees around them fell. Thinning is also the conventional method to minimize the damage caused by storm winds (Gilman, 2002) and may reduce the wind-sail of the tree (Lilly, 2001). Research examining *Acer rubrum* showed that crown reduction decreased drag by 144 N at wind speeds of 20 $m*s^{-1}$ and crown thinning decreased drag by 103 N at wind speeds of 20 $m*s^{-1}$ (Smiley & Kane, 2006). In a study examining *Populus trichocarpa* (Torr. & A. Gray), *Alnus rubra* (Bong.) and *Betula papyrifera* (Marsh.) (Vollsinger et al., 2005) removal of whole branches from the tree had little effect on reduction (p-value 0.392) of drag per unit branch mass. A study examining the effect of wind speed on drag of various conifers found that pruning did not have significant effect on drag per unit of branch mass at wind speeds of 20 $m*s^{-1}$ (Rudnicki et al., 2004). These two studies indicate that the removal of tree mass is what matters when trying to reduce drag, confidence in the results would be greatly increased if there were more supporting studies. More information about the effect of pruning to reduce wind induced stresses on shade trees is needed.

Objectives

The overall objective of the present study is to determine how tree stability can be improved through pruning. Specific objectives were to:

- Determine how three pruning methods influence drag for Freeman maple (*Acer x. freemanii*), swamp white oak (*Quercus bicolor* (Willd.)) and shingle oak (*Quercus imbricaria* (Michx.)) at various wind speeds.
- Correlate the effects of pruning on drag with easily obtained field dendrometric information

Method and Materials

Species and growing conditions

Species selected for the project were Freeman maple, swamp white oak, and shingle oak (Table 1). Trees were located at the Urban Horticulture Center of Virginia Tech (UHC), in Blacksburg, Virginia, at 80 degrees, 25 minutes W by 37 degrees, 14 minutes N at an elevation of 2000ft. Temperatures average 51.4 degrees F, with annual rainfall of 39.98" and 28.0" in snowfall. Groseclose and Poplimento on 2 to 7 % slopes are the soil types at the site. These are well drained, gently sloping soils on ridge tops. Groseclose is a fine, mixed, semiactive, mesic Typic Hapludults and Poplimento is a fine, mixed, subactive, mesic Ultic Hapludalfs. All trees were planted in rows spaced at 2m apart, similar to nursery stock production, and ranged in age from 4 to 7 years.

Computer Programs and Equipment

During the research, a 1000 kg (2500 lb.) capacity Dillon EDxtreme dynamometer (Weigh-Tronix, Fairmont, MN) measured the load on the trees at ½ second intervals while the data was captured on a laptop computer. Wedgelink® (MicroRidge Systems Inc., Sunriver, OR.) software was used to collect load measurements during testing. The dynamometer was also used to measure tree mass and the mass of branches, twigs, and leaves removed by pruning.

Wind speeds were measured at one-second intervals by two cup-anemometers connected to a separate laptop computer, and recorded using SensorMetric® (Southbridge, MA) software. The anemometers were attached to the leading edge of the tree sled by metal rods. They were placed at two different heights above the cab of the truck. One anemometer was on the passengers' side; placed 1.2m high in the canopy and the other anemometer was on the drivers' side, placed at 2.4m high in the canopy.

A tree sled designed by the Bartlett Tree Research Lab in Charlotte, North Carolina was used to secure the tree to the back of pick up truck. The sled was 2.44m long by 1.37m wide and occupied the entire bed of the truck. The sled was secured to the bed of the pickup truck with ropes and ratcheting straps so that it did not move during

Table 1: Average tree morphometric measures for each species. HCP stands for center of pressure height, X is the direction perpendicular to the pickup truck's motion, and Y is the direction parallel to the truck's motion.

Species	N	Height (m)	Crown Height (m)	Crown Width (Y) (m)	Crown Width (X) (m)	HCP (m)	Mass (kg)	Caliper (Y) (mm)	Caliper (X) (mm)	Diameter at 76 cm (Y) (mm)	Diameter at 76 cm (X) (mm)
Freeman Maple	16	4.83	3.67	2.40	2.10	2.19	20.3	79.2	81.0	66.2	67.5
Swamp White Oak	13	4.45	3.46	3.23	3.20	1.76	22.1	88.7	90.2	76.3	76.5
Shingle Oak	18	4.62	3.57	4.04	3.79	1.99	25.0	89.9	90.4	73.9	75.4

testing. A 1.27cm steel bolt through the base of the tree secured the tree on a pivot point at the rear of the tree sled (Figure 1).

Digital images of tree crowns were taken with an Olympus® Camedia digital camera, model C-2500L and used for later crown dimension analysis (see below). Images were segmented in the Adobe® Photoshop® v. 6.0, and were then analyzed using ImageJ software (Wayne Rasband, Research Services Branch, National Institute of Mental Health, Bethesda, MD).

Pruning Specifications

All pruning conformed to the American National Standards Institute (ANSI) A300 for Tree Care Operations-Tree, Shrub, and Other Woody Plant Maintenance-Standard Practices (Pruning) (ANSI, 2001). "Thin" is selective pruning to reduce the density of live branches. Thinning should remove foliage evenly throughout the canopy, and no more than 25% of the living canopy shall be removed in one growing season. "Raise" is selective pruning to provide vertical clearance. In this experiment the limit to the vertical clearance was 25% of the height of the living crown. "Reduce" is selective pruning to decrease tree height and/or spread. In this experiment, all trees that were reduction pruned were reduced by 25% of the crown height and by 12.5% of crown width parallel to the front of the truck.

Wind Test

Trees were not tested if ambient wind exceeded $1.79 m*s^{-1}$ (4mph). Before beginning the experiment, the truck speedometer was checked against a radar gun to ensure its accuracy and make any necessary calibrations. In addition, the speedometer was checked by traveling at a set speed across a standard distance. Anemometers were calibrated to vehicle speed daily by recording anemometer and speedometer readings at set time intervals during test runs without a tree in the sled.

All trees were measured for total height but only the top 4.33m was used if tree height exceeded 4.33m. Trees needed to be less than 4.33 m so they could safely be secured to the truck to pass under the overhead wires that cross the road used for testing. All branches and foliage below 3.26m from the top of the tree was removed to ensure that only the trunk was below the top of the truck. A 1.27cm hole was drilled 4.28m below

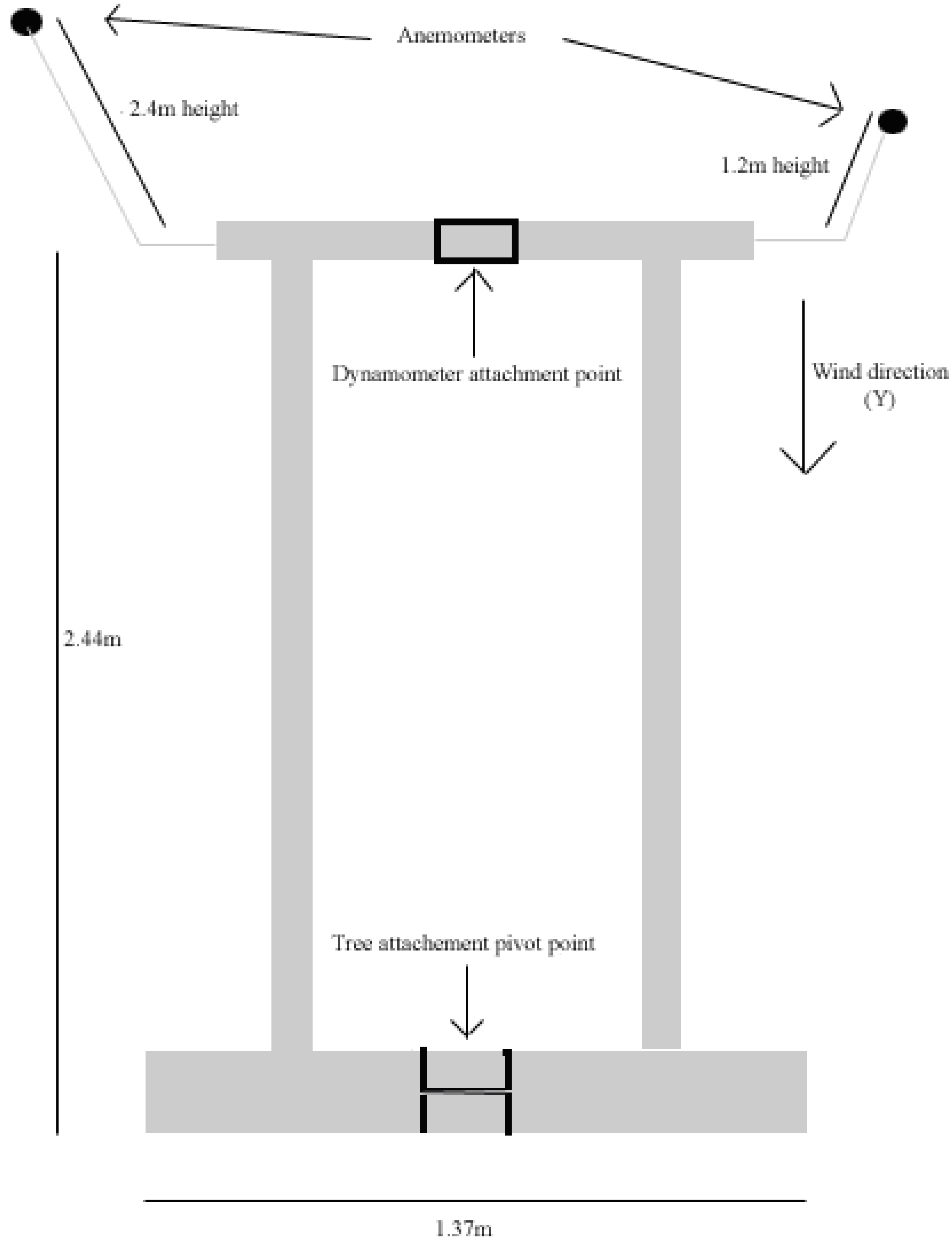

Figure 1: Bird's-eye schematic of tree sled. Truck is not shown and figure is not drawn to scale.

the top of the tree. This hole was then used to attach the tree to the pivot point of the sled.

Each tree was randomly assigned one of three pruning types, thin, raise, or reduce, equally distributed among three species tested. Diameter of the trunk was measured at the drilled hole in the X and Y direction as well as 0.76m above the drilled hole. X is defined as the direction perpendicular to the pickup truck's motion and Y is defined as the direction parallel to the truck's motion. Total tree height (if the tree was less than 4.33m tall), crown shape, crown height after lower branches were removed, and crown width in the X and Y directions were collected (Figure 2).

Prior to placing in the sled, the tree fresh mass was also measured. The mass of the tree was taken at the center of gravity, the point where the tree could be picked up off the ground and the tree stem lay parallel to the ground. Distance from the bottom of the stem to the center of gravity and diameter at the center of gravity in the X and Y direction were recorded. The tree was then secured to the tree sled.

With the dynamometer attached to the tree sled by a carabineer (arborist clip), a steel cable approximately 1m in length connected the dynamometer to the strap-carabineer system around the tree. The strap-carabineer system was attached to the tree 76.2 cm from the bottom of the trunk. This is the height of the dynamometer when it is attached to the sled. A metal squared tube about 0.76 m in length and with an eye bolt at the end was fashioned and placed in the truck's hitch receiver. A short length of rope adjusted by a Blake's hitch and connected by a carabineer and 1in webbing strap to the rear of the tree was secured to the tube to prevent the tree from falling forward on the truck cab when the vehicle was braking. Once the tree was placed in the sled and was secured, a digital image was taken in the Y direction.

The complete ensemble (Figure 3) was driven to the test site, where the tree was checked to make sure it was upright and the dynamometer was set to zero. Once the tree was upright, data recording began. The truck was accelerated smoothly from 0 to $24.5m*s^{-1}$, and then slowed to a stop over a 0.8km straight and nearly level course. The course was repeated driving in the opposite direction, again accelerating smoothly from 0 to $24.5m*s^{-1}$ and recording data in the same manner as the first run.

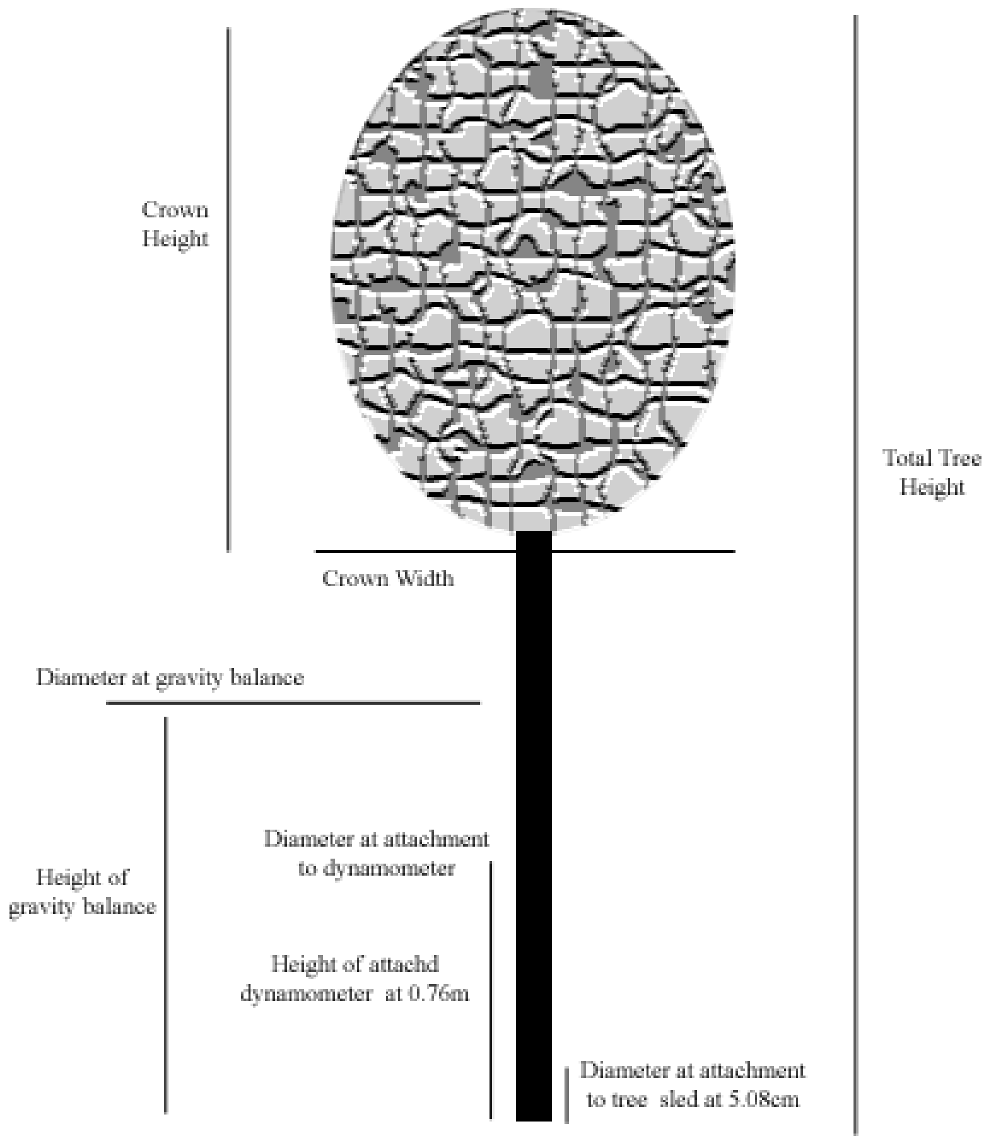

Figure 2: Diagram of various measurements collected on each tree. Diameters and crown width were measured in X and Y directions. Figure is not drawn to scale.

Figure 3: Completed assembly of tree, tree sled (in truck bed) and truck before the test began**.**

The tree was then taken back to the UHC to be pruned and photographed before the next run. Only the canopy of the tree (i.e., the area of the tree above the cab of the pickup truck) was photographed. Prior to any pruning, trees were "cleaned" (ANSI 2001, §4.10) by selectively removing dead, diseased and/or broken branches larger than 2.5 cm in diameter. Then the tree was pruned according to the randomly assigned pruning treatment.

The mass of leaves, twigs, and branches removed by pruning was recorded and a second digital image of the tree after pruning was taken in the Y direction. The tree was then driven back to the test area and again tested as described above. Once the second test run was completed, the tree was returned to the UHC where the tree was reweighed and the distance from the bottom of the stem to the center of gravity after pruning was recorded. The total tree height, crown height and crown width in the X and Y directions were taken again because raise and reduce treatments changed some of those dimensions. The general characteristic shape of the crown was also noted.

Data Manipulation

For each tree, the following data manipulations were conducted. The wind speed measurements from the two anemometers were averaged. Load measurements were multiplied by 4.448 to convert from pound-force to Newtons. Because load measurements were collected twice as frequently as wind speed measurements, wind speeds for successive readings were averaged to produce wind speeds at 0.5 second intervals. Intentionally, recording of wind speeds and loads were started at different times before making the test run. This was necessary because wind speeds and loads were not collected by the same software, and because there was a slight delay in recording wind speeds by the anemometers. Wind speeds and loads were matched by matching the maximum wind speed and maximum load for each run.

Daily calibrations of the anemometers and speedometer revealed that the truck's acceleration was non-linear at speeds less then 11 $m*s^{-1}$. To avoid difficulty in calculating acceleration in the non-linear range, data collected at speeds less than 13.4 $m*s^{-1}$, were not analyzed.

Wind speed was measured instantaneously, which means that the recorded loads reflected drag plus a force due to truck acceleration. In order to remove the force associated with acceleration (F_{ACC}) Newton's Second Law was used. Newton's Second Law equation is a follows:

$$F_{ACC} = \rho V a \qquad [2]$$

where a is the acceleration of the truck

ρ is the density of air, 1.226kgm^{-3}

V is the volume of the canopy.

Acceleration values were derived by plotting vehicle velocity versus time. The maximum wind speed for both runs of a tree in the pruned or unpruned condition were matched up and then assigned a new, common time value so both lines could be plotted against a common time scale. The slope of the best fit line for a plot of velocity versus time is the acceleration. Two best fit lines were created, one for each run; if the percent difference between line slopes was less than 25%, the geometric mean of the slopes was taken as the value for (a) in equation [2]. If the slopes differed by more than 25%, 2 values for (a) were used in equation [2], one for each run. Tree crown volume was estimated using an equation for an egg (Narushin, 2005) since this shape best fit most tree crown shapes:

$$V = (0.6057 - 0.0018B)LB^2 \qquad [3]$$

where *B* is equal to the maximum width (i.e., canopy width parallel to the front of the truck)

L is the maximum length (i.e., canopy height).

The force associated with acceleration was removed from measured loads, isolating the drag on the tree due to wind. Because of the set up for measuring loads (Figure 4), the measured load included both the drag and the reaction force at the bolt where the tree was attached to the sled. To determine drag from the measured loads, moment equilibrium was used, which requires a measurement of the center of pressure height. Distance to the center of gravity will tend to underestimate the center of pressure height because of the exaggerated effect of the heavy trunk. Distance to the centroid of canopy area was difficult to determine because of the difficulty in segmenting images (described below). Because of this, center of pressure was also estimated as the geometric mean of the distance to the center of gravity and the distance to the centroid of area. Each of these distances was used in the equation for moment equilibrium:

$$D_i = LC*0.76/(HCP)_i \qquad [4]$$

where D is drag,

LC is the dynamometer value minus F_{ACC},

0.76 is the height of the attached dynamometer on the trunk

HCP is the height of the center of pressure.

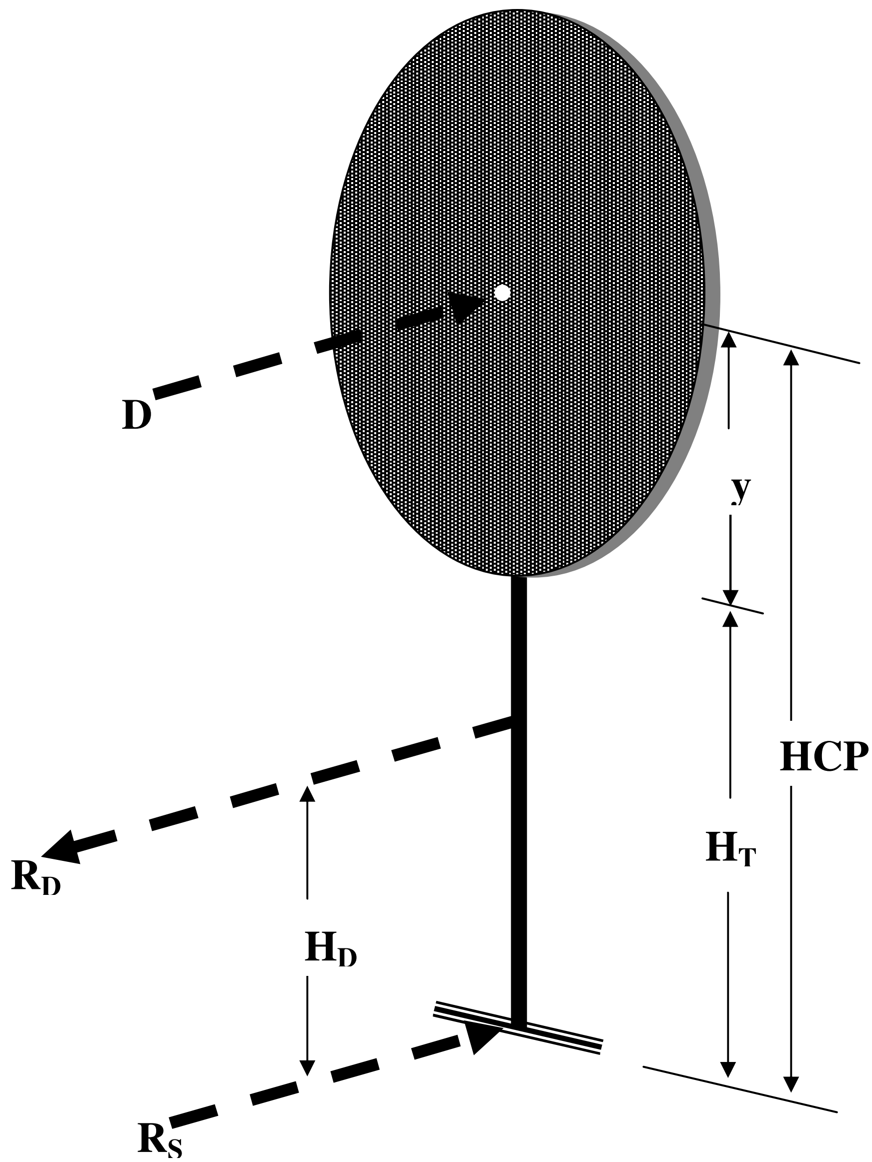

Figure 4: Schematic diagram of trees tested; the truck is not shown and the diagram is not drawn to scale. The open circle in the middle of the crown represents the centroid of the crown, D is drag, R_D is the reaction force measured by the dynamometer, R_S is the reaction force where the tree attaches to the sled, H_D is the distance between the dynamometer attachment to the trunk and the pin securing the trunk to the sled (0.76 m), y is the distance from the bottom of the crown to the centroid, H_T is the distance from the base of the tree to the top of the truck cab, and HCP is the height of the center of pressure. The heavy dashed arrows represent the line of action and sense of each force, but are not drawn to scale. Image was taken from Kane and Smiley (2006) with permission from NRC Research Press.

In addition to calculating drag, bending moment (BM), was calculated as follows:

$$BM = LC * 0.76m \qquad [5]$$

Digital Image Analysis

Digital images were imported into Adobe® Photoshop® v. 6.0 and segmented using tolerance of 15 and 2 extremely contrasting colors, white and black for analysis. Segmenting the images removed background image (white) from the actual tree image (black) (Figure 5). Segmented images were analyzed using ImageJ software to find the total canopy area and centroid of area. Images were scaled by dividing the ImageJ output of the number of pixels corresponding to canopy height and width by the measured canopy height and width, respectively. Because the image did not include the trunk, 0.9652 m (i.e., the distance between the top of the cab and the bed of the truck) was added to the scaled centroid of area values. All image analyses were completed for pruned and unpruned trees.

Data Analysis

Drag, in Newtons (N), and bending moment, in N*m, data collected before and after pruning were compared for Freeman maple (n=16), shingle oak (n=18) and swamp white oak (n=13). Drag (from equation [4]) and bending moment (from equation [5]) were compared for a wind speed of 22.4 $m*s^{-1}$, taken from a continuous set of values. Drag and bending moment values were normalized by dividing them by the mass of the tree. Differences in tree mass, height to center of gravity, height of center of photographed crown, crown height and crown width were calculated by subtracting pre- from post-treatment values for each pruning by species combination. The effects of pruning type and wind speed on original and normalized drag and bending moment values were analyzed using analysis of variance (ANOVA). Paired differences (before and after pruning) of drag and bending moment values were analyzed in the same way. Tukey's (HSD) means separation procedure was used to test for differences between means at the 0.05 alpha level. Relationships between measures of drag and tree characteristics for each pruning method and species were predicted using simple linear regression. Residuals were analyzed to check assumptions of equal variance and independence. All ANOVA and linear regressions were performed using PROC GLM and PROC REG in SAS (SAS Institute, Cary, NC. ver. 9.1).

Figure 5: Example of the black and white image segmented in Photoshop and analyzed in ImageJ.

Results

Pruning Treatments

Prior to pruning for all three species, there were no differences in drag or bending moment among pruning treatments. There was some evidence for Freeman maple that drag of trees to be reduction pruned was less than trees to be thinned or raised (Table 2).

Reduction of drag and bending moment differed by pruning type within each species. For Freeman maple, reduction pruning reduced drag more than thinning and raising; raising was also the least effective method for reducing bending moment (Table 3). When reduction in drag and bending moment were normalized by mass removed during pruning, reduction pruning remained the most effective pruning type. Although raising and thinning were equally effective at reducing drag normalized by mass removed, thinning was more effective than raising for reducing bending moment normalized by mass removed during pruning (Table 3). Normalized by crown area removed during pruning, reduction in both drag and bending moment were greater for thinning and reduction pruning than raising (Table 3). Raising actually increased drag and bending moment per unit crown area (Table 3).

For swamp white oak, raising was the most effective treatment in reducing drag, while reduction pruning was the most effective treatment in reducing bending moment (Table 3). Raising and thinning were equally effective at reducing drag per unit tree mass removed; while reduction pruning reduced bending moment per unit tree mass most effectively (Table 3). Normalization by crown area removed caused all pruning types to increase drag and bending moment relative to the amount of area removed; the greatest increase in drag and bending moment occurred with thinning pruning (Table 3).

For shingle oak, there was some evidence to suggest that raising reduced drag more effectively than thinning or reduction pruning, but all treatments reduced bending moment equally well (Table 3). When drag was normalized by tree mass removed, all pruning types reduced drag equally well, but reduction pruning reduced bending moment more effectively than raising (Table 3). As occurred with swamp white oak, normalization by crown area removed caused all pruning types to increase drag and bending moment, but the increase was smallest for reduction pruning (Table 3).

Table 2: Mean differences of drag (ΔD) (N), bending moment (ΔBM) (N*m), drag per unit mass removed (ΔD/Δm) (N/kg), bending moment per unit mass removed (ΔBM/Δm) (N*m/kg), drag per unit area removed (ΔD/ΔA) (N/m^2), and bending moment per unit area removed (ΔBM/ΔA) (N/m) at 22.4 m/s by pruning method.

Species	Pruning Method	ΔD	ΔBM	ΔD/Δm	ΔBM/Δm	ΔD/ΔA	ΔBM/ΔA
Freeman Maple	Raise (n=4)	105 a[1]	214 a	1.75 a	1.00 a	-30.8 a	-127 a
	Thin (n=6)	113 a	379 b	1.50 a	7.50 b	-3.33 b	12.8 b
	Reduce (n=6)	158 b	521 b	3.50 b	13.5 c	9.67 b	50.0 b
	P-value	**0.0009**	**<0.0001**	**0.006**	**<0.0001**	**<0.0001**	**<0.0001**
Swamp White Oak	Raise (n=5)	129 a	217 a	2.60 a	2.20 a	-60.6 ab	-193 a
	Thin (n=4)	110 b	224 a	2.50 a	3.50 a	-84.5 b	-213 a
	Reduce (n=4)	85.5 b	288 b	0.50 b	6.00 b	-51.0 a	-92.0 b
	P-value	**0.0001**	**0.0417**	**0.0001**	**0.0835**	**0.0259**	**0.0009**
Shingle Oak	Raise (n=7)	174 a	296 a	1.43 a	-1.00 a	-112 ab	-300 a
	Thin (n=5)	107 a	236 a	0.20 a	0.80 ab	-140 b	-334 a
	Reduce (n=6)	109 a	277 a	0.17 a	2.00 b	-91.3 a	-197 b
	P-value	**0.0641**	**0.7196**	**0.7833**	**0.0143**	**0.0015**	**<0.0001**

[1]means within a column followed by the same letter are not different by Tukey's HSD at $\alpha = 0.05$

Wind Velocity

For all species, the absolute reduction in drag and bending moment due to pruning, as well as the reduction in drag and bending moment per unit tree mass removed was consistent among wind speeds (Table 3). However when normalized by crown area removed, drag and bending moment increased post-pruning, and the increase was greater at greater wind speeds for shingle and swamp white oaks (Table 3).

Drag and Tree Characteristics

Pruning treatment influenced which tree characteristics (mass, height, crown height, crown width, crown area, and trunk diameter) best predicted post-pruning drag. When the three species were pooled together, tree mass was the best predictor of post-pruning drag for all pruning treatments (Table 4). Trunk diameter was the second best predictor of post-pruning drag for raised and thinned trees, while crown width was the second best predictor of post-pruning drag for reduced trees (Table 4). For all pruning methods, crown area was the worst predictor of drag (Table 4). Across all pruning types, tree mass was the best predictor of post-pruning bending moment (Table 4). Tree height was the second best predictor of post-pruning bending moment for raised trees, while crown width was the second best predictor of post-pruning bending moments for reduced trees and crown height was the second best predictor of post pruning bending moments for thinned trees (Table 4). Crown width was the worst predictor of bending moments for raised trees, while crown area was the worst predictor for reduced and thinned trees (Table 4).

Pruning Effects on Tree Dimensions

The effect of pruning on tree dimensions (mass, center of pressure height (HCP), and crown area) differed by species. Reduction pruning removed more tree mass and lowered HCP more than thinning and raising, but pruning treatments reduced crown area equally for Freeman maple (Table 5). Each pruning type removed an equal mass of foliage and twigs for swamp white oak, while reduction pruning reduced HCP more than thinning and raising (Table 5). For shingle oak, raising removed more mass, while reduction pruning reduced HCP more than raising or thinning (Table 5). For all species, raising and thinning increased HCP after pruning.

Table 3: Mean differences of drag (ΔD) (N), bending moment (ΔBM) (N*m), drag per unit mass removed (ΔD/Δm) (N/kg), bending moment per unit mass removed (ΔBM/Δm) (N*m/kg), drag per unit area removed (ΔD/ΔA) (N/m^2), and bending moment per unit area removed (ΔBM/ΔA) (N/m) by wind speed.

Species	Wind Speed (m/s)	ΔD	ΔBM	ΔD/Δm	ΔBM/Δm	ΔD/ΔA	ΔBM/ΔA
Freeman Maple (n=16)	22.4	128 a[1]	391 a	2.31 a	8.13 a	-5.31 a	-8.25 a
	20.1	117 a	356 a	2.31 a	7.81 a	-3.31 a	-3.25 a
	17.9	106 a	323 a	2.25 a	7.56 a	-1.25 a	1.31 a
	15.6	95.4 a	288 a	2.13 a	7.38 a	0.75 a	6.50 a
	13.4	84.7 a	255 a	2.13 a	6.94 a	2.81 a	11.4 a
	P-value	**0.0743**	**0.2848**	**0.9821**	**0.989**	**0.8479**	**0.8442**
Swamp White Oak (n=13)	22.4	110 a	241 a	1.92 a	3.76 a	-65.0 a	-168 a
	20.1	107 a	233 a	2.38 a	4.38 a	-54.2 ab	-141 a
	17.9	101 a	225 a	2.53 a	4.92 a	-43.9 ab	-114 ab
	15.6	96.0 a	217 a	2.61 a	5.53 a	-33.3 ab	-86.8 ab
	13.4	91.0 a	217 a	2.84 a	6.00 a	-23.0 b	-60.9 b
	P-value	**0.7017**	**0.8233**	**0.7668**	**0.8097**	**0.0283**	**0.0116**
Shingle Oak (n=18)	22.4	134 a	273 a	0.67 a	0.50 a	-113 a	-276 a
	20.1	124 a	250 a	0.94 a	0.94 a	-97.1 ab	-238 ab
	17.9	114 a	228 a	1.00 a	1.22 a	-81.4 abc	-203 abc
	15.6	104 a	207 a	1.22 a	1.67 a	-65.3 bc	-165 bc
	13.4	93.8 a	185 a	1.44 a	1.94 a	-49.7 c	-129 c
	P-value	**0.7208**	**0.7072**	**0.9369**	**0.9417**	**<0.0001**	**0.0001**

[1] means within a column followed by the same letter are not different by Tukey's HSD at α= 0.05

Table 4: Post-pruning prediction of drag (D) and bending moment (BM) at 22.4 m/s from tree characteristics. The best predictor (based on adj-R^2 value) is underlined and the slope (β) and intercept (B) for that relationship are presented in the right-most column.

Pruning Type			Tree Mass (kg)	Tree Height (m)	Crown Height (m)	Crown Width (m)*	Trunk Diameter (m)**	Crown Area (m^2)	β, B for best predictor
Raise (n=16)	D	P value	<0.0001	0.0187	0.0061	<0.0001	<0.0001	0.9804	28.7, 36.6
		adj-R^2	0.7346	0.3069	0.1362	0.5074	0.5262	-0.0222	
	BM	P value	<0.0001	0.0015	0.0314	0.3183	0.0069	0.0906	53.3, 53.6
		adj-R^2	0.8522	0.5160	0.2559	0.0054	0.3977	0.1431	
Reduce (n=16)	D	P value	<0.0001	0.6188	0.5786	0.0001	0.0009	0.8462	42.3, -26.0
		adj-R^2	0.7254	-0.0519	-0.0473	0.6284	0.5191	-0.0684	
	BM	P value	<0.0001	0.4705	0.0730	0.0044	0.0051	0.9131	118, -38.8
		adj-R^2	0.8135	-0.0309	0.1552	0.4104	0.3985	-0.0704	
Thin (n=16)	D	P value	<0.0001	0.0729	0.0517	0.0001	0.0001	0.9222	19.4, 51.0
		adj-R^2	0.7181	0.1553	0.1901	0.5178	0.6149	-0.0706	
	BM	P value	<0.0001	0.0052	0.0026	0.0449	0.0051	0.4663	97.7, -10.1
		adj-R^2	0.6612	0.3980	0.4500	0.2040	0.3984	-0.0301	

*Calculated as the geometric mean of X and Y crown width
**Calculated as the geometric mean of X and Y trunk diameter at pivot point

Table 5: Mean percent change due to pruning for tree mass, center of pressure height (HCP), and crown area by treatment for each species.

Species	Pruning Method	%DIFF Tree Mass	%DIFF HCP	%DIFF Crown Area	%DIFF Crown Height	%DIFF Crown Width
Freeman Maple	**Raise** (n=5)	11.7 a[1]	-8.50 a	28.9 a	24.2 a	6.61a
	Thin (n=6)	15.0 a	-2.35 a	20.7 a	0.00 b	0.00 a
	Reduce (n=6)	23.7 b	5.61 b	26.8 a	12.4 c	21.1 b
	P-value	**0.0012**	**0.0038**	**0.6184**	**<0.0001**	**0.0003**
Swamp White Oak	**Raise** (n=5)	12.8 a	-10.6 a	48.0 a	13.4 a	7.83 a
	Thin (n=4)	11.3 a	-3.29 a	51.2 a	0.00 b	0.00 b
	Reduce (n=4)	13.3 a	7.28 b	40.4 a	16.8 a	17.5 a
	P-value	**0.8136**	**0.0005**	**0.2311**	**0.0460**	**0.0126**
Shingle Oak	**Raise** (n=7)	18.7 a	-8.91 a	57.8 a	8.15 a	0.00 a
	Thin (n=5)	12.4 b	-1.30 a	56.9 a	0.00 b	0.00 a
	Reduce (n=6)	14.4 b	4.50 b	46.5 a	20.6 c	21.9 b
	P-value	**0.0025**	**0.0012**	**0.2523**	**<0.0001**	**<0.0001**

DIFF= Differences of before treatment and after treatment
[1] means within a column followed by the same letter are not different by Tukey's HSD at α= 0.05

Discussion

Differences among pruning methods and species

Since drag is proportional to area (Vogel, 1994), removing crown area through pruning did reduce drag similarly to what other researchers have found (Moore & Maguire, 2005; Vollsinger et al., 2005; Smiley & Kane, 2006). However given the way we calculated drag, crown area had little to effect on drag in comparison to tree mass.

Tree species responded quite differently to pruning methods; therefore, interpretation of the results cannot be applied uniformly across all species. There may be many different reasons for why each pruning treatment worked differently for each species. As researched, mass was an excellent predictor of drag and location of mass in the canopy may have played a role in determining what pruning method worked the best. With Freeman maple, most of the foliage mass was higher in the canopy because of the crown shape. Therefore, the reduce pruning method did work better than the other methods for that species in reducing drag and bending moment. For similar reasons, raise pruning worked better for swamp white oak. Swamp white oak tended to have a more broad rounded shape canopy placing more foliage and mass lower in the tree. In addition, the removal of whole branches, which is conducted in the raise pruning, removes more mass from the lower area of the canopy.

Foliage characteristics may have also played a role in the reduction of drag and bending moment. Oaks tend to have a thicker more rigid leaf in comparison to maples; this may have given the Freeman maple an advantage in that they may have been able to reconfigure in the wind reducing their crown area more than the oaks. However, the flexible branches of the maple may have decreased the porosity of the canopy when exposed to the higher wind speed. Vollsinger (2005) and Rudnicki (2004), discussed this in their research that stiffer branched canopies create an increase in porosity in the canopy as wind speed increases. Unlike Vollsinger's (2005) research, our trees were taller and more massive, so there is a chance that at $20m*s^{-1}$ tested trees may have not achieved minimal frontal area like that of Vollsinger (2005). With larger trees and more foliage mass, the leaves and branches would bounce off one another in the reconfiguration as the wind passed through the canopy in the maples. However, in the oaks branches would have remained more ridged and less likely to interfere with one another.

Form very likely contributed to the differences in species response to pruning treatment. Swamp white oak had crowns that were broader and rounder. This would have distributed their foliage over a wider area and lower in the tree in comparison to Freeman maple; thus making the raise pruning treatment more effective at reducing drag.

It is interesting that crown area reduction did not change significantly with pruning method; however, the amount of drag reduction was significantly altered by pruning method. This may be caused by the change in the location of the centroid for each of the pruning methods. Similar, changes in the location of HCP were experienced by Smiley and Kane (2006). Smiley and Kane (2006) found that reduction pruning and crown thinning lowered the location of the center of pressure by 17 and 12cm respectively. Possibly HCP increased in our study due to the selective removal of branches. We may have favored thinning the lower branches more than the upper branches, in the thin pruning because of ease and these changes in HCP were noticeable but only by a small percentage.

In addition to canopy and crown characteristics of the trees, tree mass may have played a role in determining what pruning method worked better. Freeman maple tended to have less mass then swamp white oak. This predisposed the Freeman maple to initially experience less in drag and bending moment. However, when normalized by tree mass, the effectiveness of the pruning method lessened. Raise pruning was most effective for swamp white oak because this method removed more mass then the other methods. Smiley and Kane (2006) were as successful in linking mass removal with a pruning method (P=0.03). Reduction pruning was quite effective for Freeman maple, which removed the most mass of all pruning methods. A similar occurrence was documented by Smiley and Kane (2006) in their pruning of red maple (*Acer rubrum* L).

Reducing bending moment is more important that reducing drag because of the potential structural failures that can occur due to bending moment. Drag is a force, while bending moment is force times distance. In this research this distance was at the attachment point of the tree to the sled; in the field this point is just above the root plate. Since the bending moment can be used to calculate a stress, knowledge of the bending moment of a tree will allow greater predictability of failure and steps can then be taken to protect a tree from failure. While the reduction in drag was more specific to a pruning method, the reduction in bending moment across the pruning methods was less consistent for Freeman maple. Freeman maple failed to show a tight relationship between the pruning methods that reduce bending moment the most because the force at the top wind speed was similar in both pruning methods, thin and reduce. The lack of crown porosity from pruning may have contributed to this. In our research, reducing pruning decreased bending moment in swamp white oak; Smiley and Kane (2006) found similar results with reduce pruning.

Shingle oak did not have one treatment that better reduced drag or bending moment. Similar findings occurred in drag and bending moments normalized by mass. Possibly the sail of the shingle oak did not decrease with the increase of wind speed. Although this conclusion was not verified with photos of the canopies during testing, this could indicate that the frontal area of the shingle oak may decrease very early in the testing or does not reach minimal sail area until a higher wind spend then $22.4 m*s^{-1}$. It may also be possible that drag and bending moment of shingle oak was equally affected by the pruning methods.

Differences among pruning methods by drag normalization

When the drag is normalized by mass there are little changes to the drag per unit mass. Rudnicki (2004) found similar results to yours in that pruning had little effect on drag per unit mass. When normalized by crown area, changes in drag and bending moments became negative, indicating an increase after pruning. This is contrary to previous results and our research that removing mass will decrease drag (Moore & Maguire, 2005; Vollsinger et al., 2005; Smiley & Kane, 2006). Obviously, our estimates of crown area were reduced more by the pruning methods than the changes in drag and bending moment. Our crown area calculations estimate only the crown silhouette which must have been reduced more by our pruning than the actual leaf area in the crown interacting with the wind. The trees were pruned based on what was believed to be adequate removal of foliage according to the ANSI A300 standards; however, our findings indicate almost twice the recommended limit to prune in one season of growth.

Differences in drag and bending moment by velocity

Unlike the classic drag equation, equation [1], where drag is proportional to velocity squared, our findings show that drag had a linear relationship with velocity. This was similar to other research by Vollsinger et al. (2005), Smiley and Kane (2006) and Kane and Smiley (2006). This occurred without regard to pruning method and species

What is interesting to note is that normalization of these values by tree area caused an increase in bending moment at the different wind speeds. This most likely occurred because normalization by crown area was calculated using a two dimensional object to estimate a three dimensional object. In addition, the area of the canopy is dynamic, reconfiguring at the different wind speeds.

Tree characteristic predictions

It is important to reduce drag and bending moment in trees to reduce the likelihood of structural failures during high wind events. Loads can obviously be minimized by removing foliage from the trees. This research has shown that drag and bending moment can be predicted by tree mass for all pruning treatments. Pruning removes mass from the tree, creating less surface area for air particles to hit thereby reducing drag. While pruning does reduce crown area and crown area may have been a poor predictor of drag because it is constantly reconfiguring (Vogel, 1989). Previous research also discusses the lack of consistency with crown area during the experiment, decreasing in area (Vollsinger et al., 2005) and in some cases increasing slightly the crown area (Rudnicki et al., 2004). Pruning also allows for more rapid reconfiguration by reducing the frontal area of the tree. Other characteristics, for example crown width and crown area, worked well in predicting drag because drag was based on the centroid of the image of the tree. It was the crown's dimensions that determined how much surface area of the tree would be in the path of the air flow. By reducing mass or certain crown characteristics, drag and bending moments are reduced because of the decrease of surface area in contact with the air and the height at which the drag is measured. The removal of mass also helps in the reduction of bending moment because the more mass above the point where bending moment is recorded the larger the load is expressed at the bending moment point.

While tree mass, crown width and crown area were good predictors of drag and bending moment, other measures of tree characteristics were poor predictors of drag and bending moment. Tree characteristics such as crown height and tree height may have produced negative adjusted r-squared values because of the pruning treatment it was predicting. Reduce pruning tends to remove foliage from the top of the tree, decreasing the size of the crown height and tree height. Crown area also was not a good predictor, again mostly likely because of the use of a two dimensional image to predict a three-dimensional object. Pruning treatments had variable impacts on crown area and therefore would be a bad predictor of drag after pruning.

Limitations

There are many limitations when applying this research to real world applications. The sizes of trees tested where of small stature and were not mature. The desire to apply the results to large shade trees should be considered with extreme caution because trees that are less than 3.5m are morphologically different from taller trees (Mayhead, 1973). Additional caution should be exercised when prescribing these results to other species. Our results show clear differences occurred between species most likely due to crown and foliage differences and how they affect drag. Additionally, the properties of the wood will vary among species (Panshin & Zeeuw, 1980). Aside from differences among species and tree size, another limitation is wind speed. Our findings were only conducted to wind speeds at 22.4 $m*s^{-1}$, and may not be useful in higher wind speeds where the tree may reach minimum wind sail (Vogel, 1989) and where large events, such as hurricanes, cause more wide spread damage to trees. In addition, wind was only tested in one direction and during a major event wind may change velocity and direction, altering the sway frequency of the tree (Milne, 1991).

While this research sheds some light on the influence pruning can have over the effect of drag and bending moment, additional caution should be used. The method used in this research to calculate drag is a limiting factor because it does not follow the traditional equation of calculating drag. Moreover, the use of reduce pruning can create decay problems in trees and trees may stress and develop epicormic branches that will increase the potential risk of a tree. Future testing with a better variety of species is desired to accommodate the diversity that occurs in the urban forest.

Conclusions

This research has shown that the effects of drag were lessened best by reduction pruning in Freeman maple and best by raise pruning in swamp white oak. In shingle oak no particular pruning treatment was better at reducing drag. For bending moment Freeman maple responded worst with raise pruning, swamp white oak responded best with raise pruning and similar to drag shingle oak was equally effected by pruning for bending moment. This research also indicated that tree mass is an excellent predictor for drag and bending moment. When researching drag, it is also beneficial to measure bending moments because it is a better indicator of the structural stresses placed on the tree. In addition, the normalization by tree mass indicates that an arborist can focus more on how the tree is pruned more then how much mass is removed.

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