Wind tunnel measurements of crown streamlining and drag relationships for three conifer species

Mark Rudnicki, Stephen J. Mitchell, and Michael D. Novak

Abstract: Estimating the wind force or drag acting on tree crowns is central to understanding both the chronic effects of wind and the calculation of critical wind speed in windthrow prediction models. The classical drag equation is problematic for porous, flexible tree crowns whose frontal area declines as wind speeds increase and branches streamline. Juvenile crowns of three morphologically different conifers, western redcedar (*Thuja plicata* Donn ex D. Don), western hemlock (*Tsuga heterophylla* (Raf.) Sarg.), and lodgepole pine (*Pinus contorta* Dougl. ex Loud.), were exposed to wind speeds from 4 to 20 m/s in a wind tunnel. At 20 m/s, streamlining reduced the frontal area by 54% for redcedar, 39% for hemlock, and 36% for lodgepole pine. Crown drag coefficients calculated using frontal area in still air varied with wind speed. At 20 m/s, they were 0.22, 0.47, and 0.47 for these species, respectively. Drag was proportional to the product of mass and wind speed and also to the product of wind speed squared and wind speed specific frontal area. Lodgepole pine and redcedar had lower drag per unit of branch mass than did hemlock. Removing branches by pruning had little effect on drag per unit branch mass.

Résumé : L'estimation de la force du vent ou de la traînée agissant sur la cime des arbres est essentielle à la compréhension des effets chroniques du vent et au calcul de la vitesse critique des vents dans les modèles de prédiction du chablis. L'équation classique de la traînée est problématique pour les cimes poreuses et flexibles des arbres dont la surface frontale diminue lorsque la vitesse du vent augmente et que les branches se profilent. Des cimes juvéniles de trois conifères morphologiquement différents, soit le thuya géant (*Thuja plicata* Donn ex D. Don), la pruche de l'Ouest (*Tsuga heterophylla* (Raf.) Sarg.) et le pin de Murray (*Pinus contorta* Dougl. ex Loud.), ont été exposées en soufflerie à des vents de 4 à 20 m/s. À 20 m/s, le profilage a réduit la surface frontale de 54 % pour le thuya géant, de 39 % pour la pruche de l'Ouest et de 36 % pour le pin de Murray. Les coefficients de traînée calculés à partir de la surface frontale en air calme varient selon la vitesse du vent. À 20 m/s, ils étaient respectivement de 0,22, 0,47 et 0,47 pour ces espèces. La traînée était proportionnelle au produit de la masse et de la vitesse du vent, ainsi qu'au produit du carré de la vitesse du vent et de la surface frontale ajustée selon la vitesse du vent. Le pin de Murray et le thuya géant présentaient des traînées par unité de masse des branches inférieures à celle de la pruche. L'enlèvement des branches par élagage a eu peu d'effet sur la traînée par unité de masse des branches.

[Traduit par la Rédaction]

Introduction

Trees experience wind throughout their lives. Chronic wind loading affects tree growth, while extreme wind loading can cause branch loss, stem breakage, or uprooting (e.g., Robertson 1987; Telewski 1995). Windthrow risk can be modeled using equations that predict the wind speed necessary to overturn a tree (critical wind speed) and the probability of a wind of this speed acting on the tree in a given location. This approach is used in mechanistic windthrow risk models such as ForestGales and HWIND (Gardiner et al. 2000). Estimating the wind force or "drag" acting on the tree crown is central to understanding both the chronic effects of wind on trees and the calculation of critical wind speed.

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The classical formula for wind drag D (measured in newtons, N) in the direction of wind flow on an object placed in a steady airstream is

$$D = 1/2\, C_d \rho A U^2 \quad [1]$$

where C_d is the drag coefficient (dimensionless), ρ is the air density (kg/m^3), A is the frontal area (m^2), and U is the wind speed (m/s) (Mayhead 1973; Smith et al. 1987; Peltola and Kellomäki 1993; Hedden et al. 1995). Total drag is the sum of pressure and skin-friction components (Niklas 1992). The drag coefficient models the complex dependencies of drag on shape and flow conditions. Unlike bluff bodies, tree crowns are both porous and flexible. This presents unique problems when computing the drag coefficient. As wind force increases, branches and foliage move into alignment with the wind direction, reducing the crown frontal area (streamlining) and therefore the pressure component of drag. Thus, streamlining depends on the mechanical and aerodynamic properties of stems, branches, and foliage (Niklas 1992). A number of authors have used eq. 1 for calculating critical wind speeds assuming a fixed frontal area (e.g., Mayhead 1973; Smith et al. 1987; Peltola and Kellomäki

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1993; Hedden et al. 1995). Others have attempted to account for the reduction of frontal area by estimating branch deflection under load (e.g., Wood 1995; Spatz and Bruechert 2000). Hedden et al. (1995) provide an estimate of crown streamlining derived from measured deflection of individual branches under applied load. There have been very few empirical studies where crown drag and crown streamlining have been measured simultaneously, and direct measurements of reduction in crown frontal area are not reported in the literature.

Mayhead (1973) reported results of wind tunnel tests on a small sample of conifers used in British forestry. Drag coefficients were determined for wind speeds from 9 to 26 m/s, assuming a constant projected frontal area determined from photographs of crowns in still air. Mayhead plotted drag coefficient versus wind speed for each tree and fitted regressions of the generalized form

$$[2] \qquad C_d = C + aU + bU^2$$

where C, a, and b are constants. He noted that the curves differed between and within species and no general equation could be fit. The drag coefficients reported by Mayhead for his maximum wind speed have been used by a number of authors in windthrow risk studies (e.g., Peltola et al. 1997; Moore and Gardiner 2001), with the assumption that 26 m/s is close to the critical wind speed for tree failure and that the rate of reduction in drag coefficient with increasing wind speed is low for wind speeds above 26 m/s.

Mayhead et al. (1975) reexamined drag equations for Sitka spruce (*Picea sitchensis* (Bong.) Carrière) and lodgepole pine (*Pinus contorta* Dougl. ex Loud.) and reported nonlinear equations relating drag to wind speed and branch mass (M_b). Since frontal area represents two of the three dimensions in volume, and mass is related to volume via crown density, mass to the 2/3 power is substituted for frontal area. For lodgepole pine and Scots pine (*Pinus sylvestris* L.), they provide the following equation:

$$[3] \qquad D = U^2 M_b^{2/3}[0.0256\exp(-0.004124U^2) + 0.01643]$$

Using this approach avoids the problem of estimating still air or wind-speed-specific crown frontal area in wind tunnel experiments or field evaluations. Furthermore, the drag–mass relationship has ecological implications. In a high wind environment, a low drag per unit mass of foliage would be advantageous and may be a factor in differential survival during disturbance events. Despite the utility of drag in windthrow prediction and the ecological implications of drag–mass relationships, there has been no follow-up to the work of Mayhead et al. (1975).

The objectives of this study were to quantify crown frontal area reduction for three conifer species with different foliage morphologies, to compare drag coefficients between species using both still air (static C_d) and speed specific (dynamic C_d) estimates of crown frontal area, and to investigate the relationship among drag, branch mass, and wind speed for these species. All measurements were carried out in a wind tunnel.

Table 1. Mean sample tree dimensions and weights for western redcedar (C), western hemlock (H), and lodgepole pine (P).

					Full crown		Post prune 1		Post prune 2			
Species	n	Bole diameter (cm)	Frontal area (triangle)	Video frontal area/triangle frontal area	Mass (kg)	Frontal area (m^2)	Mass (kg)	Frontal area (m^2)	Mass (kg)	Frontal area (m^2)	Bole only mass (kg)	Full crown area/mass (m^2/kg)
C	9	4.12 (0.33)	1.24 (0.13)	0.85	3.04 (0.42)	1.05 (0.25)	2.46 (0.34)	0.83 (0.21)	1.94 (0.27)	0.50 (0.14)	1.36 (0.19)	0.35
H	9	4.85 (0.74)	0.90 (0.16)	0.87	4.55 (1.09)	0.90 (0.20)	3.66 (0.86)	0.76 (0.20)	2.81 (0,63)	0.52 (0.16)	1.95 (0.41)	0.20
P	10*	4.16 (0.32)	0.96 (0.14)	0.97	4.53 (0.76)	0.93 (019)	3.55 (0.61)	0.81 (0.17)	2.58 (0.46)	0.54 (0.12)	1.62 (0.20)	0.21

Note: Standard deviations are in parentheses.
*Only nine lodgepole pine trees were used for analysis.

Table 2. Analysis of variance results for effects of species and pruning for wind speed of 20 m/s.

						Treatment differences					
						Species*			Prune		
Variable	Source	df	MS	F	$P > F$	C	H	P	0	1/3	2/3
Crown frontal area / still air crown frontal area	Species	2	0.2435	68.5	<0.0001	a	b	c			
	Prune	2	0.5493	154.4	<0.0001				c	b	a
	Species×Prune	4	0.0033	0.9	0.4436						
	Error	72	0.0036								
	Total	80									
Drag / unit of branch mass	Species	2	325.4	12.6	<0.0001	a	b	a			
	Prune	2	6.1	0.2	0.7921				a	a	a
	Species×Prune	4	43.9	1.7	0.1611						
	Error	72	25.9								
	Total	80									
Drag / unit of crown frontal area	Species	2	28 342.0	88.7	<0.0001	a	c	b			
	Prune	2	11 906.3	37.3	<0.0001				c	b	a
	Species×Prune	4	451.9	1.4	0.2379						
	Error	72	319.6								
	Total	80									

Note: Means for levels of species or prune with different letters are significantly different ($p < 0.05$). df, degrees of freedom; MS, mean square.
*C, western redcedar; H, western hemlock; P, lodgepole pine.

Materials and methods

Sampling was restricted to symmetrical, open-grown, 2.5–5 m tall saplings of lodgepole pine (*P. contorta*), western hemlock (*Tsuga heterophylla* (Raf.) Sarg.), and western redcedar (*Thuja plicata* Donn ex D. Don). Ten lodgepole pine trees grown from seed from a British Columbia central interior (continental climate) seed source were obtained from The University of British Columbia South Campus field site. Nine hemlock and nine redcedar trees from coastal provenance seed were obtained from the Malcolm Knapp Research Forest, 50 km east of The University of British Columbia. The stem bases were wrapped in plastic with saturated sponges immediately after cutting. Tree crowns were wrapped in burlap and kept cool and moist to minimize transpiration losses during transport and storage. Wind tunnel measurements on the pine samples were completed within several hours of sample collection, while those for hemlock and redcedar were completed within 2 and 4 days, respectively.

The University of British Columbia Department of Mechanical Engineering wind tunnel has a test section that is 1.65 m high, 2.44 m wide, 18.3 m in length, and generates a laminar flow of up to 20 m/s. The wind speed is near uniform throughout the cross section except for a thin zone near the walls (<5 cm thick). Dynamic air pressure ΔP (Pa) was monitored with differential pressure transducers at several points around the opening of the tunnel test section. The measured ΔP is converted to wind speed U using Bernoulli's law.

$$[4] \qquad U = \sqrt{2\Delta P/\rho}$$

Air density was calculated three times per day using readings from a barometer and thermometer mounted adjacent to the wind tunnel and the ideal gas law

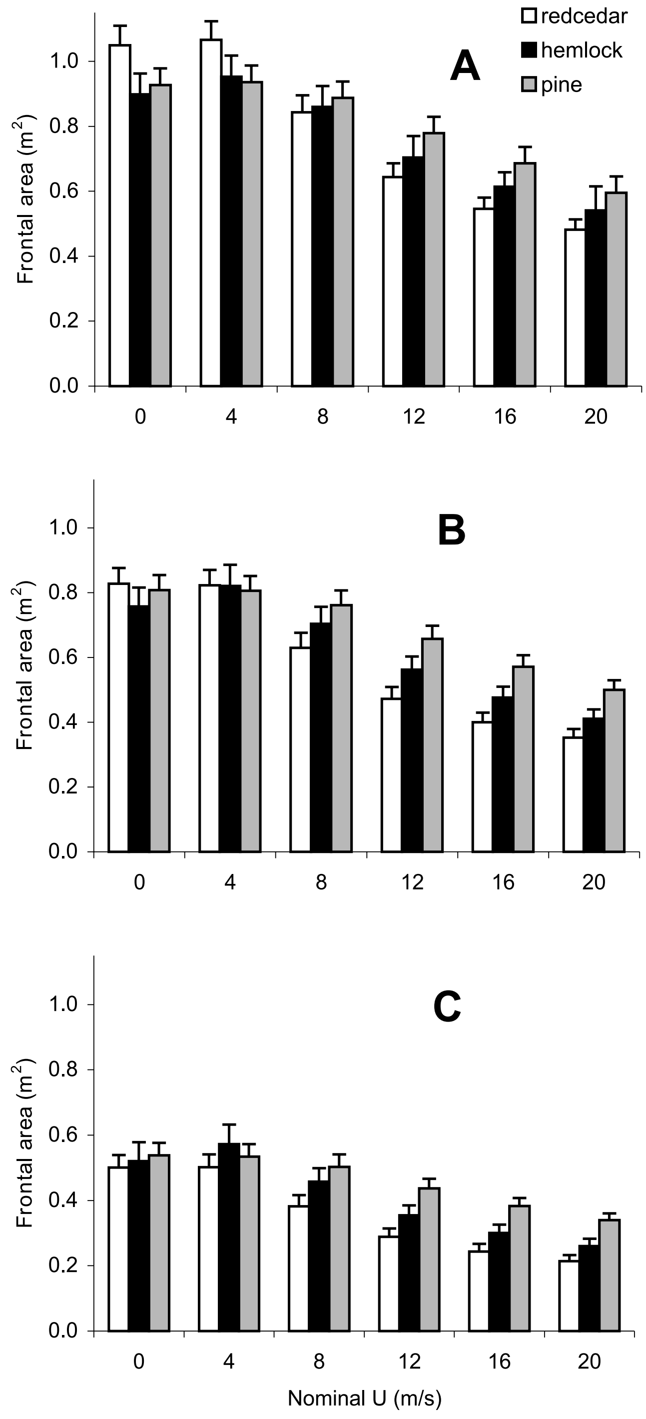
$$[5] \qquad \rho = P/R_d T$$

where P is the barometric pressure, R_d is the gas constant for dry air, and T is the absolute air temperature.

Crowns were cut to a height of 1.9 m through removal of the current year's leader and lower branches were trimmed so that foliage was at least 5 cm from the ceiling and floor of the tunnel. Samples were weighed using an S-type load cell (model AST-100, Precision Transducers, Auckland) before mounting. Trees were mounted using a bucket made of plate steel that held the base of the stem with eight 1 cm diameter bolts. The bucket was bolted to a near frictionless air table located just under the floor of the tunnel. The air table transferred drag force to a load cell (model PT-1000-30kg, Precision Transducers). All instruments were monitored with a central data acquisition computer via an analogue-to-digital interface card (Daqboard model DBK16, IOtech, Inc., Ohio, U.S.A.). Wind pressure and drag data were collected at 100 Hz. After tree installation, the crown width and length perpendicular to the direction of wind flow was measured for calculation of the geometric frontal area in still air. Assuming a triangular frontal shape, crown length equalled the triangle height, while crown width at the base equalled the triangle base. Trees were subjected to progressive wind speeds of 4, 8, 12, 16, and 20 m/s, with 30 s of exposure at each speed. Wind speeds and crown frontal areas stabilized after 15 s, with averaged measures of drag and wind pressure taken from the final 10 s of each wind speed level.

A video camera mounted in the wind tunnel 15 m downstream of the tree recorded each run. The crowns were brightly lit against a black tunnel background to increase image contrast. Image scale was established in still air at the beginning of each run using a black and white chequered board held to the side of each tree bole. Similarly, a 2-m scale bar was held across the length and width of the tree to enable detection of any vertical or horizontal image distor-

Fig. 1. Frontal area (m^2) of western redcedar, western hemlock, and lodgepole pine crowns digitized from video image at nominal wind speeds (U) from 0 to 20 m/s for (A) unpruned, (B) 1/3 pruned, and (C) 2/3 pruned crowns. Error bars are ±1 SE.



tion. The fan was then started. Still images were captured from the video during the still air scaling at 0 m/s and during the final 10 s of each wind speed level. Images were cropped to remove any nonblack background and then pixilated (2.08×10^{-5} m^2/pixel). Crown pixel counts were obtained using the Geomatica (PCI Geomatics, Richmond Hill, Ont., Canada) unsupervised classification function (three classes). The crown frontal area was determined by multiplying the crown pixel count by the pixel size.

To further investigate the relationship between drag and crown mass, we reduced the initial branch mass by approximately one third by pruning entire branches (while attempting to preserve crown symmetry). Pruned trees were subjected to the same set of wind speeds, and drag was recorded using the same methodology described above. A second pruning treatment left one third of the initial branch mass. Pruned branches were weighed after each pruning using the S-type load cell.

To evaluate the effects of repeated loading on pruned samples, we conducted a preliminary investigation that demonstrated that drag at a given wind speed was consistent for repeated cycles of wind loading, indicating that tree crowns recovered their initial shape and retained their aerodynamic properties following cessation of wind loading. Therefore, we assumed that repeated wind loading did not contribute to the differences in drag between successive prunings. We also checked total mass of pruned branches and final bole against mass of the unpruned tree to check for loss of moisture or needles during successive runs. Total mass loss was less than 1% for nearly all trees.

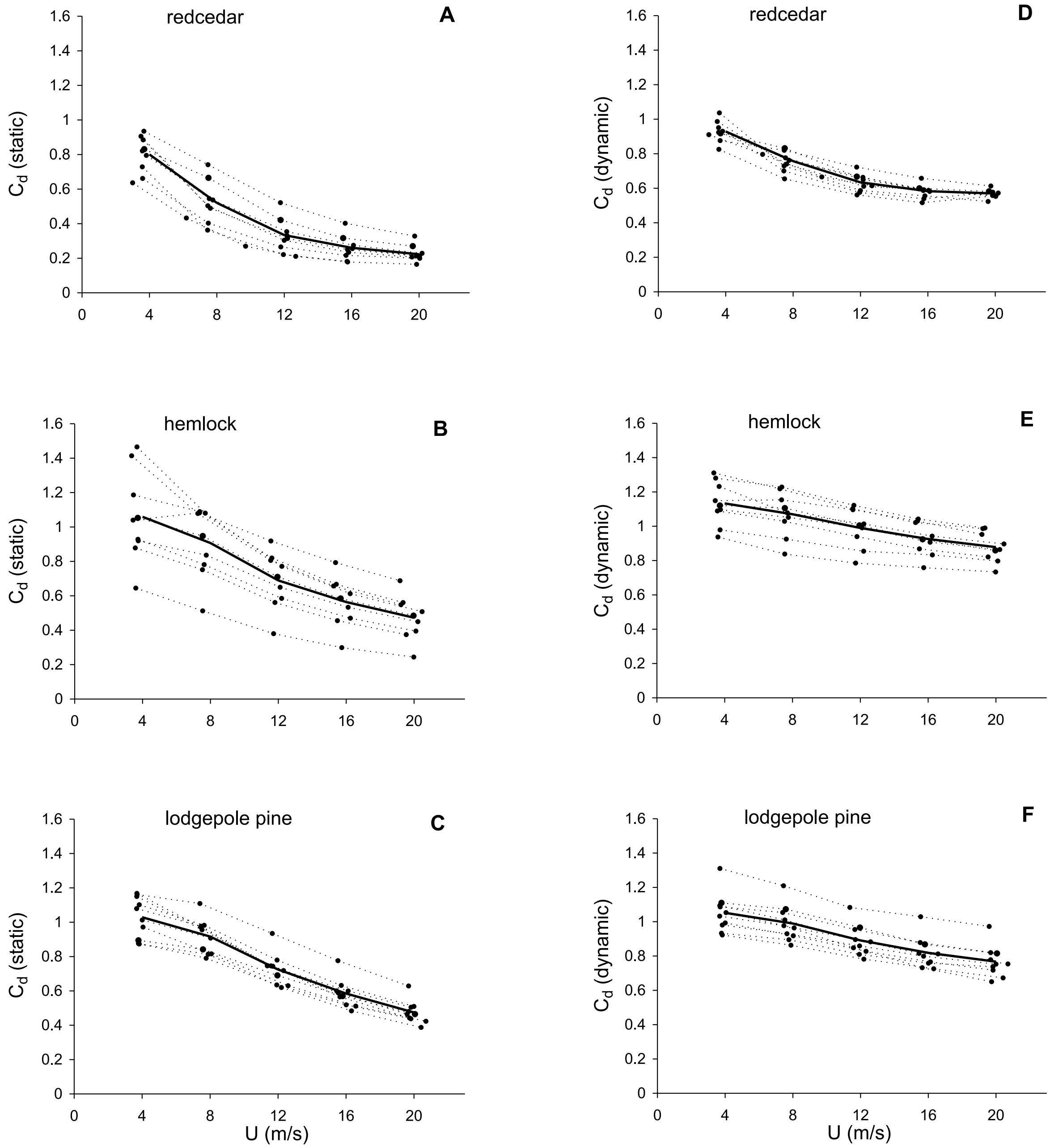
Drag coefficients were calculated for unpruned crowns using eq. 1 with both still air and wind-speed-specific frontal areas. Linear regressions (SAS Institute Inc. 1989) were fitted with and without intercepts to investigate the relationship between drag and the product of mass and wind speed and between drag and the product of frontal area and wind speed. The resulting models were compared with each other and with nonlinear models in the form of eq. 3 using root mean square error (RMSE) as a measure of fit. Model parameters were compared between species and between pruning treatments. Pretest species differences in crown properties were tested using analysis of variance. The effects of species and pruning on reduction in initial crown frontal area, drag per unit frontal area, and drag per unit branch mass at 20 m/s were tested using analysis of variance and Tukey's test for testing differences between means.

Results

Still air crown frontal areas obtained from video image classification were smaller than geometric frontal areas calculated assuming a triangular frontal shape for redcedar and western hemlock, but were similar for lodgepole pine (Table 1). In all calculations of drag coefficient and further examinations of frontal area, we used crown frontal area obtained from the video image. For unpruned crowns, the still air frontal area was similar for each species ($p = 0.18$). Crown mass was similar for hemlock and pine, while redcedar crowns were lighter ($p = 0.0008$). Branches (including foliage) contributed 64% of the crown mass in pine, while redcedar and hemlock had proportionally less branch mass (56% and 57%, respectively). On average, the first prune removed 35% of the branch mass and the second removed 66%, which is consistent with the intended removal levels (Table 1).

At 20 m/s, frontal area reduction differed between species for unpruned crowns (Table 2). Redcedar had significantly greater reduction in frontal area (54%) than western hem-

Fig. 2. Drag coefficients calculated using still air frontal area for wind speeds (U) from 4 to 20 m/s for (A) western redcedar, (B) western hemlock, and (C) lodgepole pine. Drag coefficients calculated using wind-speed-specific frontal area for (D) western redcedar, (E) western hemlock, and (F) lodgepole pine. Dashed lines are individual trees, while means are heavy solid lines.



lock (39%) and lodgepole pine (36%) (Fig. 1A). The result was similar for pruned crowns (Figs. 1B, 1C). The frontal area increased slightly between 0 and 4 m/s before rapidly decreasing. This effect was greatest in hemlock and became more pronounced for this species with pruning (Figs. 1A–1C). The drag coefficients calculated using still air frontal area (Figs. 2A–2C) declined more rapidly with increasing wind speed and were consistently lower at 20 m/s than those calculated using wind-speed-specific frontal area (Figs. 2D–2F). The redcedar drag coefficient exhibited the most curvilinear response and appeared to stabilize between 16 and 20 m/s (Figs. 2A, 2D).

Examining drag at each wind speed revealed a near linear increase in drag with crown mass for each species. Accordingly, several variations on the classical drag formula were explored with intercepts held at zero in accordance with expected physical relationships (Table 3; because of incomplete data, only nine lodgepole pine trees were used for analysis). All of our models had coefficients of determination in excess of 0.90 (Table 4). While the classical formula, with drag proportional to the product of wind speed squared and frontal area in still air (eq. 1), produced a low RMSE, this was further reduced by using wind-speed-specific frontal area. The product of wind speed and crown mass also

Table 3. Comparison of models for predicting crown drag for western redcedar (C), western hemlock (H), and lodgepole pine (P).

Independent variables	Species	RMSE
U^2A_s	C	10.8
	H	15.9
	P	14.2
U^2A_d	C	5.6
	H	7.4
	P	8.0
UA_d	C	10.8
	H	19.0
	P	16.6
$U^2M_b^{2/3}$	C	10.0
	H	12.9
	P	13.2
UM_b	C	5.8
	H	9.9
	P	10.1
UM_c	C	5.3
	H	10.7
	P	9.61
$U^2M_b^{2/3}[\exp(U^2) + b_0]$	P*	37.3
$U^2M_b^{2/3}[\exp(U^2)]$	C†	6.6
	H	6.3
	P	7.0

Note: Linear models have intercept set to 0. Drag is predicted in newtons. RMSE is the root mean square error. Independent variables are combined into a single term in each model and include wind speed (U), branch mass (M_b), crown mass (M_c), static frontal area (A_s), and dynamic frontal area (A_d).

*With Mayhead et al. (1975) parameters for pine, result converted to newtons.

†With new parameters.

produced a low RMSE and was slightly better than using branch mass for two of the three species. The formula provided by Mayhead et al. (1975) for lodgepole pine (eq. 3) did not predict our lodgepole pine data well, over-predicting drag by 50% at 20 m/s (Fig. 3). Refitting models of this form for each of the three species improved the RMSEs substantially; however, after inspection of the correlation matrix, the model was refit without the intercept to avoid over-fitting.

A region of nonlinearity was noted for very low wind speeds. Because these equations will be used for predicting wind loading at moderate to high wind speeds, the best model forms were refit with intercepts. As expected, there were differences between species in the drag relationships (Table 4). For the range of tree sizes and wind speeds measured, the product of wind speed and branch mass provided very good predictions (Fig. 3). At 20 m/s, unpruned hemlock had higher drag per unit branch mass than lodgepole pine and redcedar (Table 2; Fig. 4A). Redcedar had the lowest drag per unit of frontal area, hemlock had the highest, and lodgepole pine was intermediate (Table 2; Fig. 4B). At 20 m/s, pruning did not significantly effect drag per unit of branch mass. However, the trend in drag per unit branch mass with each level of pruning was opposite for redcedar and lodgepole pine (Fig. 5).

Discussion

This study is the first to investigate the effect of streamlining on crown frontal area and to incorporate speed-specific crown frontal area into predictions of drag. Streamlining reflects the flexibility of branches and stem, the ability of small branches and foliage to twist, and the ability of branches to move without interference from other branches. An interesting result was the small increase in frontal area at 4 m/s for all species. While detailed measurements were not taken, branch movement was observed through a window in the side of the wind tunnel. As wind speeds increased from 0 m/s, windward-facing branches bent upwards and flattened perpendicular to the wind flow (Fig. 6). Similarly, for branches initially perpendicular to wind direction, the windward edges lifted and rotated upwards. In each case, these branches presented a greater frontal area at 4 m/s than in still air. As wind speeds further increased, the branches bent further to leeward and foliage began to align with wind direction, producing the expected decrease in frontal area.

Examination of the images of frontal area revealed species differences in crown configuration under wind loading (Fig. 7). Lodgepole pine branches were flexible and crown profile was reduced in height and width, with crowns becoming more compact and less porous with increasing wind speed. The redcedar crown profile was also reduced somewhat in height and width but became much more porous as the individual foliage elements aligned with wind direction. Western hemlock was intermediate in behaviour, with a moderately reduced profile and slightly increased porosity.

For objects with Reynolds numbers between 10^3 and 10^5, drag coefficients are approximately 2, 1, and 0.4 for a flat strip perpendicular to flow, a cylinder, and a sphere, respectively (Campbell 1986). The dynamic drag coefficients in this study were within the expected range and declined from 0.9 to 0.6 for redcedar, 1.1–0.9 for hemlock, and 1–0.9 for pine. Since change in frontal area was accounted for, this decline presumably reflected the changes in alignment of branches and foliage and increased shelter of leeward drag elements. The larger decline for redcedar is logical given the flatness and flexibility of its foliage.

Wind speeds as low as 15 m/s are sufficient to cause windthrow (e.g., Oliver and Mayhead 1974); however, windthrow researchers generally report drag coefficients obtained for higher wind speeds. Mayhead (1973) obtained drag coefficient values of 0.20 and 0.14 for lodgepole pine (sample of one tree) and western hemlock (sample of two trees), respectively, at wind speeds of 30 m/s using still air frontal area. Mayhead et al. (1975) obtained values of 0.35 for lodgepole pine (n = 24) at wind speeds of 26 m/s, and they recommended using this value for calculating windthrow risk for lodgepole pine. At our maximum speed of 20 m/s, we obtained values of 0.22, 0.47, and 0.47 for redcedar, hemlock, and lodgepole pine, respectively, using still air frontal area. Our value for lodgepole pine is comparable with that obtained by Mayhead et al. (1975) over the same range of wind

Table 4. Models for predicting crown drag for western redcedar (C), western hemlock (H), and lodgepole pine (P).

Independent variable	Species	b_0	b_1	SE_{b0}	SE_{b1}	RMSE	r^2
A. Linear regressions.							
U^2A_d	C	6.01ab	0.31a	1.12	0.01	4.3	0.96
	H	3.08a	0.53c	1.88	0.01	7.2	0.97
	P	7.43b	0.42b	1.74	0.01	6.9	0.97
UM_b	C	–2.91a	1.96	1.78	0.08	5.7	0.93
	H	–8.43b	2.21	2.69	0.08	9.0	0.95
	P	–11.39b	2.06	2.76	0.07	8.6	0.94
UM_c	C	–3.93a	1.11a	1.61	0.04	5.0	0.95
	H	–10.74b	1.31b	2.90	0.05	9.4	0.95
	P	–13.65b	1.36b	2.41	0.04	7.3	0.96
B. Nonlinear regressions.							
		c_0	c_1	SE_{c0}	SE_{c1}	RMSE	I^2*
$U^2M_b^{2/3}[c_0 \exp(c_1U^2)]$	C	0.2417a	–0.001 95a	0.0167	0.000 23	6.6	0.91
	H	0.2854b	–0.001 65b	0.0113	0.000 13	6.3	0.98
	P	0.2611a	–0.001 69ab	0.0118	0.000 14	7.0	0.97

Note: Intercepts (b_0, c_0) and slopes (b_1, c_1) that are significantly different between species have different letters. Drag is predicted in newtons. RMSE is the root mean square error. Independent variables are combined into a single term in each model and include wind speed (U), branch mass (M_b), crown mass (M_c), and dynamic frontal area (A_d).

*Adjusted coefficient of determination.

Fig. 3. Comparison of actual drag for lodgepole pine with predictions using Mayhead et al.'s (1975) nonlinear drag equation with original parameters (MGD), Mayhead et al.'s formula with new parameters (MGD new), and the product of wind speed and branch mass (UM_b) for wind speeds from 4 to 20 m/s.

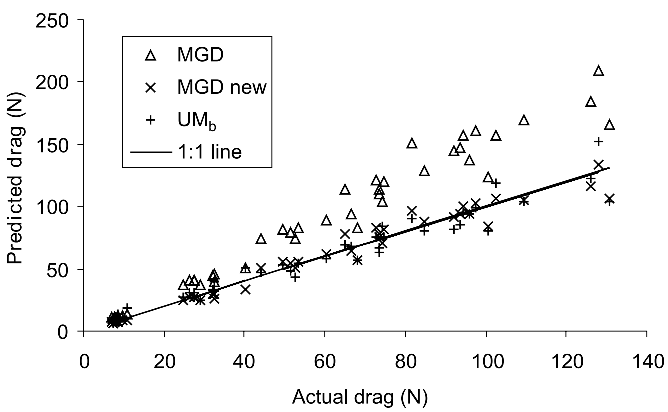
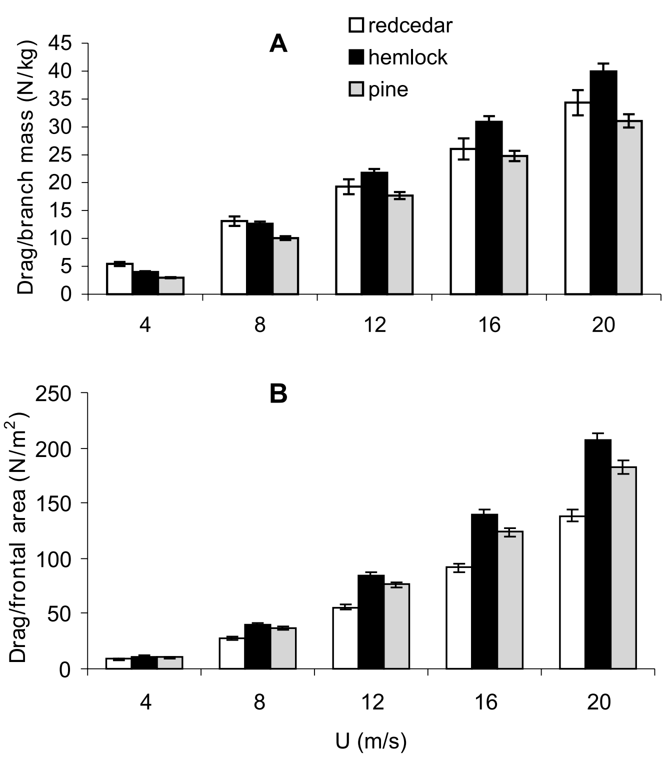


Fig. 4. (A) Drag per unit branch mass (N/kg) and (B) drag per unit frontal area (N/m^2) for western redcedar, western hemlock, and lodgepole pine for wind speeds (U) from 4 to 20 m/s. Error bars are ±1 SE.



speeds. While the hemlock drag coefficient was still declining at our maximum speed, we recommend a value of 0.40 be used. This is much higher than that suggested by Mayhead (1973). Given the shape of our curves for redcedar, a value of 0.22 would be appropriate.

Mayhead et al. (1975) found that drag is related to wind speed and crown mass and presented a nonlinear equation for drag prediction. The linearity of the relationship between drag and the product of branch mass and wind speed over the wind speeds tested in this study suggests an even simpler formula in which M_b/U is substituted for $(C_dA\rho)/2$ in eq. 1. The equivalency of these formulas reflects not only the decline in frontal area with increasing wind speed suggested by Nobel (1981), but also the decline in dynamic drag coefficient. For application in windthrow risk estimation, formulas using branch or crown mass eliminate the potential errors from using drag coefficients obtained for a fixed wind speed using still air frontal areas. Using these formulas also avoids the difficulty in estimating frontal area at different wind

Fig. 5. Drag per unit branch mass (N/kg) for unpruned, 1/3 pruned, and 2/3 pruned crowns for (A) western redcedar, (B) western hemlock, and (C) lodgepole pine for wind speeds (*U*) from 4 to 20 m/s. Error bars are ±1 SE.

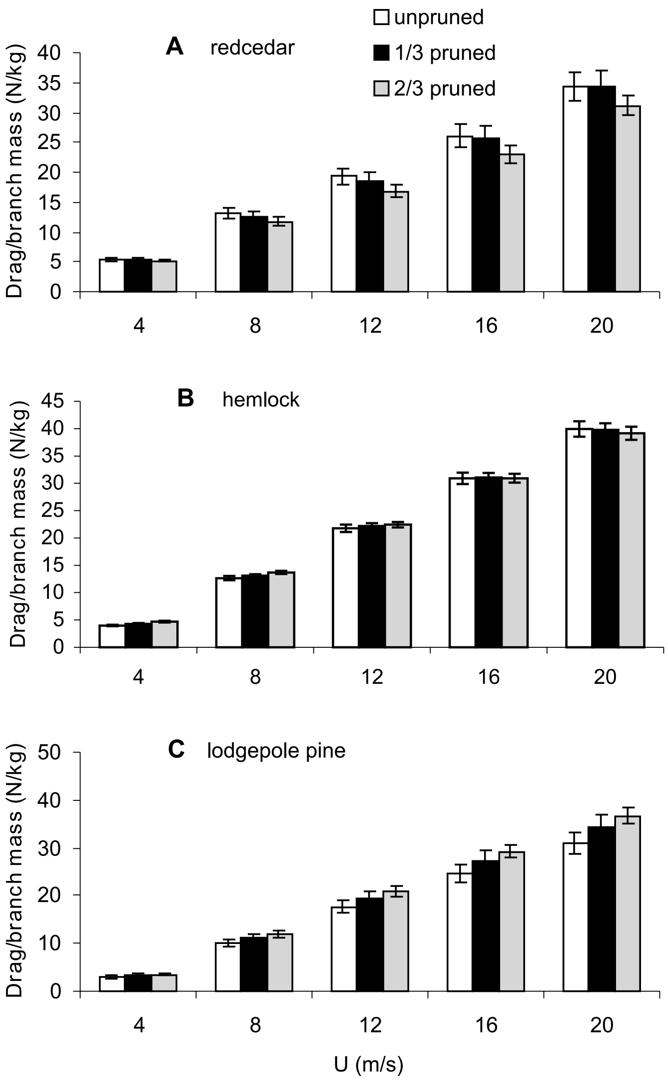
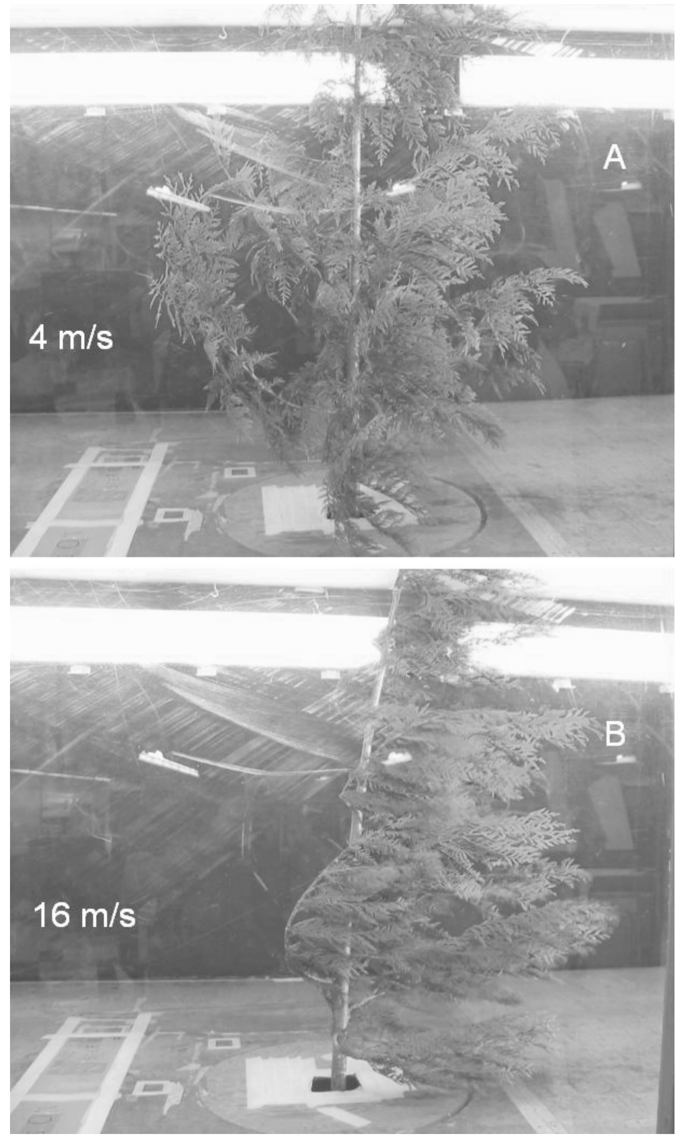


Fig. 6. Side photographs of western redcedar at (A) 4 m/s and (B) 16 m/s.

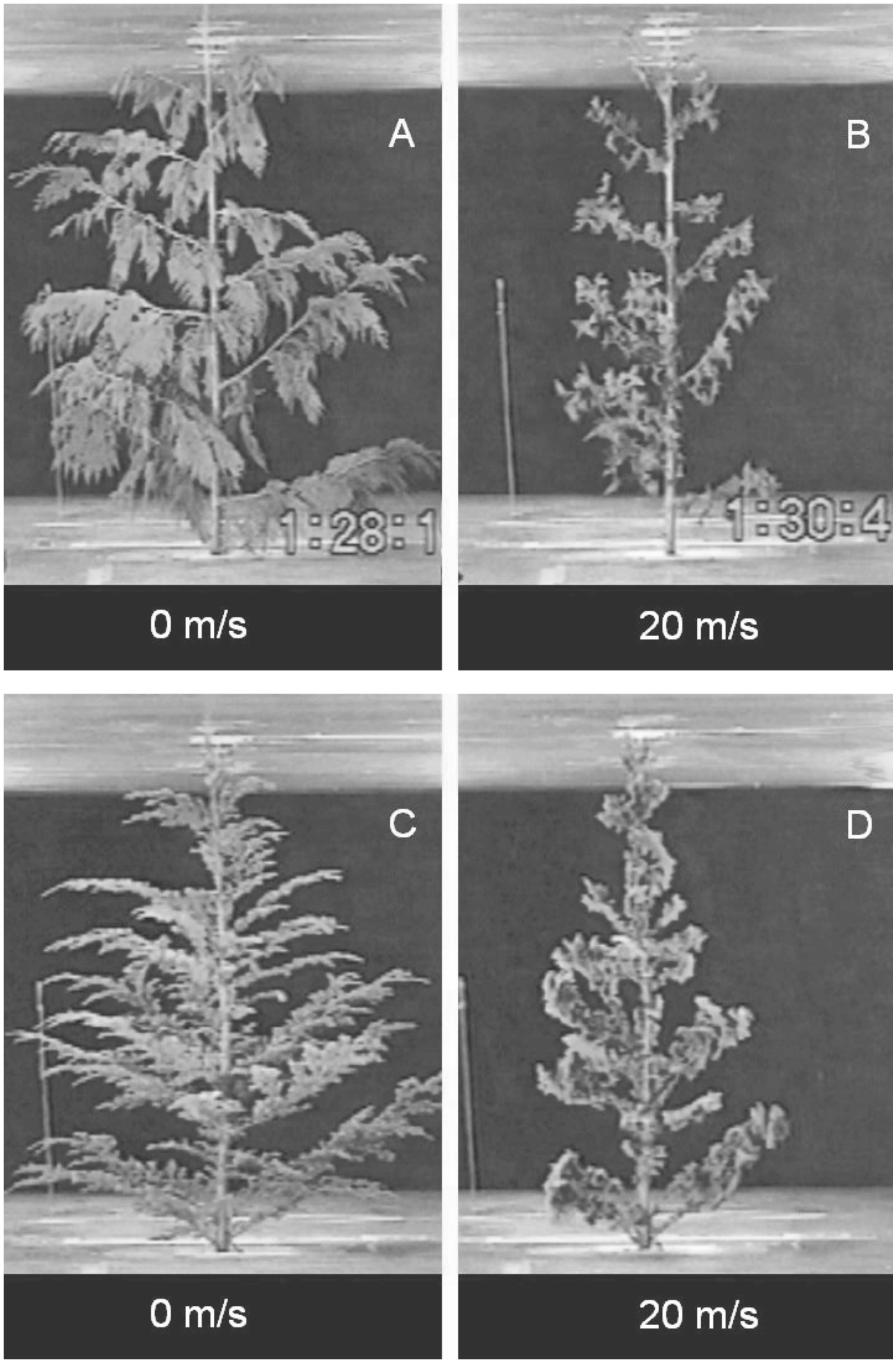


speeds for use with dynamic drag coefficients. Crown mass is easily obtained for cut samples during winching tests and is related to tree size parameters such as diameter at breast height (DBH) and tree height (Ter-Mikaelian and Korzukhin 1997). Furthermore, crown mass is highly correlated with sapwood cross-sectional area within a given stand (e.g., Long and Smith 1988).

While the Mayhead et al. (1975) nonlinear formula provides a good fit with our data, their equation substantially over-predicts drag for our lodgepole pine trees when their parameters are used. Presumably, this discrepancy reflects differences in crown morphology and the greater branch flexibility in our juvenile trees. Mayhead et al. (1975) used larger, more mature trees grown from coastal provenance lodgepole pine seed. Additional tests with trees from different age classes and provenances will be necessary to evaluate within-species variability in crown properties and any systematic effects of these factors on drag. Given the magnitude of the difference in predictions and the broad application of drag equations obtained with small sample sizes, incorrect estimation of drag could be a significant source of error in mechanistic windthrow risk models.

For a given wind speed, redcedar has much lower drag per unit of frontal area than hemlock, and pine is intermediate. Presumably, this results from the alignment of individual foliage elements with the wind. This alignment gives the redcedar foliage elements aerodynamic properties similar to flat plates, whereas pine and hemlock foliage elements remain more cylindrical. The relatively low drag per unit branch mass in pine was unexpected and probably reflects the increasing alignment of branches with the wind and the greater degree of internal shelter as wind speeds increase and crowns compact. Mayhead et al. (1975) reported that their debranching experiments confirmed the strong relationship between branch mass and drag, but they provided no quantitative results. We found a similar result. The opposing trends in the effects of pruning on drag per unit of branch mass for redcedar and lodgepole pine are consistent with the

Fig. 7. Frontal photographs of (A) western redcedar in still air, (B) western redcedar at 20 m/s, (C) western hemlock in still air, (D) western hemlock at 20 m/s, (E) lodgepole pine in still air, and (F) lodgepole pine at 20 m/s.

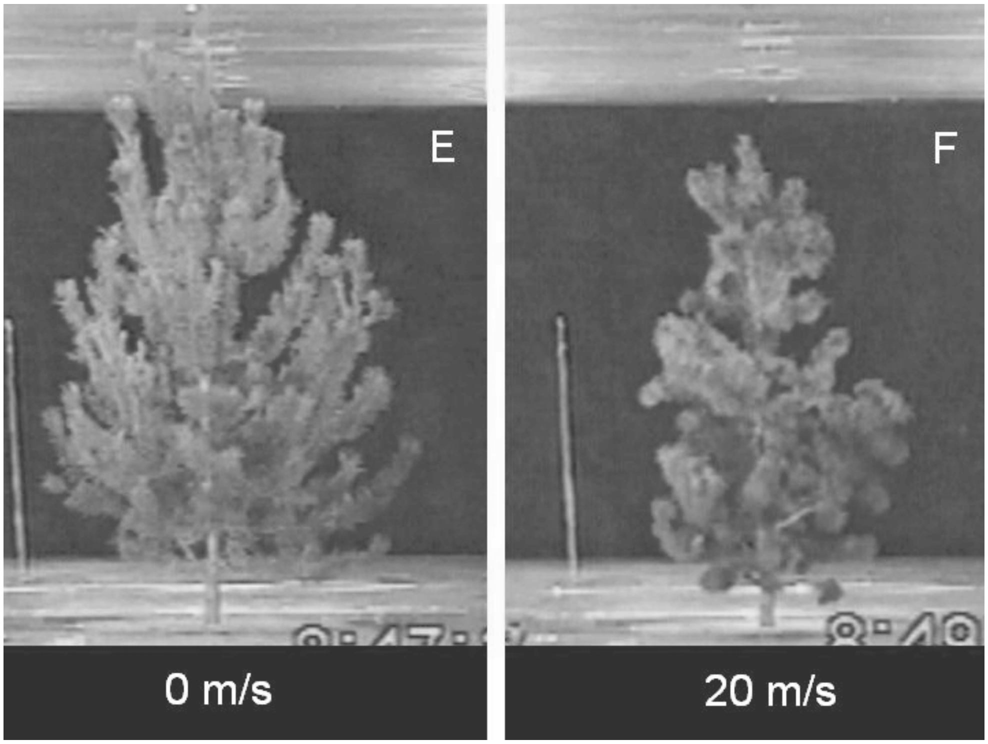


different manner of streamlining observed in each species. Individual redcedar foliage elements appeared to streamline most efficiently when branches did not interfere with one another. For pine, however, pruning appears to have increased the exposure of individual branches. Branch and foliage level drag relationships will be investigated further in future studies.

Conclusions

Over the range of wind speeds investigated in this study, redcedar, hemlock, and lodgepole pine crowns streamline. This streamlining results in variable drag coefficients and a near linear relationship between drag and the product of branch mass and wind speed. Between-species differences in

Fig. 7. (*concluded*).



drag relationships reflect differences in streamlining, within-crown sheltering, and foliage shape. Similarities in the drag–mass relationship for redcedar and lodgepole pine indicate that there are several mechanisms by which trees can maintain low drag. Given the small sample sizes in this and previous drag studies, further work is needed to investigate the variability of drag relationships within species for trees of different age classes and provenances.

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