Wind and Trunk Stress on Shade Trees

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NATURE OF WORK:

Trunk failure will occur when stress exceeds the strength, or modulus of rupture (MOR), of the wood. The ratio of MOR to stress at a given wind speed is the factor of safety, that is, the 'over-design' of the tree trunk to withstand extreme drag-induced bending moments.

Our Questions:

1) Which morphometric measurements best predict ***Drag*** and ***Drag-induced Bending Moment***?
2) What is the critical wind speed that causes trunk failure?

Measurements:

Modulus of Rupture (MOR) from wood samples
Drag (D) tested on live, landscape-sized trees in full leaf
Wind Speed (m/s)

Calculations:

Drag-induced bending moment (M) at the base of the tree = product of drag and a lever arm that is equal to the height of the center of pressure of the crown (HC): ***M=D*HC***.

Bending stress (s) = a measure of the drag-induced bending moment divided by the second moment of area of the trunk cross-section, which quantifies the trunk's resistance to bending: ***$s=32M/(\pi ab^2)$***, where a and b are, respectively, the trunk cross-sectional dimensions normal and parallel to the wind direction.

Critical wind speed = predicted wind speed where bending stress = MOR (i.e. when trunk would break)

Species Tested:

Freeman maple (*Acer x freemanii*), swamp white oak (*Quercus bicolor*), and shingle oak (*Quercus imbricaria*)

METHODS:

We cut trees just above the root flare and fastened the entire tree above the cut in a steel sled mounted in the rear of a pickup truck (see pictures below). The truck was then driven on a straight, nearly level course from 0 to 24.5 m/s (0 to 55 mph). We measured wind speeds with two three-cup anemometers, one attached to either side of the cab of the pickup truck. We measured loads with a 9800 N capacity Dillon dynamometer, with an accuracy of 9.8 N. The dynamometer was attached to an anchor point on the sled by a steel cable and to the tree by a polyester webbing sling. We used moment equilibrium to convert measured loads into actual drag (for details of this procedure, see Kane and Smiley (2006)). To match wind speeds with load measurements, wind speeds at subsequent one-second intervals were averaged to create values for each half-second interval. For wind speeds between 13.4 and 24.5 m/s, we plotted mean ***drag*** and ***bending moment*** versus wind speed from two test runs and fit a straight line to the data including both runs. From the fitted line, we predicted drag and bending moment at 5 wind speeds (13.4, 15.6, 17.9, 20.1, 22.4 m/s) for each tree. For each species we then plotted trunk bending stress against the five wind speeds and set the equation for the best-fit line equal to mean ***modulus of rupture*** of wood samples to predict the critical wind speed at which the trunk would break.

LITERATURE CITED:

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Table 1. Results of the analysis of variance (ANOVA) for the effects of species (Freeman maple (Af), shingle oak (Qi), and swamp white oak (Qb)) and wind speed on drag, bending moment (M), stress (s), factor of safety (SF), and drag coefficient (C_D). Means are only presented for 22.4 m/s since the species x wind speed interaction was not significant for any variable.

		ANOVA				Mean Separation^	
Variable	Source	df	MS	F	P>F	Species (n)	Mean⊗ (SD)
Drag (N)	Species	2	453 879	24.78	<.0001	Af (16)	524 (151) a
	Wind speed	4	567 052	30.96	<.0001	Qb (13)	563 (143) a
	Species x wind speed	8	7125	0.39	0.9258	Qi (18)	712 (184) b
	Error	220	18 318				
	Total	234					
M (N*m)	Species	2	761 378	5.37	0.0053	Af (16)	1 525 (433) ab
	Wind speed	4	3 541 511	24.97	<.0001	Qb (13)	1 355 (347) a
	Species x wind speed	8	14 444	0.10	0.9991	Qi (18)	1 634 (529) b
	Error	220	141 808				
	Total	234					
Drag/Area (N/m^2)	Species	2	5 807	13.80	<.0001	Af (16)	141 (35.6) a
	Wind speed	4	26 562	63.11	<.0001	Qb (13)	117 (17.6) b
	Species x wind speed	8	89.2	0.21	0.9886	Qi (18)	131 (16.6) c
	Error	220	421				
	Total	234					
Drag/Mass (N/kg)	Species	2	161	24.38	<.0001	Af (16)	25.7 (2.27) a
	Wind speed	4	1 140	173.12	<.0001	Qb (13)	25.6 (3.48) a
	Species x wind speed	8	5.11	0.78	0.6245	Qi (18)	29.3 (3.32) b
	Error	220	6.59				
	Total	234					
M/Area (N/m^2)	Species	2	233 575	60.33	<.0001	Af (16)	412 (109) a
	Wind speed	4	171 706	44.35	<.0001	Qb (13)	281 (44.7) b
	Species x wind speed	8	2 678	0.69	0.6986	Qi (18)	297 (54.5) b
	Error	220	3 871				
	Total	234					
M/Mass (N*m/kg)	Species	2	1 935	47.17	<.0001	Af (16)	75.0 (7.72) a
	Wind speed	4	7 235	176.34	<.0001	Qb (13)	61.8 (8.74) b
	Species x wind speed	8	26.0	0.63	0.7483	Qi (18)	66.1 (5.40) c
	Error	220	41.0				
	Total	234					
C_D	Species	2	0.154	12.3	<.0001	Af (16)	0.46 (0.12) a
	Wind speed	4	0.301	24.16	<.0001	Qb (13)	0.38 (0.06) b
	Species x wind speed	8	0.001	0.08	0.9997	Qi (18)	0.43 (0.05) c
	Error	220	0.012				
	Total	234					
σ_{BASE}& (kPa)	Species	2	1301 620 713	94.05	<.0001	Af (16)	30 021 (3 682) a
	Wind speed	4	908 497 035	65.64	<.0001	Qb (13)	19 335 (3 834) b
	Species x wind speed	8	15 517 574	1.12	0.3499	Qi (18)	22 668 (5 447) c
	Error	220	13 839 932				
	Total	234					
σ_{CABLE}& (kPa)	Species	2	5 236 674 446	25.23	<.0001	Af (16)	43 155 (23 941) a'
	Wind speed	4	1 547 691 710	7.46	<.0001	Qb (13)	21 330 (4 314) b'
	Species x wind speed	8	64 920 398	0.31	0.9607	Qi (18)	29 099 (19 242) b'
	Error	220	207 536 235				
	Total	234					
SF_{BASE}&	Species	2	82.0	95.5	<.0001	Af (16)	1.72 (0.33) a
	Wind speed	4	41.1	47.93	<.0001	Qb (13)	3.18 (0.57) b
	Species x wind speed	8	1.27	1.48	0.1647	Qi (18)	2.76 (0.61) c
	Error	220	0.86				
	Total	234					
SF_{CABLE}&	Species	2	86.1	67.18	<.0001	Af (16)	1.43 (0.57) a
	Wind speed	4	32.2	25.17	<.0001	Qb (13)	2.92 (0.81) b
	Species x wind speed	8	1.33	1.04	0.4085	Qi (18)	2.44 (0.73) c
	Error	220	1.28				
	Total	234					

⊗Drag coefficients were calculated using measured still air crown frontal areas.
^Means followed by the same letter within a wind speed are not different at p=0.05 (Tukey's HSD).
&"CABLE" indicates that the variable was calculated based on measurements taken at the height at which the dynamometer cable attached to the tree (0.76 m); "BASE" indicates that the variable was calculated based on measurements taken where the tree was attached to the steel sled.
'indicates that $\sigma_{CABLE} > \sigma_{BASE}$

RESULTS AND DISCUSSION:

Drag, drag coefficient, bending moment, stress, and factor of safety differed among species in accordance with physical parameters (Table 1). More massive trees experienced greater drag and bending moment, but stress was greater for trees with smaller diameter trunks. Drag and bending moment increased linearly with wind speed (data not shown). **Overall, *Tree mass and trunk diameter reliably predicted drag and bending moments; crown dimensions, including crown area, were less reliable predictors (Table 2).*** Crown reconfiguration (from wind) varied only slightly among species, and drag coefficients were similar to previously reported values from trees of similar size.

Since trunk stress for all species was greater at the height of the cable than at the base of the tree, critical wind speed for trunk breaking was based on failure at the height of the cable. Factors of safety based on MOR of wood samples may be misleading because trunk strength can be less than MOR of wood samples. Peltola et al. (1999) and Fons and Pong (1957) found that stem strength was, respectively, 85% and 70% of MOR values from the literature. ***For factors of safety based on MOR, 85% MOR, and 70% MOR, respectively, we estimated that critical wind speeds for Freeman maple were 28, 25, and 21m/s (63, 56,and 47 mph); for swamp white oak, 60, 51, and 43 m/s (134, 114,and 96 mph); for shingle oak, 49, 42, and 35 m/s (110, 94,and 78 mph).*** Wind speeds based on MOR for Freeman maple and 70% MOR for swamp white oak and shingle oak are similar to the wind speed at which Mayhead (1973) reported damage to conifers during wind tunnel testing. It is not entirely appropriate to extrapolate to wind speeds beyond those tested because reduction in frontal area will no longer be effective beyond some critical wind speed and the relationship between drag and wind speed may change. Peltola et al. (1999) predicted that trunks of birch (*Betula* spp.) would break at wind speeds between 13.1 and 29.1 m/s; taller and more slender trees were more susceptible to failure. The difference between their predictions and ours may be attributed to 1) their use of average MOR values from the literature, 2) their predictions were made for larger trees, and 3) Freeman maple, swamp white oak, and shingle oak trunks were noticeably less slender.

Our study illustrates dramatic differences between species in resistance to trunk breakage during storm wind. Our empirical data will also be useful for development of mathematical models that reliably assess risk of tree damage from catastrophic storms.

Table 2. Intercepts (B), slopes (β), coefficients of determination (R^2), and root mean square error (RMSE) for regressions of drag (top half of table) and bending moment (M**)** (bottom half of table) calculated at 22.4 m/s versus measures of tree size for Freeman maple (Af, n=16), swamp white oak (Qb, n=13), and shingle oak (Qi, n=18). Standard errors (SE) follow slopes and intercepts. Single underlined RMSE / R^2 values indicate the best correlation; double underlined values indicate the second best correlation. Means for correlation coefficients across all species are presented in the far right column; means for each species are presented in the bottom row of each half of the table.

		Af	Qb	Qi	Af	Qb	Qi	Af	Qb	Qi	
	Measure	B^ (SE)	B^ (SE)	B^ (SE)	**β**^ (SE)	**β**^ (SE)	**β**^ (SE)	RMSE / R^2	RMSE / R^2	RMSE / R^2	Mean RMSE / R^2
Drag	Mass (kg)	-68.0 (51.2) a	1.02 (122) b	177 (38.0)* b	29.2 (2.46)* a	25.7 (5.46)* b	21.5 (1.46)* b	47 / 0.91	86 / 0.67	49 / 0.93	61 / 0.84
	Crown Height (m)	-834 (463) a	582 (459) b	-266 (249) ab	369 (125)* a	-5.56 (133) b	273 (68.8)* a	123 / 0.38	149 / 0.00	134 / 0.50	135 / 0.29
	Crown Width (m)	-237 (257) a	-253 (150) a	-187 (253) a	338 (113)* a	261 (47.7)* a	230 (64.3)* a	123 / 0.39	77 / 0.73	141 / 0.44	114 / 0.52
	Tree Height (m)	-932 (772) a	-362 (1016) a	-618 (314) a	301 (159)& a	208 (228) a	287 (67.5)* a	140 / 0.20	144 / 0.07	130 / 0.53	138 / 0.27
	Trunk Dia (m)	-580 (177)* a	-295 (251) a	-570 (240)* a	13 585 (2 163)* a	9 536 (2 775)* a	14 416 (2 679)* a	80 / 0.74	104 / 0.52	113 / 0.64	99 / 0.63
	Area (m^2)	102 (158) a	-165 (149) a	-130 (123) a	113 (41.4)* a	152 (30.7)* a	156 (22.4)* a	127 / 0.35	83 / 0.69	94 / 0.75	102 / 0.60
	Mean							89 / 0.46	89 / 0.40	100 / 0.59	93 / 0.48
M	Mass (kg)	-117 (186) a	-4.49 (296) a	82.6 (98.3) a	81.1 (8.92)* a	62.2 (13.3)* a	62.4 (3.76)* a	171 / 0.86	209 / 0.67	128 / 0.95	169 / 0.83
	Crown Height (m)	-2 824 (1217)* a	1 331 (1113) a	-1 417 (651)* a	1182 (330)* a	6.93 (321) b	852 (180)* a	324 / 0.48	362 / 0.00	352 / 0.58	346 / 0.35
	Crown Width (m)	-310 (801) a	-531 (406) a	-1 014 (715) a	815 (353)* a	604 (129)* a	678 (182)* a	382 / 0.28	209 / 0.67	398 / 0.47	330 / 0.47
	Tree Height (m)	-3 970 (1992) a&	-1 570 (2396) a&	-2 510 (811)* a	1 136 (411)* a	658 (539) a	895 (174)* a	361 / 0.35	340 / 0.12	335 / 0.62	345 / 0.36
	Trunk Dia (m)	-1 791 (428)* a	-762 (597) a	-1 947 (724)* a	40 816 (5 237)* a	23 521 (6 589)* a	40 289 (8 099)* a	194 / 0.81	247 / 0.54	341 / 0.61	261 / 0.65
	Area (m^2)	485 (482) a&	-333 (393) b	-769 (364) a&b	278 (126)* a	352 (81.0)* a	444 (66.1)* a	387 / 0.26	220 / 0.63	279 / 0.74	295 / 0.54
	Mean							146 / 0.73	153 / 0.55	133 / 0.88	144 / 0.72

^Read across each row, slopes and intercepts for each species followed by the same letter are not different at p=0.05 (Tukey's HSD).
*indicates that the slope or intercept is not equal to 0 (p<0.05).
&p≤0.08

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