Scaling Effects of Standing Crop Residues on the Wind Profile

R. M. Aiken,* D. C. Nielsen, and L. R. Ahuja

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

R.M. Aiken, Northwest Res. Ext. Center, 105 Experiment Farm Road, Kansas State Univ., Colby, KS 67701; D.C. Nielsen, USDA-ARS, Central Great Plains Research Station; and L.R. Ahuja, USDA-ARS, Great Plains Systems Research. Received 3 June 2002. *Corresponding author (raiken@ksu.edu).

Published in Agron. J. 95:1041–1046 (2003).

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 (κ ~ 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.

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

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

$$\frac{z_{o(st)}}{h} = a(C_{fd}\text{SAI})^{0.5} \qquad (C_{fd}\text{SAI}) < 0.2$$
$$\frac{z_{o(st)}}{h} = a\left(1 - \frac{d}{h}\right) \qquad (C_{fd}\text{SAI}) > 0.2 \qquad [5]$$

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

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

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 ($-0.003 < \text{Ri} < 0.003$) (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

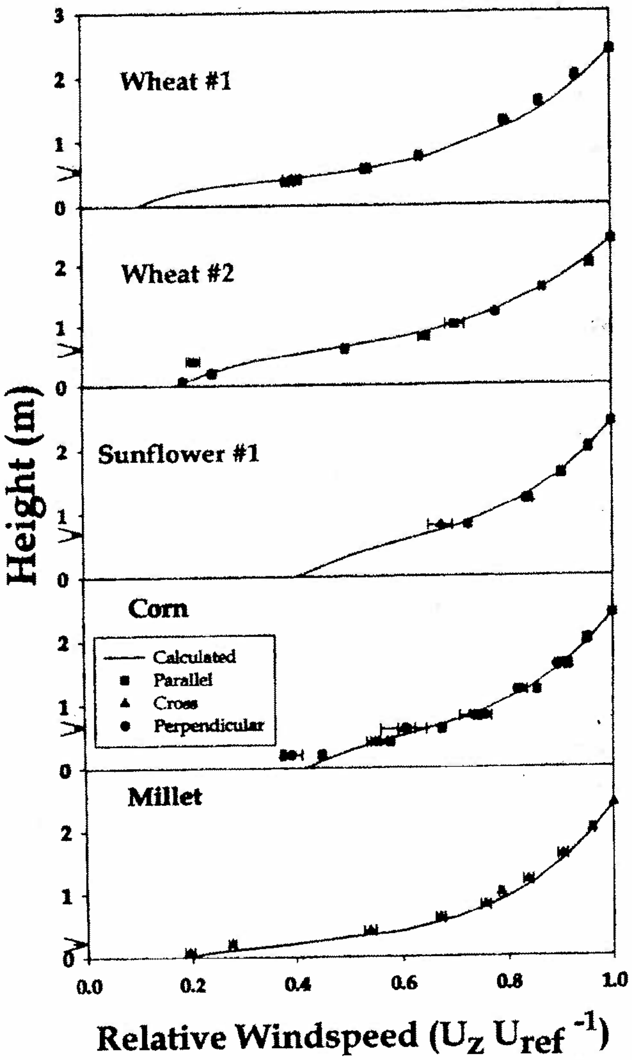

Fig. 2. Relative wind speed scaled to wind speed at reference height (2.4 m) above and within standing stems of wheat, sunflower, corn, and millet. The ordinate, height, is presented on the vertical axis; arrows indicate height of standing stems. The continuous function was calculated from Eq. [1] and [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

Sauer, T.J., J.L. Hatfield, and J.H. Prueger. 1996. Aerodynamic characteristics of standing corn stubble. Agron. J. 88:733–739.

Sauer, T.J., J.M. Norman, C.B. Tanner, and T.B. Wilson. 1995. Measurement of heat and vapor transfer coefficients at the soil surface beneath a maize canopy using source plates. Agric. For. Meteorol. 75:161–189.

Shuttleworth, W.J., and R.J. Gurney. 1990. The theoretical relationship between foliage temperature and canopy resistance in sparse crops. Q.J.R. Meteorol. Soc. 116:497–519.

Tanner, C.B., and Y. Shen. 1990. Water vapor transport through a flail-chopped corn residue. Soil Sci. Soc. Am. J. 54:945–951.

Thom, A.S. 1971. Momentum absorption by vegetation. Q.J.R. Meteorol. Soc. 97:414–428.

Van de Ven, T.A.M., D.W. Fryrear, and W.P. Spaan. 1989. Vegetation characteristics and soil loss by wind. J. Soil Water Conserv. 44:347–349.

Van Doren, D.M., Jr., and R.R. Allmaras. 1978. Effect of residue management practices on the soil physical environment, microclimate, and plant growth. p. 49–83. *In* W.R. Oschwald (ed.) Crop residue management systems. ASA Spec. Publ. 31. ASA, CSSA, and SSSA, Madison, WI.