Scaling Effects of Standing Crop Residues on the Wind Profile

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ABSTRACT

Standing senescent stems increase the aerodynamic roughness of the surface, reducing wind energy available for momentum transfer at the soil surface, such as for wind erosion, and also the soil–atmosphere convective exchanges of heat, water vapor, and trace gases. We conducted studies to determine the predictive accuracy of an algorithm derived for plant canopies to scale effects of standing crop residues on the wind profile. We used this algorithm to calculate aerodynamic properties (displacement height and roughness length) of standing crop residues related to the log wind profile equation. We also calculated apparent roughness length from wind profiles measured under neutral stability conditions over stems of wheat (*Triticum aestivum* L.), corn (*Zea mays* L.), millet (*Panicum miliaceum* L.), and sunflower (*Helianthus annuus* L.) using calibrated single-needle and cup anemometers. A least-squares fit of roughness length calculated by an algorithm derived for crop canopies indicated a systematic, positive bias when it was applied to standing stems. After adjusting for bias, calculated windspeeds generally were contained in 80% confidence intervals for observations above and within the crop stubble. Predictive root mean square errors (RMSE) within profiles ranged from 0.6 to 4.6% of reference wind speed. The nonlinear forms of the scaling algorithms are consistent with theory and wind tunnel observations, representing an advance over parameterization schemes assuming a linear relation with residue height. This advance warrants evaluation of the adjusted algorithm for simulation of microclimate in the soil–residue–crop canopy regime. Application to momentum transfer problems requires further investigation of drag partitioning.

Standing crop residues alter wind profiles and wind velocity near the soil surface. These effects help protect soils from wind erosion by reducing soil water loss (Van Doren and Allmaras, 1978); absorbing the erosive force of wind (Lyles and Allison, 1976); and shielding the soil from saltating particles (Hagen and Armbrust, 1994). Standing residues also help reduce water erosion by reducing the kinetic impact of raindrops (Van Doren and Allmaras, 1978). Crop residues alter the biological environment near the soil surface (Doran et al., 1984). They affect emergence and development of crops and their plant, insect, and microbial pests by modifying preplant soil warming (Bristow and Abrecht, 1989); soil water recharge (Doran et al., 1984; Nielsen, 1998); and the transpiration fraction of total evaporation, before canopy closure (Lascano et al., 1994).

Knowledge of impacts of surface crop residue on surface-exchange processes can enhance evaluation of alternative land-management practices. Quantitative knowledge of standing residue effects on threshold wind velocities for soil erosion supports management guidelines (Hagen, 1996; Nielsen and Aiken, 1998; McMaster et al., 2000). Effects of standing stems on eddy diffusion affect convective transport of heat, water vapor, and trace gases. Near-surface conductance can regulate soil–atmosphere exchanges due to strong concentration gradients near this interface (Reicosky and Lindstrom, 1993; Nobel, 1983, p. 473). Standing crop residue effects on the wind profile alter threshold velocities for wind erosion, the near-surface biological environment, and soil–atmosphere exchange of heat, water vapor, and greenhouse gases.

Standing stems alter convective exchanges and near-surface (<0.05 m) wind velocities by absorbing kinetic energy and modifying aerodynamic roughness. These effects are readily quantified as a log-linear decrease in wind velocity relative to distance above the land surface. The slope of this relationship reflects the friction velocity, while the intercept can be interpreted as the aerodynamic roughness of the surface, or roughness length. Vertical stems tend to raise, or displace, the level of near-zero wind velocity while increasing aerodynamic roughness and altering friction velocity (Pereira and Shaw, 1980). Though displacement height and aerodynamic roughness are phenomenological coefficients, they tend to scale with crop canopy characteristics including height (Campbell, 1973; Rosenberg et al., 1983) and leaf area (Choudhury and Monteith, 1988). Analogous relationships exist between residue architecture (horizontal projected stem area) and threshold velocities required to initiate soil erosion (Hagen, 1996).

Our research objective was to derive a modified algorithm, which quantifies effects of standing stems on wind profiles above and within sparse canopies and to conduct field measurements of wind profile and geometries of standing residues for wheat, corn, millet, and sunflower to validate the modified algorithm.

THEORY

Standing senescent stems increase the aerodynamic roughness of the subcanopy substrate, reducing wind energy available for momentum transfer at the soil surface (Hagen, 1996) and also the soil–atmosphere convective exchanges of heat, water vapor, and trace gases (Thom, 1971). This effect appears to be proportional to silhouette area index (SAI), the horizontal projected area of roughness elements per unit of land area (Nielsen and Aiken, 1998). Plant geometry provides a useful basis for analysis of drag partitioning (Raupach, 1992), soil erosion (Raupach et al., 1993; Van de Ven et al., 1989), evaporation (Choudhury and Monteith, 1988; Dolman and Wallace, 1991), and wind velocities within the roughness sublayer (Pereira and Shaw, 1980). Standing stems may differ from growing plants in the relative significance of skin friction

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Abbreviations: LAI, leaf area index; RMSE, root mean square errors; SAI, silhouette area index.

and form drag (Campbell, 1973, p. 72–73) in the absence and presence of leaves.

Gradient-diffusion or K theory guides inference of aerodynamic transfer processes. This theory is contradicted by the countergradient fluxes observed within forest canopies (Denmead and Bradley, 1985). Raupach (1989) developed Lagrangian methods that accounted for countergradient flow by distinguishing near-field and far-field components of dispersion. Near-field effects reduce to zero near the soil surface, where the characteristic time scale approaches zero and the near-surface turbulence becomes inhomogeneous (Raupach, 1989; Dolman and Wallace, 1991). The K theory provides a reasonable approximation of far-field effects, which are expected to govern heat and vapor transports from ground-level sources.

Dolman and Wallace (1991) reported similar performances of Lagrangian and K theory quantifications of turbulent transfer for a dual-source energy-balance model of evaporation. Tanner and Shen (1990) found a linear relationship between vapor conductance through a mulch of flail-chopped corn residue and wind speed 11 mm above the mulch layer. Sauer et al. (1995) also observed linear relationship between heat and vapor conductances above source plates and wind speed measured 0.03 m above the source plates. Because near-surface resistances can exceed aerodynamic resistance by an order of magnitude, errors in surface energy-balance simulations are likely to result from uncertainty in near-surface, rather than above-canopy, aerodynamic transfer coefficients.

The wind speed profile ($U(z)$, m s^{-1}) above a crop canopy has been quantified by the log-linear function derived from the first moment of eddy diffusion

$$U(z) = \frac{U_*}{\kappa}\ln\left(\frac{z-d}{z_o}\right) \qquad z \geq h \qquad [1]$$

where U_* is friction velocity (m s^{-1}), κ is von Karmon's constant ($\kappa \sim 0.41$), z is height above the soil surface (m), d is zero displacement plane (m), and z_o is a roughness length scale (m) (Rosenberg et al., 1983). Within crop canopies of height, h, wind speed has been quantified as a function of wind speed at canopy height, U_h (m s^{-1}) (Landsberg and James, 1971; Thom, 1971; Pereira and Shaw, 1980):

$$U(z) = U_h\left[1 + \alpha\left(1 - \frac{z}{h}\right)\right]^{-2} \qquad z < h \qquad [2]$$

where the damping effect of crop canopy, α, is specified as

$$\alpha = \left(2 \times \left(1 - \frac{d}{h}\right) \times \ln\left[\left(1 - \frac{d}{h}\right)\left(\frac{z_o}{h}\right)^{-1}\right]\right)^{-1} \qquad [3]$$

Thus, wind speed profiles above and within crop canopies can be calculated from a reference wind speed given knowledge of the aerodynamic parameters of displacement height, d, and roughness length, z_o (Rosenberg et al., 1983 p. 139).

Extending wind profile theory to sparse canopy of standing crop stems requires a procedure to quantify the aerodynamic parameters d and z_o. We hypothesize that in sparse canopies, these effects can be scaled by SAI, given appropriate substitution for leaf area index (LAI). Specifically, we extend the algorithm of Choudhury and Monteith (1988) to standing stems, specifying d/h, relative displacement height, as a function of aerodynamic drag (C_{fd}, dimensionless) and SAI.

$$\frac{d}{h} = 1.1 \times \ln\left[1 + (C_{fd} \times \mathrm{SAI})^{0.25}\right] \qquad [4]$$

Following Shuttleworth and Gurney (1990), we compute z_o as the sum of roughness lengths for standing stems ($z_{o(st)}$) and surface ($z_{o(s)}$) layers, where $z_{o(st)}$ is represented, according to Choudhury and Monteith (1988), as

$$\frac{z_{o(st)}}{h} = a(C_{fd}\mathrm{SAI})^{0.5} \qquad (C_{fd}\mathrm{SAI}) < 0.2$$

$$\frac{z_{o(st)}}{h} = a\left(1 - \frac{d}{h}\right) \qquad (C_{fd}\mathrm{SAI}) > 0.2 \qquad [5]$$

with the value of a set to 0.3. Here the aerodynamic drag coefficient C_{fd} represents form drag of individual residue elements, perpendicular to fluid flow, distinguished from skin drag, tangential to fluid flow (Campbell, 1973), and from total surface drag (Raupach, 1992). We take, as a first approximation for C_{fd}, values reported in Campbell (1973, p. 74), representing a range of stem height/diameter ratios. We compute SAI from

$$\mathrm{SAI} = d_s hN \qquad [6]$$

where d_s is stem diameter (m), h is stem height (m), and N is number of stems per square meter. Surface roughness ($z_{o(s)}$) can result from tillage-induced ridges (McInnes et al., 1991) and random roughness, as well as effects of flat residue cover. We compute $z_{o(s)}$ as the maximum of ridge ($z_{o(rg)} = 0.07\ h_{rg}$; McInnes et al. (1991), where h_{rg} is ridge height) or random roughness ($z_{o(rr)} = 0.9$ mm, from prior investigations of log-linear profiles over flat sunflower residues).

MATERIALS AND METHODS

We measured wind velocity profiles over stems of wheat, corn, millet, and sunflower at five sites within the USDA-ARS Central Great Plains Research Station (6.4 km east of Akron, CO) following the 1995 harvest and at two sites on cooperating farmers' fields within 3 km of the research station. Profiles were characterized using calibrated cup anemometers (Qualimetrics Model 2032 with stated accuracy of 0.07 m s^{-1} and threshold of 0.5 m s^{-1}; and RM Young Model 3101 with a stated accuracy of 0.5 m s^{-1} and threshold of 0.5 m s^{-1}) at 0.40-, 0.60-, 0.80-, 1.00-, 1.20-, 1.60-, 2.00-, and 2.40-m heights and a wind direction sensor (RM Young Model 3301) at a 2.40-m height located in fields to achieve fetch/height ratios exceeding 200:1. Near-surface wind speeds for wheat, millet, and bulk corn sites were quantified using single-needle anemometers (Bland et al., 1995, Soiltronics Model SNA-22; similar to the Thermal Logic Ceramic Cylinder Anemometer, which has a stated accuracy of 0.2 m s^{-1}) deployed at 0.07 and 0.20 m above the soil surface. Wind profiles over sunflower did not include measurements <0.8 m; profiles over the wheat (Site 1) did not include measurements <0.4 m. An onsite data logger (Campbell Scientific, Logan, UT) sampled wind speeds and direction each minute and recorded 15-min average values.

Wind speed data were categorized into wind direction classes, relative to row direction (parallel, −22.5° to 22.5°; cross, 22.5° to 67.5°; or perpendicular, 67.5° to 112.5°), where fetch exceeded 200:1. We selected wind profiles with neutral stability conditions ($-0.003 < \mathrm{Ri} < 0.003$) (where Ri is Richardson number) evaluated by wind and temperature profiles (2.0- and 0.3-m heights) at a similar site. We calculated apparent roughness length for wind profiles above roughness elements and parameterized d by Eq. [4]. We used linear regression (regressing predicted values on observed values) and root mean square error (RMSE) to quantify bias and precision in calculations of z_o (Eq. [5]) and to quantify the predictive accuracy of calculated relative wind-speed profiles above and within roughness elements (Eq. [1] and [2]) parameterized by

Eq. [3], [4], and [5]. We scaled wind speed data relative to reference wind speed for comparative purposes.

We measured standing residue geometry by sampling three to eight representative locations within 80 m upwind of the anemometer mast. At each sampling location, we measured row spacing, stem height, number of stems per unit area, and stem diameter.

RESULTS

Residues at the selected experimental sites (Table 1) were characteristic of semiarid crop systems. Sunflower stubble represented the simplest system, with roughness elements approximating the shape of thin vertical cylinders. Corn stubble, comprised of husks, leaves, and broken stems, added complexity to the roughness elements. The tillering growth habit of wheat added to row orientation effects, resulting in a stiff hedge structure. The structure of roughness elements in the millet field was the most complex, because the crop was planted on ridges (height of 30 mm and spacing of 0.21 m) into standing wheat stubble.

The roughness length calculated from Eq. 5 exceeded roughness length obtained from wind profile measurements (Fig. 1, RMSE = 0.00049). A least squares fit of the constant a in Eq. [5] yielded a value of 0.24 (RMSE = 0.00028) compared with the value of 0.3 reported in Choudhury and Monteith (1988) for crop canopies. Subsequent analyses of wind profiles are evaluated using the fitted value for the constant a in Eq. [5].

Wind speeds calculated by Eq. [1] to [5], with the new value for a were generally contained in 80% confidence limits for observations above and within residue canopies (Fig. 2). Data for Sunflower 2 and Wheat 3 are not shown, because wind profiles are similar to those shown and with less predictive bias. The greatest variability in wind speed observations coincided with residue height; for example, variability in wind speed for the corn profile was greatest at 0.6 m, which was also the height of the standing stubble. The precision component of predictive accuracy is high, as indicated by coefficients of determination exceeding 0.98 (Table 2). Zero bias was obtained for 5 of the 12 cases; bias in slope that offset bias in intercept for two cases, and bias in intercept only for five cases. Predictive errors (RMSEs) ranged from 0.6 to 4.6% of reference wind speed. The adequate fit indicated by Table 2 is expected, because the revised coefficient, a, for Eq. [5] was derived from wind profiles observed above the roughness elements.

DISCUSSION

Scaling approaches that account for effects of standing stems should reduce uncertainty in simulation models. Earlier scaling approaches applied to standing stems involved simple linear functions of stem height (Campbell, 1973). The nonlinear dependence of Eq. [4] and [5] on SAI and C_{fd} represent an improvement, which is consistent with relationships for roughness elements derived by Raupach (1992) and with wind tunnel observations of Hagen and Armbrust (1994). Advances in scaling effects of canopy architecture may derive from advanced second-order closure models of turbulent transfer (Pereira and Shaw, 1980), which provide the theoretical basis for the scaling approach evaluated here.

Our evaluation is limited to wind speed. Inference for drag partitioning requires further experimental verification, because the parameterization of d and z_o affects U_* and subsequent analysis of drag and shear stress. Our experience with linear regression of wind speed on height indicates that multiple solutions for d and z_o can yield similar coefficients of determination (results not shown)—a characteristic of interdependent parameters. This interdependence is explicit in the second equality of Eq. [5]. McInnes et al. (1991) found a similar result for aerodynamic properties of ridge-tilled soils.

Raupach (1992) derived solutions for d/h and z_o/h, as functions of SAI. These solutions consider effects of

Table 1. Residue geometry for aerodynamic properties

Crop	Height	Diameter	Frequency	Row Width	SAI†	C_{fd}†
	m	mm	no. m^{-2}	m	m^2 m^{-2}	
Wheat 1	0.38	3.3	453	0.30	0.57	0.51
Wheat 2	0.59	2.7	156	0.30	0.25	0.54
Wheat 3	0.32	2.8	588	0.30	0.53	0.51
Sunflower 1	0.65	27	2.50	0.70	0.044	0.45
Sunflower 2	0.50	23	2.80	0.70	0.032	0.44
Corn	0.60	14	3.94	0.70	0.033	0.47
Millet‡						
Wheat	0.10§	3	114	0.21	0.067	0.49
Millet	0.20	4.4	84	0.21	0.074	0.47

† Silhouette area index (SAI) is the horizontal projected area of roughness elements per unit of land area. The aerodynamic drag coefficient C_{fd} represents form drag of an individual residue element, perpendicular to fluid flow.

‡ The millet field was composed of both wheat and millet stems, resulting from direct drill planting of millet into standing wheat stubble. We computed an effective SAI as the sum of the components. Ridge height was 30 mm.

§ The stem length of 0.20 m was used in SAI calculations; the height of stem tips above the soil surface was 0.10 m, due to disturbance by planting operations.

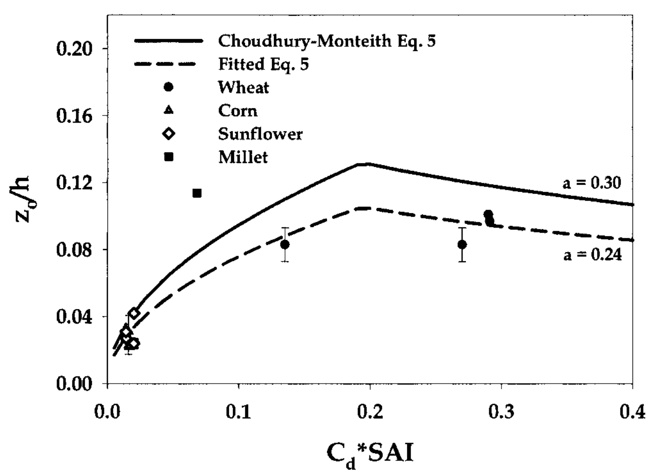

Fig. 1. Roughness length, scaled by height of standing stems and depicted in relation to canopy drag. The continuous function was calculated from Eq. [5] using suggested (Choudhury and Monteith, 1988) and fitted values for the coefficient *a*. Observed roughness length and 80% confidence intervals constructed from standard error about the means were calculated from wind profiles over standing crop residues using Eq. [1] and [4].

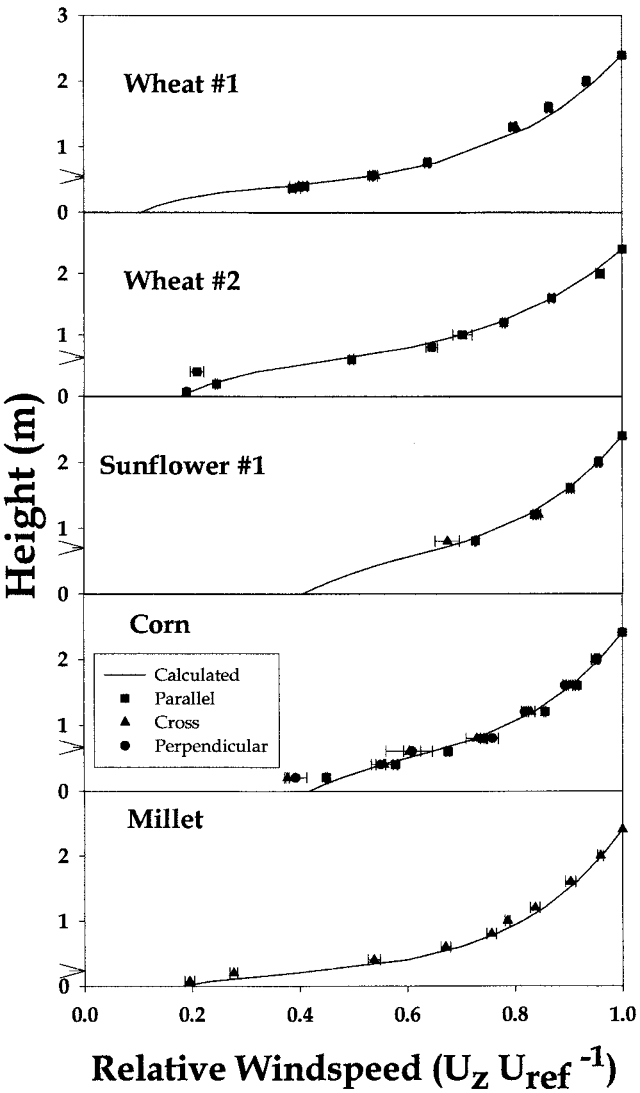

Fig. 2. Relative wind speed scaled to wind speed at reference height (2.4 m) above and within standing stems of wheat, sunflower, corn, and millet. The ordinate, height, is presented on the vertical axis; arrows indicate height of standing stems. The continuous function was calculated from Eq. [1] and [2], parameterized by Eq. [3] to [5] using a fitted value of 0.24 for the coefficient *a*. Observed wind speeds and direction relative to row orientation are depicted with 80% confidence intervals constructed from standard errors about the means.

residue geometry, C_{fd} and downwind sheltering on the partition of total surface shear stress on standing residue and soil components. The ratios of d/h computed by Eq. [4] for residue geometries reported here are 20 to 35% lower than that calculated by corresponding algorithms presented in Raupach (1992). However, the ratios of z_o/h computed by Eq. [5] correspond with those resulting from analogous algorithms in Raupach (1992). Applying Eq. [4] and [5] to characteristics of corn stubble reported in Sauer et al. (1996) results in d and z_o values that are 72 and 52% relative to reported values, respectively; however, values calculated from Eq. [4] and [5] are contained within a single standard deviation of reported values. Equations [4] and [5] give results that are consistent with independent field determinations; algorithms in Raupach (1992) provide an alternative procedure for parameterizing d and z_o, as functions of SAI.

The form drag coefficient (C_{fd}) computed from Campbell (1973, p. 73) for individual cylindrical roughness elements, perpendicular to fluid flow, is approximately twice that discussed in Raupach (1992). Sauer et al. (1996) reported values for total surface drag coefficient (C_D) for standing corn stubble ranging from 0.0061 to 0.0085, which are two orders of magnitude smaller than values computed for individual roughness elements, C_{fd}. A relationship between C_{fd} and C_D may be established, assuming total shear stress, τ, is absorbed by the roughness elements (valid for SAI $>$ 0.03; Sauer et al., 1996). The drag force per unit ground area acting on roughness elements, τ_R(SAI), can be computed considering the drag force on individual roughness elements τ_R; the height, diameter and number of roughness elements per unit area, i.e., SAI; and interacting sheltering effects (Raupach, 1992, Eq. [14] and [15] therein). Neglecting sheltering effects, a form drag coefficient (C_{fd}) corresponding to a total surface drag coefficient (C_D) can be computed from the C_D/SAI ratio. For the conditions reported in Sauer et al. (1996) and assuming a mean corn stubble diameter of 0.02 m, the SAI ranged from 0.034 to 0.039; corresponding C_{fd} values, for a mean SAI of 0.036, range from 0.17 to 0.24. It can be shown that considering sheltering effects, after Raupach (1992), the range of C_{fd} values would shift to 0.20 and 0.28. These values are consistent with the value of 0.25 discussed in Raupach (1992).

A defect in the representation of within-canopy wind speeds specified by Eq. [2] is the failure to converge to the proper limit (zero wind speed) at the soil surface, though the general agreement with observations at 0.07 m above the surface indicates validity within the canopy. However, the nonzero wind speeds calculated for the soil boundary by Eq. [2] can be interpreted as a characteristic wind speed associated with surface eddies, or within-canopy air flow. Energy-balance models of soil evaporation can be particularly sensitive to uncertainties in near-surface wind-speed calculations, which are used to compute transfer coefficients for soil–atmosphere exchanges of mass and energy (Tanner and Shen, 1990; Aiken et al., 1997).

The scaling approach represented by Eq. [4] and [5] is adequate to quantify effects of standing stems on wind speed profiles above and within these roughness elements. Biases exist in noncalibrated comparisons of calculations derived from canopy theory. However, following calibration, residual errors were 0.5 to 4.6% of reference wind speed. Further evaluation of the coefficient a used in Eq. [5] is warranted, because we used the same profile data to derive the coefficient and to evaluate subsequent wind speeds. Further work also is required to evaluate the adequacy of Eq. [4] and [5] for drag partitioning and to investigate aerodynamic properties of complex surfaces containing ridges and standing stems.

Whether bias contributes to simulation error depends on the objectives of the simulation model. The algorithm

Table 2. Bias and predictive accuracy of Thom algorithm (Eq. [2] and [3]) and Choudhury-Monteith parameters (Eq. [4] and [5]) for relative wind velocity above and within canopies of standing crop residues.

Site	N†	a_0	a_1	R^2	RMSE
			Wheat 1		
Parallel wind	6	−0.061 (0.022)*	1.089 (0.035)	0.994	0.0276
Cross wind	4	−0.064 (0.023)	1.091 (0.037)	0.993	0.0285
			Wheat 2 ‡		
Parallel wind	3	0.035 (0.040)	0.944 (0.043)	0.984	0.0390
			Wheat 3		
Parallel wind	3	−0.029 (0.010)	1.021 (0.031)	0.997	0.0140
			Sunflower 1		
Parallel wind	2	−0.069 (0.002)**	1.071 (0.011)**	1.000	0.0095
Cross wind	6	0.090 (0.017)**	0.900 (0.068)	0.983	0.0176
			Sunflower 2		
Parallel wind	4	−0.016 (0.005)*	1.016 (0.028)	0.998	0.0046
Cross wind	6	0.015 (0.003)**	0.989 (0.015)	0.999	0.0055
			Corn ‡		
Parallel wind	11	0.003 (0.020)	0.986 (0.039)	0.990	0.0193
Cross wind	3	0.109 (0.027)	0.880 (0.047)	0.983	0.0389
Perpendicular	4	0.092 (0.028)*	0.900 (0.049)	0.982	0.0354
			Millet ‡		
Cross wind	4	0.100 (0.023)*	0.902 (0.028)*	0.992	0.0458

* Intercept (a_0) is significantly different from 0, slope (a_1) significantly different from 1 at 5% probability level.
** Intercept is significantly different from 0, slope significantly different from 1 at 1% probability level.
† Number of profiles analyzed.
‡ Profile includes observations within standing stem canopy.

should be suitable for applications to crop energy balance, microclimate, and within-canopy pest populations, where sensitivity to near-surface wind speed likely exceeds sensitivity to above-canopy transfer coefficients and counter-gradient flow regimes are less common. The similarity between our results and those of Raupach (1992) and Hagen (1996) indicates that the algorithms may be suitable for process-level wind erosion and drag partitioning, though further work is warranted.

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