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Effects of Pruning Dose and Type on Trunk Movement in Tropical Storm Winds

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Abstract. We built a machine with a propeller capable of generating 33.5 m/s (75 mph) winds to determine the influence of pruning dose and American National Standards Institute A300 pruning type on trunk movement of *Quercus virginiana* 'QVTIA' PP #11219, Highrise® at various wind speeds. Trunk movement was regressed against wind speeds and pruning doses for each tree tested. Increasing wind speed increased trunk movement, and the magnitude of the increase depended on pruning dose and pruning type. Increasing pruning dose reduced trunk movement and the magnitude of the reduction was greater at higher wind speeds. The predicted trunk movement of thinned trees was statistically greater than movement of structurally pruned, raised, and lion's tailed trees at wind speeds of 20.1 m/s (45 mph) and was greater than all pruning types at 26.8 m/s (60 mph). There was no difference in movement among reduced, raised, structurally pruned, and lion's tailed trees; and there were no statistical differences in trunk movement among pruning types at the lower wind speeds. We found that thinning the outer edge of the crown was one of the least effective pruning types for reducing trunk movement in wind.

Key Words. Crown raising; crown reduction; crown thinning; lion's tailing; pruning dose; pruning type; structural pruning; wind.

Mattheck and Breloer (1994) speculated that pruning can reduce damage from winds because it reduced the surface area of the tree crown, but Mayhead (1973) and others found mass to be a better predictor of drag than crown area. Duryea et al. (1996) noted that pruned trees withstood wind damage from Hurricane Andrew better than their unpruned counterparts; unfortunately, the pruning type or amount was not identified so interpretation is impossible. Ham and Rowe (pers. comm.) thought that despite losing over 4,800 street trees, damage to the city of Charlotte, North Carolina, U.S. from Hurricane Hugo was lessened by a program of routine maintenance, including pruning. Pruning is recommended as a means of reducing wind damage to trees (Matheny and Clark 1994; Gilman 2002; Harris et al. 2004). Research supporting recommendations for pruning trees to reduce wind damage is almost nonexistent in the primary literature.

Moore and Maguire (2005) mention that the natural frequency and damping ratio of Douglas fir trees was not affected by removing low branches (crown raising) until more than 66% of the crown was removed. This may be attributable to mass damping and foliage drag in the lower crown and higher wind velocities at higher elevations. Rudnicki et al. (2004) and Vollsinger et al. (2005) reported that pruning did not influence streamlining (drag coefficients) in the coniferous or hardwood species tested. However, they noted that their test specimens were small so the effect of streamlining was difficult to defend. One of the most recent studies showed that crown reduction reduced drag per unit mass removed about the same as crown thinning in wind speeds up to 20.1 m/s (45 mph) on *Acer rubrum* saplings (Smiley and Kane 2006). Increasing porosity in a conifer-shaped crown by thinning also predictably reduced drag (Hoag et al. 1971).

The American National Standards Institute (ANSI; 2001) recommends limits to pruning as defined by a percent of foliage removed within one growing season. However, ANSI provides no information about how to quantify the percent of foliage removed. Other resources refer back to the ANSI pruning standard on questions of dose (Gilman and Lilly 2002). They also advise the practitioner to quantify pruning dose based on the desired objective or the appearance of the tree after pruning (Waring et al. 1982). Thus, the measurement of pruning dose by practitioners is largely qualitative and subjective, and there is no published measurement of the accuracy of visual estimates. The objective of this study was to determine the influence of pruning dose and pruning type on trunk movement at various wind speeds of tropical storm force velocity. Trunk movement below the bottom of the crown was used to evaluate pruning and wind effects because, everything else being equal, trunk deflection should be related to failure potential along this portion of the trunk.

MATERIALS AND METHODS

Trees

Trees (clonal, cutting-propagated live oak trees, *Quercus virginiana* 'QVTIA' PP #11219, Highrise®) were selected for physical similarities described subsequently from trees at Marshall Tree Farm (Morriston, FL), U.S. Department of Agriculture (USDA) hardiness zone 8a. Wood properties vary very little among trees within a clone (Mosedale et al. 1996). Marshall Tree Farm (MTF) planted the trees from #5 containers [25 cm (10 in) wide at the top × 30 cm (12 in) deep] into Orlando fine sand or Sparr fine sand in June 2000. Trees were dug and placed in wire baskets January 2003.

In May 2003, the following tree physical characteristics were evaluated from 50 trees: trunk diameter (caliper) 15 cm (6 in) from the ground; distance between top-most root and the lowest branch, total crown height (TCH) determined by measuring maximum height (distance from top of rootball to top of the crown), minimum height (distance from top of rootball to origin of the lowest branch), and subtracting minimum from maximum; crown diameter (CD) as the average width of a crown measured at its widest point in two perpendicular directions; height to vertical center of a crown as one-half TCH plus minimum height; trunk taper calculated as –(R-r)/R (Leiser and Kemper 1973) where R = trunk radius at 15 cm (6 in) above the top-most root and r = radius at 1.37 m (4.52 ft) above the top-most root; projected crown frontal area 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 1 = 0.333 × TCH and radius 2 = 0.5 × CD); and crown volume as calculated from the volume of a cone plus one half the volume of an ellipsoid. We used this to estimate the shape of the crown of Highrise® live oak, which appears as a cone resting on top of half an ellipse. On 6 November 2003, 44 of these trees representing those most similar to the mean of each of these characteristics were moved from MTF to the Environmental Horticulture Teaching Unit (Gainesville, FL, USDA hardiness zone 8b); 27 of these were used in this study. Test trees averaged 8.9 cm [3.56 in; standard deviation (SD) = 0.14] caliper, 6.1 m (20.13 ft; SD = 0.42) tall, and 1.9 m (6.27 ft; SD = 0.87) crown diameter. Trees were irrigated regularly, including the day before testing.

Experimental Design

Three effects were evaluated: 1) pruning dose; 2) pruning type; and 3) wind speed. From those three effects, 60 treatment combinations (five pruning types × four pruning doses × three wind speeds) were targeted. Trees were randomly assigned to a pruning type. The physical characteristics used to select the 27 trees from the nursery were used to compare trees assigned to pruning types. There were no differences in tree characteristics among pruning types with one exception. The elevation to the vertical center of the canopy was statistically ($P = 0.039$) less [3.63 m (11.98 ft)] for trees assigned to the thinned pruning type than for those assigned to the reduced pruning type [3.91 (12.90 ft)]. Because that was the only difference among types, no further adjustments were made in the assignment of trees to pruning types. The five pruning types included 1) lion's tailed; 2) raised; 3) reduced; 4) structural; and 5) thinned. Each tree within a type was pruned to four targeted pruning doses in the following sequence: 1) no pruning (0% foliage removed); 2) 15% foliage removed; 3) 30% foliage removed; and 4) 45% foliage removed. Actual doses were measured after foliage was removed from the tree and these doses varied from the targeted doses as described subsequently. Within a pruning dose, each tree was subjected to a sequence of three targeted wind speeds of 6.7 m/s (15 mph), 13.4 m/s (30 mph), and 20.1 m/s (45 mph). Actual wind speeds were measured while trees were blown with gusts up to 33.5 m/s (75 mph). Trees were blown when ambient winds were less than 2.2 m/s (5 mph).

Pruning doses used in the statistical analyses were not the targeted doses but were the measured percentage of total tree foliage dry weight removed. Foliage on parts of the crown removed by pruning was stripped from branches and dried separately from branches to calculate actual percentage foliage removed (pruning dose) on all pruned trees. Mean total tree foliage dry weight was measured by stripping all foliage from 13 trees after they were tested and drying to a constant weight [mean 2 kg (4.4 lb; standard error = 0.13)]. Measured percentage of foliage removed (i.e., actual pruning dose) on each test tree was calculated as dry weight of foliage removed during pruning ÷ mean total tree foliage dry weight (2 kg) × 100. Total removed dry mass (branches + foliage) was highly correlated with removed foliage dry mass ($R^2 = 85\%$); removed foliage percentage was used in the data analysis.

Pruning types were blocked in time so that each block contained a lion's tailed, raised, thinned, and reduced tree. One block was pruned, then the next, and so on. Trees in the fifth pruning type, structural pruning, were pruned after all other trees in the study were tested. This is described in detail subsequently. One person was chosen to prune all trees to maintain consistency, and trees were pruned on the day of testing.

The first four lion's tailed trees were blocked in time with other pruning types. The 15% pruning dose removed all primary and higher order branches [1.27 cm (0.51 in) diameter and smaller] at the trunk and along branches within the lowest 15% of crown height and the most interior 15% of crown radius. The 30% and 45% pruning doses were applied in a similar fashion. We dried and weighed removed foliage and found too little was removed to meet our targeted dose levels. Therefore, after testing of all blocked trees, three additional trees were lion's tailed, but pruning dose was estimated visually in an attempt to remove targeted doses.

The first three raised trees were blocked in time with other pruning types. The central leader was marked at 15%, 30%, and 45% of TCH. The 15% pruning dose was applied by removing all primary lateral branches at the trunk beginning at the base of the crown up the main leader to the 15% mark. The 30% and 45% dose levels were applied in a similar fashion. We dried and weighed removed foliage and found foliage removed at each dose exceeded targeted levels so after testing of all blocked trees, three additional trees were included to better approximate targeted pruning doses. Pruning dose for the additional raised trees was estimated visually in an attempt to remove the targeted doses. Pruning was carried out as before, but if removal of a large limb would have caused an excessive dose, it was treated as a second leader and raised as per the main leader.

The first four reduced trees were blocked in time with other pruning types. The main leader was marked at 85%, 70%, and 55% of TCH. Pruning was accomplished by first removing the main leader at the designated mark followed by heading the exterior of the remaining crown to reestablish each crown's original three-dimensional shape but in a smaller version. No foliage was removed from interior parts or from the lower side of a crown. We dried and weighed removed foliage and found foliage removed from three trees exceeded targeted pruning doses. Therefore, after testing of all blocked trees, three additional trees were reduced by visually approximating targeted dose levels.

Four trees were thinned and blocked in time with other pruning types. Thinning was conducted by making removal and reduction cuts throughout the entire crown, especially at the outer half of the crown. No branches were removed from the trunk. Pruning dose was determined in the field as a visual estimate of live foliage removed. Thinning produced a uniformly dense tree without changing the crown's dimensions.

Two trees were structurally pruned. Structural pruning involved making primarily reduction cuts (with occasional removal cuts) to shorten and slow growth of stems competing with the main trunk and to develop scaffold branches. No branches were removed from the trunk. Little thought was given to crown size, shape, or density. Pruning dose was determined in the field as a visual estimate of live foliage removed.

Winds were generated using a 1988 Chevrolet 5.7 L (1.48 gal) engine, a 2-1-power reduction unit, and a two-blade Sensenich 2 m (6.6 ft), left-hand rotation composite propeller (Sensenich Wood Propeller Co., Inc., Plant City, FL). The engine was mounted in an airboat secured onto two concrete piers so the propeller's midpoint was at the estimated crown center of pressure on an average unpruned crown. This corresponded to one-third average total crown height, or an elevation of 3.1 m (10.23 ft) from the ground. This provided a vertical wind profile shown in Figure 1. Maximum winds were near the estimated crown center of pressure. Because the top third of the crown in these Highrise® live oaks had very little foliage on a few thin stems, this positioned about 20% of crown foliage (estimated) outside the wind field shown in Figure 1 on the average tree. This may have biased results because the entire canopy was not in the main wind field on all trees; however, trees bend during testing, which brought more of the crown into the main wind field.

Wind speed was measured 4 m (13.2 ft) from the propeller at the height equal to the estimated crown center of pressure (which we estimated for most trees as approximately one-third the way up the crown) with a Campbell anemometer (Met One 034B; Campbell Scientific, Inc., Logan, UT). It was calibrated by Campbell Scientific before purchase and we checked this calibration against the speedometer of a Jeep Grand Cherokee by extending it 48 cm (19.2 in) straight out the passenger window as it was driven from 4.5 m/s (10 mph) to 31.3 m/s (70 mph) in increments of 4.5 m/s (10 mph). Calibration with speedometer was within 3% of Campbell's calibration for all wind speeds.

Experimental Procedure

The tree trunk was positioned 6 m (19.8 ft) from the propeller. The rootball [mass of tree in the rootball = 288 kg (633.6 lb)] was secured in a 272 kg (598.4 lb) steel basket and cover plate fabricated to match the dimensions of the rootball. When secured with the solid steel cover plate fixed to the earth with four threaded rods sunken in concrete, the trunk remained stable in the rootball without rotating under load from the wind (Jones 2005). To account for any rotation of the trunk in the rootball during the 4-min blow period, we rezeroed the cable extension transducers (CETs) before blowing the tree again. Eight CETs [63 cm (25.2 in; PT1A-UP-5K-M6-SG; Celesco Transducer Products Inc., Chatsworth, CA] were attached to the trunk 46 cm (18.4 in), 76 cm (30.4 in), 107 cm (42.8 in), and 137 cm (54.8 in) above the top-most root in the rootball. Because trunk movement responded similarly among treatments for all positions (Jones 2005), only data for the topmost CET is reported. The CETs were mounted to vertical posts positioned 4.6 m (15.18 ft) from the trunk so that cables approached the trunk parallel to the ground (Figure 2). Each was positioned so the cable from one CET approached the tree 90° from the other one centered on a straight line between the tree and the center of the propeller. Trigonometry was used to calculate the horizontal movement of the trunk from its starting point in the wind field.

Motor revolutions per min (rpm) to wind speed correlations indicated that to achieve six targeted wind speeds, testing needed to be performed at 0 rpm, 1250, 2000, and 2750, back to 1250 rpm, and finally at 0 rpm. Data were collected at the second 1250 rpm and second 0 rpm to evaluate if the tree had shifted or lost foliage during the test. There was no statistical difference between trunk deflection at the first 1250 rpm and the second 1250 rpm test; nor was there a difference in trunk deflection between 0 rpm before and after the test (Jones 2005). This meant that trees neither lost significant foliage nor shifted in the rootball during the test; however, foliage can dry during a wind test of more than approximately 10 min and this can influence crown reconfiguration during the test (Vogel 1989). Because all trees were blown similarly, the effect of foliage drying on comparisons among pruning types is thought to be negligible. However, individual models for each tree may have over estimating trunk movement. Data were collected for 2 min at ambient conditions (0 rpm) and for 4 min at each rpm for a total of 20 min per tree per pruning dose.

Trunk deflection was measured for 4 min at each targeted wind speed before pruning; then the tree was pruned at the 15%

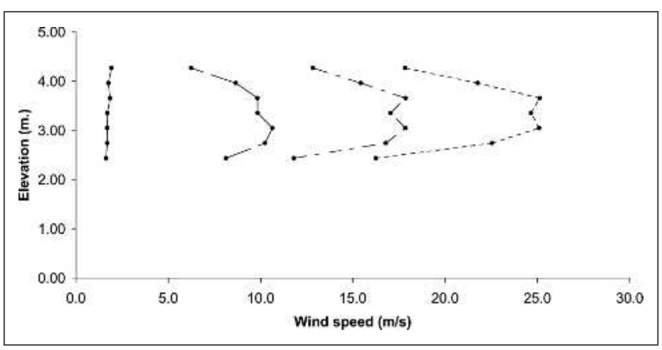

Figure 1. Vertical profile of average generated wind speeds measured on three different days (27 May 2004, 9 March 2005, and 15 March 2005). Profiles represent ambient, 1250, 2000, and 2750 (left to right) motor revolutions per min. Wind speeds were recorded at 0.5 Hz for 4 min at each elevation and averaged across days within an elevation.

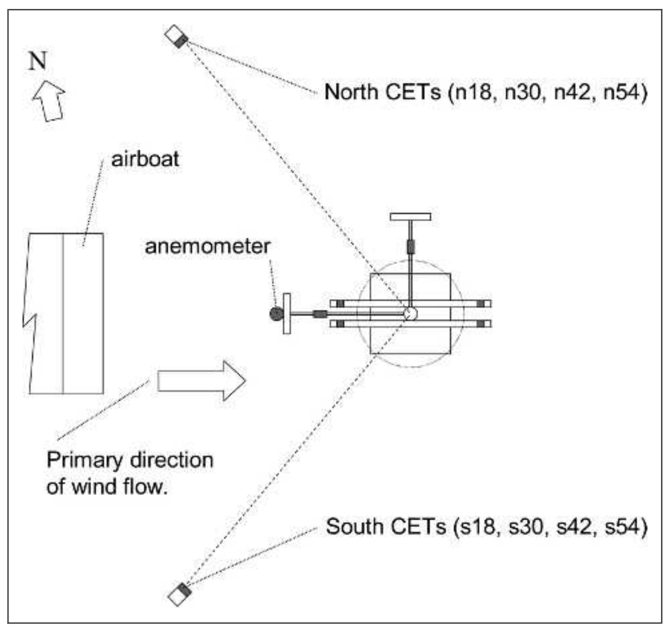

Figure 2. Schematic of tree (small open circle), metal basket (dotted circle) and tree-securing mechanism (square with two top supports), cable extension transducer (CETs), and anemometer positions. Numbers in parentheses indicate distance (in inches) from ground to position of CET on trunk.

targeted dose and deflection measured at each wind speed, the tree was pruned at the 30% targeted dose and deflection measured at each speed, and then at the 45% targeted dose and deflection measured. Trees returned to prewind crown structure before blowing at the next pruning dose; crossing branches were untangled and no branches broke. Therefore, data were collected 24 different times (six targeted wind speeds × four pruning doses) on each tree. The first four lion's tailed, reduced, and thinned trees, and the first three raised trees, were blocked in time forming an incomplete block design; then the last three lion's tailed, raised, and reduced trees, and the two structurally pruned trees were blown in no particular order.

Measurements from CETs and anemometer were taken at 0.5 Hertz (every 2 sec). This infrequent interval could have resulted in losing data resolution, especially in gusts of wind. The data acquisition system (DAQ) consisted of a Campbell Scientific CR10X data logger used in combination with a Campbell AM 416 multiplexer 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.

Data Analysis Strategy

Measured (not targeted) pruning dose and wind speed for each tree individually were regressed onto trunk movement using a complete two-factor linear and quadratic model (equation 1) predicting trunk movement from measured pruning dose and wind speed. Orthogonal (equal spaced) combinations of dose (0%, 15%, 30%, 45%, and 60% foliage removed) and wind speed [0, 6.7, 13.4, 20.1, 26.8 m/s (0, 15, 30, 45, 60 mph)] were selected along the linear and quadratic model response surface (25 dose × speed combinations per tree) to calculate predicted trunk movement for each tree. We were able to add the 26.8 m/s (60 mph) wind speed because winds gusted above this speed when we blew trees. We were able to add the 60% pruning dose because some trees were pruned that much as determined by weighting removed foliage.

Equation 1. Predicted trunk movement (PTM) $= b_0 + b_1$ wind speed (W) $+ b_2$ pruning dose (D) $+ b_3 W^2 + b_4 D^2 + W \times D$. b's represent coefficients for each term.

Predicted trunk movement was calculated from the equation generated for each tree. Three-way analysis of variance of PTM evaluated the effects of pruning type, dose, and wind speed. Analysis of variance (ANOVA) was run as a completely randomized design because all replicate trees within a pruning type were not included in the original block design. Least squared means were separated with Tukey's multiple range test. Data were analyzed using the SAS system for windows release 8.02 (SAS Institute Inc., Cary, NC).

RESULTS AND DISCUSSION

Actual trunk movement was regressed against measured wind speed and measured pruning dose for each tree tested (Table 1), and the resulting equation was used to predict trunk movement for that tree at orthogonal levels of dose and wind speed. Linear and quadratic terms were significant. Rudnicki et al. (2004) and Vollsinger et al. (2005) found that crown drag was related to wind speed squared when accounting for reduction in crown area attributable to reconfiguration, and Hoag et al. (1971) and Smiley and Kane (2006) both found drag related to the 1.4 power of wind speed for broad-leaved trees. Three-way ANOVA of predicted trunk movement showed that the factors pruning type, pruning dose, and wind speed had a significant effect on trunk movement (Table 2). However, interactions were significant so conclusions about each factor depended on the level of another factor. Despite the interactions described subsequently, increasing wind speed increased trunk movement (indicated by a positive b_1 coefficient for every tree; Table 1), and the magnitude of the increase depended on pruning dose and pruning type (Figure 3; Table 3) similar to findings of Smiley and Kane (2006). Increasing pruning dose reduced trunk movement (indicated by a negative b_2 or b_4 coefficient for most trees; Table 2), and the magnitude of the reduction was greater at higher wind speeds.

The pruning dose × pruning type interaction was not significant indicating that the impact of either factor on trunk movement was independent of the other. In other words, averaged across all wind speeds, increasing the amount of foliage removed (pruning dose) on one pruning type resulted in the same reduction in trunk movement as all other pruning types (data not shown). This might lead us to conclude that removing foliage from anywhere in the crown on trees of this size was equally effective at reducing trunk movement in windy weather. However, pruning type interacted with wind speed so further interpretation was needed.

The pruning type × wind speed interaction was significant (Table 2) indicating that averaged across pruning dose, the effect of wind speed on trunk movement was not the same for all pruning types (Table 3). Predicted trunk movement of thinned trees was statistically greater than movement of trees pruned by all other types except reduction at wind speeds of 20 m/s (45 mph). This agrees with Smiley and Kane (2006) who found reduced trees responded to wind similar to thinned trees up to 20.1 m/s (45 mph). However, we found that at 26.8 m/s (60 mph), thinned trees moved more than trees in all pruning types, including those that were reduced.

Perhaps if the tops of our thinned trees were within the main wind field, they would have bent more than reduced trees (which were totally inside the wind field) at a wind speed lower than 26.8 m/s (60 mph). However, if the crown top extending outside the main wind field had a significant effect on trunk movement, then other pruning types might be expected to bend less than reduced trees. Because this did not happen, differences we are reporting here appear defendable. The limited size of generated wind fields is one of the most conspicuous obstacles in the study of wind and trees with intact root systems. Mayhead (1973) noted that the leading shoots of several of the trees he tested were outside the wind flow and commented that it was not likely a significant source of error.

The leading shoots in the upper crown in our trees were outside the primary wind flow before pruning (Jones 2005). The effect of the shortened wind field might be most noticeable on the dimensionally pruned raised trees (i.e., the first four raised trees) because they were pruned with the highest dose and the crown was removed from the portion of the wind field with the highest wind speed (Figure 1); however, trunk movement of the raised trees was not statistically different from movement of lion's tailed, reduced, or structurally pruned trees. When ANOVA was carried out with the four dimensionally pruned trees removed from the data set (data not shown), the results did not change. Therefore, the size of the wind field likely did not affect comparisons among pruning types or doses.

Table 1. Regression coefficients and R^2 from a complete two-factor linear and quadratic model (equation 1) using trunk movement 1.4 m (4.62 ft) aboveground, wind speed (wind), and pruning dose (dose) for each tree.

Pruning type[z]	Tree no.[y]	Intercept	Wind	Dose	Wind × wind	Dose × dose	Wind × dose	R^2
LT	1	NS	0.03947	0.004720	0.00046	–0.00022	–0.00102	0.93
LT	2	0.05216	0.02832	–0.01594	0.00020	0.00058	–0.00044	0.91
LT	3	NS	0.05910	–0.00658	–0.00010	0.00011	–0.00073	0.81
LT	4	0.06780	0.05907	–0.00984	0.00007	0.00017	–0.00071	0.82
LT	5	–0.13997	0.05650	–0.00265	–0.00037	0.00006	–0.00036	0.76
LT	6	0.05627	0.02285	–0.00850	0.00010	0.00017	–0.00033	0.88
LT	7	NS	0.03519	–0.00653	–0.00000	0.00015	–0.00070	0.84
RA	2	NS	0.04782	NS	0.00027	0.00002	–0.00066	0.95
RA	3	–0.06430	0.02960	0.00170	0.00010	0.00001	–0.00044	0.96
RA	4	0.12652	0.04827	NS	0.00030	–0.00002	–0.00057	0.96
RA	5	NS	0.03459	0.00213	0.00033	–0.00006	–0.00034	0.98
RA	6	–0.09167	0.02932	0.00496	0.00015	–0.00004	–0.00047	0.91
RA	7	NS	0.03116	0.00245	0.00017	–0.00005	–0.00033	0.95
RE	1	0.04733	0.04321	0.00515	0.00013	–0.00017	–0.00054	0.91
RE	2	–0.09332	0.03575	0.00542	0.00041	–0.00003	–0.00040	0.90
RE	3	NS	0.05964	NS	0.00012	–0.00005	–0.00048	0.90
RE	4	NS	0.03332	0.00512	0.00028	–0.00008	–0.00031	0.97
RE	5	0.04898	0.02694	–0.00449	0.00018	0.00008	–0.00021	0.93
RE	6	NS	0.05304	NS	–0.00023	NS	–0.00021	0.75
RE	7	0.04920	0.05088	NS	0.00034	–0.00012	–0.00009	0.96
ST	1	–0.15436	0.02881	0.00379	0.00012	–0.00004	–0.00032	0.96
ST	2	NS	0.04060	–0.00576	–0.00023	0.00008	–0.00042	0.75
ST	3	–0.06809	0.04117	NS	0.00014	NS	–0.00046	0.87
TH	1	0.06958	0.04023	–0.00919	0.00060	0.00018	–0.00068	0.94
TH	2	–0.05864	0.03670	NS	0.00045	0.00003	–0.00042	0.96
TH	3	NS	0.04686	NS	0.00039	0.00004	–0.00053	0.90
TH	4	–0.15341	0.04060	0.00356	0.00029	NS	–0.00040	0.93

[z]Pruning types: LT = lion's tailing; RA = raising; RE = reduction; ST = structural; TH = thinning.
[y]Tree no.: number assigned to a tree within a pruning type.
NS = not statistically significant at $P < 0.05$.
Note: 16 trees had intercepts not equal to zero. This may have slightly over- or underestimated deflection on these trees.

There was no difference in movement among reduced, raised, structurally pruned, and lion's tailed trees at any wind speed (Table 3). All four of these pruning types created larger voids in the crown than thinning. These larger voids may have allowed the crown to reconfigure so wind passed through (Grant and Nickling 1998) or around the crown, whereas negligible wind passed through intact crowns (Zhu et al. 2000). Thinning only removed small-diameter branches along the outside of the crown and these small voids may not have allowed for as much crown reconfiguration or frontal area reduction because branches interacted with each other. This could explain the greater movement in thinned trees than other pruning types. Thinned trees might have moved most because thinning was the only pruning type in which postpruning crown dimensions did not change, so thinned trees may have presented a larger frontal area to the wind than other pruning types. Perhaps if we had thinned by removing branches entirely back to the trunk instead of removing many small branches from the outer portion of the crown-thinned trees, they would have responded similar to other pruning types because created voids would have been larger.

Table 2. Analysis of variance of predicted trunk movement using orthogonal levels[z] of wind and pruning dose from equations calculated in Table 1.

	Trunk movement 1.4 m (4.62 ft) from ground	
Source of variation	F	P > F
Pruning type[y]	41.49	<0.001
Pruning dose[x]	83.49	<0.001
Pruning type × pruning dose	0.58	0.898
Wind speed[w]	395.29	<0.001
Pruning type × wind speed	7.37	<0.001
Pruning dose × wind speed	5.96	<0.001
Pruning type × pruning dose × wind speed	0.07	1.000

[z]Orthogonal levels were 0, 15, 30, 45, and 60 for pruning dose (%) and 0, 6.7 (15), 13.4 (30), 20.1 (45), and 26.8 (60) wind speed in m/s (mph).
[y]Pruning types: lion's tailing, raising, reducing, structural, thinning.
[x]Pruning dose (percentage of foliage dry mass removed).
[w]Wind speed recorded 2.1 m (6.93 ft) in front of tree trunk.

Hoag et al. (1971) showed that distribution of foliage is a good measure of location of the resultant drag force acting on a limb. Despite the fact that the same amount of foliage on our study trees was distributed very differently between the raised (higher in the crown) and reduced (lower in the crown) trees, trunks in both pruning types moved similarly at all wind speeds. Perhaps the smaller-diameter branches in the upper crown that remained after raising could reconfigure to present a smaller frontal area to the wind than reduced trees, which had foliage borne on stiffer (larger-diameter) branches, which could not reconfigure as much. This theory remains to be tested. The top portion of the raised trees occurring outside the main wind field may also have caused lesser movement in raised trees;

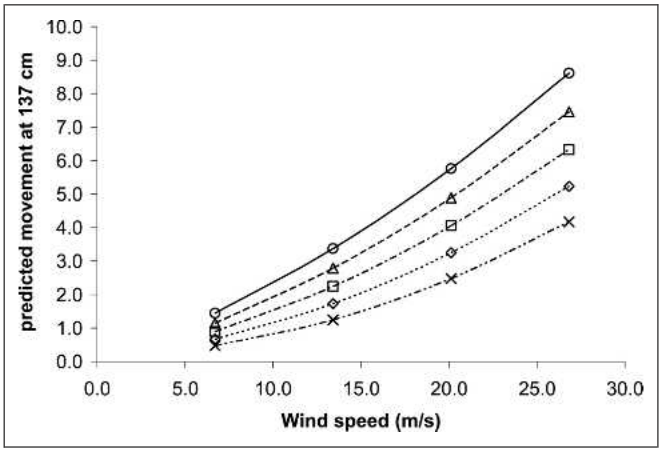

Figure 3. Predicted (from models in Table 1) trunk movement (averaged across pruning types) at increasing wind speed for five pruning doses. Interaction between pruning dose and wind speed was significant at $P < 0.0001$. The vertical axis is the least square means of trunk movement 137 cm (54.8 in) above the top-most root adjusted using Tukey's method. Lines represent different pruning doses: circles = 0% foliage dry mass removed, triangles = 15%, squares = 30%, diamonds = 45%, and Xs = 60%.

although as discussed previously, this effect may have been insignificant.

We measured pruning dose as a percent of foliage dry weight removed because foliage is the crux of the ANSI standard. Measured foliage removed [on those trees not subjected to geometric dictation of foliage removal (i.e., those not in the original blocks)] corresponded to targeted (estimated) foliage removed better on lower pruning doses (targeted = 15%, measured = 17.9%; targeted = 30%, measured = 35.9%) than at the largest dose (targeted = 45%, measured = 52.8%). This provides some comfort to arborists attempting to visually estimate pruning dosage, although Smiley and Kane's (2006) visual estimates of percent crown removed appeared to vary from actual measurements more than ours.

Trees generally moved similarly in the wind regardless of ANSI pruning type applied. Our results indicate that thinning may be a bit less effective than other pruning types at reducing motion in strong tropical storm force wind speeds. These data indicate that it could require a lower wind speed to damage thinned trees along the portion of the trunk below the crown than trees pruned in other fashions. Effects of wind gustiness, quick change of directions, and other wind characteristics of a natural system that we did not measure in this study need to be tested in subsequent studies. It may not be wise 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 the effect of pruning on the aeromechanical behavior of individual branches when they are coupled as a continuous dynamic structure. This will be challenging.

Table 3. Least squares means of predicted trunk movement by pruning type and wind speed.

	Trunk movement [cm (in)] 1.4 m (54 in) above topmost root[z]			
Pruning type[y]	6.7 m/s (15 mph)[x]	13.4 m/s (30 mph)	20.1 m/s (45 mph)	26.8 m/s (60 mph)
ST	NS	NS	3.3 (1.31) a[w]	5.3 (2.05) a
RA	NS	NS	3.8 (1.50) a	5.7 (2.25) a
LT	NS	NS	3.8 (1.51) a	6.1 (2.39) a
RE	NS	NS	4.5 (1.77) ab	6.9 (2.70) a
TH	NS	NS	5.3 (2.07) b	8.4 (3.32) b

[z]Average trunk movement predicted from regression models in Table 1.
[y]Pruning types: LT = lion's tailing; RA = raising; RE = reducing; ST = structural; TH = thinning.
[x]Wind speed at which trunk movement was predicted from regression models.
[w]Means in a column with different letters are significantly different ($P < 0.001$) from each other.
NS = not significant; there were no differences within that column.

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LITERATURE CITED

American National Standards Institute. 2001. American National Standard for Tree Care Operations—Tree, Shrub and Other Woody Plant Maintenance—Standard Practices (Pruning) (A300, Part 1). Tree Care Industry Association, Manchester, NH.

Duryea, M.L., G.M. Blakeslee, W.G. Hubbard, and R.A. Vasquez. 1996. Wind and trees: A survey of homeowners after Hurricane Andrew. Journal of Arboriculture 22:44–50.

Gilman, E.F. 2002. An Illustrated Guide to Pruning, 2nd edition. Delmar Publishers, Albany, NY.

Gilman, E.F., and S.J. Lilly. 2002. Best Management Practices: Tree Pruning. International Society of Arboriculture, Champaign, IL.

Grant, P.F., and W.G. Nickling. 1998. Direct measurement of wind drag on vegetation for application to windbreak design and modeling. Land Degradation and Development 9:57–66.

Harris, R.W., J.R. Clark, and N.P. Matheny. 2004. Arboriculture: Integrated Management of Landscape Trees, Shrubs, and Vines, 4th edition. Prentice Hall, Upper Saddle River, NJ.

Hoag, D.L., R.B. Fridley, and J.R. Hutchinson. 1971. Experimental measurement of internal and external damping properties of tree limbs. Transactions of the American Society of Agricultural Engineers 14:20–28.

Jones, S. 2005. Effect of pruning type, pruning dose, and wind speed on tree response to wind load. Master's thesis, University of Florida.

Leiser, A.T., and J.D. Kemper. 1973. Analysis of stress distribution in the sapling tree trunk. Journal of the American Society for Horticultural Science 98:164–170.

Matheny, N.P., and J.R. Clark. 1994. A Photographic Guide to the Evaluation of Hazard Trees in Urban Areas, 2nd edition. International Society of Arboriculture, Urbana, IL.

Mattheck, C., and H. Breloer. 1994. The Body Language of Trees: A Handbook for Failure Analysis. Department of the Environment, Transport and the Regions, London, U.K.

Mayhead, G.J. 1973. Some drag coefficients for British forest trees derived from wind tunnel studies. Agricultural and Forest Meteorology 12:123–130.

Moore, J.R., and D.A. Maguire. 2005. Natural sway frequencies and damping ratios of trees: Influence of crown structure. Trees—Structure and Function 19:363–373.

Mosedale, J.R., B. Charrier, and G. Janin. 1996. Genetic control of wood colour, density and heartwood ellagitannin concentration in European oak (*Quercus petrea* and *Q. robur*). Forestry 69:111–124.

Rudnicki, M., S.J. Mitchell, and M.D. Novak. 2004. Wind tunnel measurements of crown streamlining and drag relationships for three conifer species. Canadian Journal of Forest Research 34: 666–676.

Smiley, T., and B. Kane. 2006. Effects of pruning type on wind loading. Journal of Arboriculture 32:33–39.

Vogel, S. 1989. Drag and reconfiguration of broad leaves in high winds. Journal of Experimental Botany 40:941–948.

Vollsinger, S., S.J. Mitchell, K.E. Byrne, M.D. Novak, and M. Rudnicki. 2005. Wind tunnel measurements of crown streamlining and drag relationships for several hardwood species. Canadian Journal of Forest Research 35:1238–1249.

Waring, R.H., P.E. Schroeder, and R. Oren. 1982. Application of the pipe model-theory to predict canopy leaf-area. Canadian Journal of Forest Research 12:556–560.

Zhu, J., T. Matsuzaki, and K. Sakioka. 2000. Wind speeds within a single crown of Japanese black pine (*Pinus thunbergii* parl.). Forest Ecology and Management 135:19–31.

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Résumé. Nous avons construit une machine avec une hélice capable de générer des vents jusqu'à 33,5 m/s afin de déterminer l'influence du degré d'élagage ainsi que du type d'élagage selon la norme ANSI A300 par rapport au mouvement du tronc chez le *Quercus virginiana* 'QVTIA' PP #11219, Highrise® à différentes vitesses de vent. Le mouvement du tronc a fait l'objet d'une régression par rapport aux vitesses de vent et aux degrés d'élagage pour chacun des arbres évalués. Une vitesse accrue du vent faisait augmenter le mouvement du tronc et la magnitude de l'augmentation dépendait du degré et du type d'élagage. Un degré accrû d'élagage diminuait le mouvement du tronc et la magnitude de la réduction était plus grande avec de plus grandes vitesses de vent. Le mouvement prédictible du tronc d'arbres éclaircis était statistiquement plus grand que le mouvement d'arbres structuralement élagués, d'arbres rehaussés et d'arbres élagués en queues de lion à des vitesses de vent de 20,1 m/s, et il était le plus élevé par rapport à tous les types d'élagage à 26,8 m/s. Il n'y avait pas de différence de mouvement entre les arbres aux cimes réduites, rehaussées, structuralement élaguées ou élaguées en queues de lion, et il n'y avait pas de différence statistique dans le mouvement du tronc parmi les divers types d'élagage à des vitesses de vents plus faibles. Nous avons découvert que l'éclaircissage du pourtour extérieur de la couronne était parmi les types d'élagage celui qui avait le moins d'efficacité pour diminuer le mouvement du tronc face au vent.

Zusammenfassung. Wir haben eine Propeller-Maschine gebaut, die einen Windstrom von 33,5 m/s erzeugen kann, um den Einfluss von Rückschnittmenge und –typ auf die Stammbewegung von *Quercus virginiana* 'QVTIA' PP #11219, Highrise® bei verschiedenen Windgeschwindigkeiten zu bestimmen. Die Stammbewegung wurde gegen Windgeschwindigkeit und Rückschnittmenge für jeden einzelnen Baum gemessen. Zunehmende Windgeschwindigkeit erhöhte die Stammbewegung und die Magnitude war von der Schnittmenge und dem Schnitttyp abhängig. Verstärkter Rückschnitt verringerte die Stammbewegung und war größer bei hohen Windgeschwindigkeiten. Die vorherbestimmte Stammbewegung der ausgedünnten Bäume war statistisch größer als die Bewegung der strukturell beschnittenen, gezogenen „Löwenschwanz"-Bäume bei Windgeschwindigkeiten von 20,1 m/s, und war auch größer als bei allen Rückschnitttypen bei 26,8 m/s. Es gab keine Differenzen in der Bewegung bei den reduzierten, aufgezogenen, strukturell beschnittenen und „Löwenschwanz"-Bäumen und es gab keine statistischen Unterschiede in der Stammbewegung bei geringeren Windgeschwindigkeiten. Wir fanden heraus, dass das Ausdünnen der äußeren Krone eine der am wenigsten effektiven Schnittmethoden für die Reduktion von Stammbewegung im Wind ist.

Resumen. Se construyó una máquina con una propela capaz de generar vientos de 33.5 m/s para determinar la influencia de la intensidad y el tipo de poda, ANSI A300, sobre el movimiento del tronco de *Quercus virginiana*, 'QVTIA' PP #11219, Highrise®, a varias velocidades del viento. El movimiento del tronco fue analizado estadísticamente contra las velocidades del viento y las podas para cada árbol tratado. El incremento de la velocidad del viento aumentó el movimiento del tronco y la magnitud del incremento dependió de la intensidad y tipo de poda. El incremento de la intensidad de poda redujo el movimiento del tronco y la magnitud de la reducción fue mayor que las velocidades del viento más altas. El movimiento del tronco de los árboles aclarados fue estadísticamente mayor que el movimiento de los estructuralmente podados, elevados y árboles con cola de león, a velocidades del viento de 20.1 m/s (45mph) y fue mayor que todos los tipos de poda a 26.8 m/s (60mph). No hubo diferencia en el movimiento entre copas de árboles reducidas, elevadas, estructuralmente podadas y con cola de león y no hubo diferencias estadísticas en el movimiento del tronco entre los tipos de poda a velocidades del viento más bajas. Se encontró que el aclareo del límite exterior de la copa fue uno de los tipos de poda menos efectivos para la reducir el movimiento del tronco por el viento.