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Wind Erosion: The Protective Role of Simulated Standing Stubble

Leon Lyles, Bruce E. Allison
MEMBER
ASAE

ABSTRACT

WIND-TUNNEL studies indicated that for standing stubble uniformly spaced or in rows normal to wind direction, critical friction-velocity ratios (CFVR) were 1.4 to 2.0 times larger than those for stubble in rows parallel to the wind—the larger the CFVR, the more effective the stubble in preventing wind erosion of the soil. On a weight basis, 5.5 and 8.7 times more standing grain sorghum and corn stubble, respectively, than standing wheat stubble were required to provide the same wind-erosion protection. Equations presented here may be used to determine if soil will erode and the total amount that will erode for a given wind-soil-stubble condition.

INTRODUCTION

Wind erosion is a potential problem on millions of acres of cropland in the United States. Cultivated, coarse-textured, surface soils (sands, loamy sands, sandy loams) are especially susceptible, with approximately 29 million ac of these soils in the Great Plains, 7 million ac in Southeastern United States, and 6 million ac in the Lake States. Medium and fine-textured soils also may be susceptible in areas with low rainfall, limited vegetative cover, and high windspeeds.

The importance of vegetative cover in protecting the land from wind erosion cannot be overstressed (Chepil and Woodruff 1963, Zingg 1954). Many reports on wind erosion considered the effects of vegetation and vegetative residues that lowered the forces on erodible particles by partially or totally absorbing the wind drag (Chepil 1944, Chepil et al. 1955, Englehorn et al. 1952, Siddoway et al. 1965, Woodruff et al. 1972, Zingg 1954, Zingg et al. 1952). Few reports express the degree of protection provided by standing residues in terms of dimensionless parameters involving the flow (wind), the erodible size particles, stalk dimensions, and geometry. A previous study (Lyles, Schrandt and Schmeidler 1974) provided information on how nonerodible roughness elements control sand movement, but a need remains for data on taller elements, larger and smaller stalk diameters, and fewer plants per unit area than were considered in that study. This paper reports this data.

EXPERIMENTAL PROCEDURE

The experimental procedure has been described (Lyles, et al. 1974). Briefly, simulated crop stubble of wood dowels or wire—0.278, 0.66, 1.59, and 2.55-cm diameter—were oriented, with their axes normal to a wind-tunnel floor, in uniformly spaced diagonal arrays (distance between rows equal to distance between simulated stubble in the row) or in rows normal or parallel with wind direction. The same number of elements per unit area—387, 97, 24, or 11 m^{-2}—was used for two or three orientations. Spaces among the dowels or wires in a test strip (6.1 m long and 0.46 m wide) were covered with a thin layer of erodible sand particles (0.15- to 0.42-mm or 0.42- to 0.59-mm diameter), and loss rates were determined for values greater and smaller than 0.01 g/cm-width/min. The windspeed associated with the loss rate of 0.01 g/cm/min for each height-size spacing combination was defined as the stable-surface windspeed. The study involved 163 tests.

The mean velocity-profile parameter, u_*, (often used to indicate the wind's capability to erode soil particles) was obtained from the following equation:

$$\frac{\bar{u}_Z}{u_*} = \frac{1}{k} \ln\left(\frac{Z - D}{Z_O}\right) \quad \ldots\ldots\ldots\ldots \quad [1]$$

where $\bar{u}_Z$ is mean windspeed at height, Z, above some reference plane; u_*, the friction velocity (defined as $(\tau_O/\varrho)^{1/2}$, where τ_O is the shear stress at the boundary, and ϱ is air density); k is von Karman's constant (0.4); D is an effective roughness height; and Z_O is a roughness parameter. This equation is applicable to adiabatic flows in the lower 10 to 20 percent of the boundary layer. We determined u_* from $\bar{u}_Z$ measurements above the simulated stubble.

EXPERIMENTAL DATA AND OBSERVATIONS

A surface partially covered with residue or standing stubble absorbs part of u_* (drag) and reduces the drag acting on the soil surface. Consequently, free-stream velocities can be higher without erosion. However, depending on soil and stubble properties, windspeed can be increased so that drag acting on the soil will exceed the threshold (u_{*_t}), which causes erosion.

We called the dimensionless dependent variable $(u_*/u_{*t})_S$ the "critical friction-velocity ratio" (CFVR) because when this value is exceeded, erosion begins—the larger the ratio, the greater the wind-erosion protection (Lyles et al. 1974). (u_* is the total friction velocity when a surface stabilizes at a given free-stream velocity, and u_{*t} is the threshold friction velocity for the erodible particles in question.) For the small sand grains, the value of u_{*t} was 21.64 cm/sec; for large sand grains, it was 31.14 cm/sec.

Many "independent" variables and combinations of variables were correlated with $(u_*/u_{*t})_S$ using stepwise multiple regression where variables were entered in the order of their greatest contribution to variance. Because of its simplicity, nondimen-

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The authors are: LEON LYLES, Agricultural Engineer, and BRUCE E. ALLISON, Research Assistant, NCR, ARS, USDA, Manhattan, KS.

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sionality, variance accounted for, and realism of predicted values, we selected this prediction equation:

$$(u_*/u_{*t})_S = 1.638 + 17.044 \frac{NA_s}{A_t} - 0.117 \frac{L_y}{L_x} ; R = 0.901 \quad \ldots\ldots [2]$$

where

N/A_t = number of simulated stalks in area A_t (in cm^{-2})

A_s = silhouette area (projected area facing flow) of a single stalk (in cm^2)

L_y = distance (center-to-center) between stalks normal to wind direction (in cm)

L_x = distance (center-to-center) between stalks in the wind direction (in cm).

The silhouette area, A_S, for cylinders is HD, when H is cylinder height and D is cylinder diameter. Also, $N/A_t = (L_yL_x)^{-1}$; thus, $\frac{NA_s}{A_t} = \frac{HD}{L_yL_x}$

for our case. The dimensionless group, $\frac{NA_s}{A_t}$,

characterizes the stubble (stalk number, height, and diameter); the other parameter, L_y/L_x, accounts for stalk orientation to wind direction, i.e., rows normal to or parallel with the wind. For uniform diagonal arrays, $L_y = L_x$. The range of values for individual variables in equation [2] was 0.1 to 43.18 cm for H, 2.54 to 30.48 cm for L_y, and 2.54 to 60.96 cm for L_x. Values for D and N/A_t are given in the experimental procedure section.

Effect of Soil Cloddiness

Field soils seldom contain only erodible-size particles. Consequently, equation [2] would be more useful if the effect of nonerodible soil aggregates on $(u_*/u_{*t})_S$) were known. We revised a regression equation of Bisal and Ferguson (1970) so that:

$$\bar{u}_i/\bar{u}_t = (1.0236)^C \quad \ldots\ldots\ldots\ldots [3]$$

where $\bar{u}_i$ is the mean initiating velocity for soil movement (in cm/sec) measured at 30.5 cm above the soil surface; $\bar{u}_t$ is the threshold mean velocity for the Wood Mountain loam soil when C (the percentage of soil aggregates greater than 1.0 mm diameter) equals zero. Use of equation [3] should be limited to values of C between 0 and 50 percent because that range was not exceeded in their study. More research is needed to verify equation [3] and characterize the effect of C on $(u_*/u_{*t})_S$.

Assuming no significant interaction of soil cloddiness (C) and standing stubble on $(u_*/u_{*t})_S$, equation [3] may be added to equation [2] to reflect the combined effect of standing stubble and nonerodible soil aggregates on wind erosion protection:

$$(u_*/u_{*t})_S = 1.638 + 17.044 \frac{NA_s}{A_t} - 0.117 \frac{L_y}{L_x} + [(1.0236)^C - 1] \quad \ldots [4]$$

When C = 0, equation [4] becomes equation [2].

Total Soil Removal

Chepil and Woodruff (1963) suggested that total weight of soil material removed from the surface by wind measures more accurately soil erodibility than does rate of soil removal. Because of nonerodible elements (soil aggregates or vegetative material), the rate of soil loss decreases with time even if windspeed remains constant. The experimental methods we used in determining $(u_*)_S$ required measuring or calculating the total sand removed or potentially removed to the point of stability:

$$Q_T/\gamma_B = H(1 - A_c) \quad \ldots\ldots\ldots\ldots\ldots [5]$$

where Q_T is total soil removed (in g/cm^2); γ_B is bulk density of the loose surface soil (in g/cm^3); H is stubble height (in cm); and A_c is proportion of area occupied by stubble (in cm^2). For cylinders, $A_c = \frac{0.7854D^2}{L_yL_x}$

Equation [4] may be solved for H_e to obtain:

$$H_e = \frac{L_yL_x \left\{(u_*/u_{*t})_e + 0.117\, L_yL_x - 1.638 - [(1.0236)^C - 1]\right\}}{17.044D} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots [6]$$

where H_e is the stubble height associated with $(u_*/u_{*t})_e$, some possible or expected friction-velocity ratio for given wind-soil-stubble conditions that must exceed $(u_*/u_{*t})_S$ for soil to erode. Then, $H_\Delta = H_e - H_S$ is substituted for H in equation [5] that is subsequently solved for Q_T. By definition, H_S is the stubble height used in equation [4] for determining $(u_*/u_{*t})_S$. Equation [5] may be multiplied by 100 to obtain Q_T (in mt/ha).

In summary, the procedure for determining Q_T, the total soil removed before erosion stops, would be:

1 Use equation [4] to determine $(u_*/u_{*t})_S$ for given soil-stubble conditions.

2 Specify an expected level of $(u*/u*_t)_e$ that exceeds $(u*/u*_t)_S$ and compute H_e from equation [6]. Information on windspeed, duration, and frequency would be needed to make valid selections of $(u_*/u_{*t})_e$.

3 Compute H_Δ and use equation [5] to determine Q_T/γ_B.

INTERPRETATIONS AND DISCUSSION

Although similar, we recognize that dowels and wire may not react exactly like real stubble. Generally, under field conditions other vegetative materials may be on the soil surface and the post-harvest stalks may have leaves attached—grain sorghum has the greatest number; corn and wheat have successively less leaves. However, overwinter climatic effects and/or livestock grazing may remove most leaves so that during late winter and early spring—the most likely period for severe wind erosion—crop stubble should be more nearly like our simulated stubble. Also, natural winds differ in speed and direction, in convective components of turbulence (usually), and in length scale from those in laboratory wind tunnels.

In a previous study the dominant term in an equation for $(u_*/u_{*t})_S$ was H/L_x (Lyles et al. 1974). Here, we included much larger heights and fewer elements so that the dominant term is $\frac{NA_s}{A_t} = \frac{HD}{L_yL_x}$ (equation [2]). Comparing the equations for realistic values of plant population and stubble height indicated that equation [2] gave considerably lower values for $(u_*/u_{*t})_S$ under similar conditions (Table 1).

TABLE 1. COMPUTED VALUES OF $(u_*/u_{*t})_s$ FROM EQUATION [2] AND AN EQUATION USED IN A PREVIOUS STUDY FOR SELECTED CROPS AND STUBBLE DATA.

Crop	Population, stalks/ha	Height, cm	$(u_*/u_{*t})_s$*	
			Eqn [2]	Earlier study†
Wheat	3,706,500	30.48	6.87	24.23
Wheat	3,706,500	15.24	4.20	12.67
Wheat	3,706,500	2.54	1.97	3.04
Sorghum	107,600	45.72	3.01	7.02
Sorghum	107,600	30.48	2.51	5.05
Sorghum	107,600	15.24	2.01	3.08
Corn	61,800	60.96	3.15	7.09
Corn	61,800	30.48	2.34	4.10
Corn	61,800	15.24	1.93	2.61

*Assumes uniform spacing of standing stalks and stalk diameter: 0.278, 1.77, and 2.54 cm for wheat, sorghum, and corn, respectively.
†Lyles et al 1974.

TABLE 2. EFFECT OF STALK ORIENTATION TO WIND DIRECTION ON THE EROSION PROTECTION (EQUATION [2]) OF SOIL PROVIDED BY WHEAT, GRAIN SORGHUM, AND CORN.

Crop	Height, cm	Stalks, no/ha	Uniform	Orientation, normal*	Parallel*
				$(u_*/u_{*t})_s$†	
Wheat	30.48	3,706,500	6.87	6.99	4.19
Sorghum	30.48	107,600	2.51	2.62	1.32
Corn	30.48	61.800	2.34	2.43	1.71

*Assumes wheat is in 25.4-cm rows; sorghum and corn in 101.6-cm rows, with corresponding stalk diameters of 0.278, 1.77, and 2.54 cm, respectively.
†Assumes soil is all erodible particles.

Differences between the equations increased as both height and plant population increased, because these two variables were limited in the earlier work. Practically, such differences suggested that the protective role of height decreased as height increased, especially if plant spacings were also increased.

The qualitative effects of orientation on wind-erosion protection are being published elsewhere.* General conclusions (from that paper) indicated that equidistant spacing of stalks, regardless of wind direction, would protect the soil from wind erosion equally well and that the protection would equal that of stalks in rows always oriented perpendicular (normal) to wind direction.

Quantitative effects indicated that typical plant populations grown in rows normal to wind direction have CFVR's 1.4 to 2.0 times larger than those in rows parallel with wind direction (Table 2). Siddoway et al. (1965) reported that growing winter wheat oriented in rows normal to the wind was about 1.4 times as effective in preventing soil erosion as in rows parallel with wind (23-cm row spacing). Although stalks in rows normal to wind seemed slightly more effective than those uniformly spaced, the experimental data showed no differences. However, the difference between normal and uniform CFVR in equation [2] can never exceed 0.117 (the coefficient of L_y/L_x).

The term NA_s/A_t in equation [2] is a three-way interaction among stalk number, height, and size. Consequently, to examine the effect of one variable on wind-erosion protection (CVFR), the level of the other variables must be specified (Table 3). If wheat stubble were cut to 5.08 cm (to be baled for straw), doubling the stalk population would have a small effect on protecting soil against wind erosion (Table 3). In contrast, doubling the stalk population when height is 30.48 cm would appreciably increase erosion protection (Table 3). Because field plant populations for nonirrigated grain sorghum or corn are limited, doubling the height or stalk population would not greatly change $(u_*/u_{*t})_s$ (Table 3).

Chepil (1944) concluded that one blade of 15.24-cm wheat stubble provided more soil protection than three blades of 5.08-cm stubble. Our data (equation [2]) indicated they are of equal value if standing. Perhaps, stalk diameter (D) would be slightly larger for the lower plant population (one blade). Then, our data would agree with Chepil's conclusion.

On a weight basis, our data indicated that 5.5 times more standing sorghum stubble than standing wheat stubble would be needed to provide the same wind-erosion protection (Table 4). The corresponding value for standing corn stubble was 8.7; thus, about 1.6 times more corn stubble than sorghum would be required to provide equal protection (using the assumptions in Table 4).

Computations from data of Siddoway et al. (1965) revealed that to reduce wind-tunnel soil losses from small trays to "insignificant" amounts, about five times more standing fine-sorghum stubble than wheat stubble is required. The wind-erosion equation shows about four times more standing sorghum residue than wheat is required to hold soil losses to 11.2 mt/ha/yr (Woodruff et al. 1972). Generally, corn and sorghum residues presumably equally control wind erosion (Hayes 1972). This reasoning assumes that all the plant, except the grain, remains in the field, where the size of the cornstalk (larger in diameter and length than sorghum stalk) compensates for its plant population (less than sorghum's).

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TABLE 3. THE EFFECT OF STALK HEIGHT AND PLANT POPULATION OF WIND-EROSION PROTECTION PROVIDED BY SEVERAL CROPS.

Crop	Height, cm	Plant population, stalks/ha	$(u_*/u_{*t})_s$*	Change
Wheat	5.08	2,471,000	2.12	
Wheat	5.08	4,942,000	2.71	0.59
Wheat	30.48	2,471,000	5.09	
Wheat	30.48	4,942,000	8.66	3.57
Sorghum	22.86	107,600	2.26	
Sorghum	45.72	107,600	3.01	0.75
Sorghum	45.72	86,500	2.71	
Sorghum	45.72	173,000	3.91	1.20
Corn	30.48	61,800	2.34	
Corn	60.96	61,800	3.15	0.81
Corn	15.24	37,100	1.77	
Corn	15.24	74,100	2.01	0.24

*Assumes soil is all erodible particles; stalks are uniformly spaced; and stalk diameters are 0.278, 1.77, and 2.54 cm for wheat, sorghum, and corn, respectively.

TABLE 4. WEIGHTS OF STANDING CROP RESIDUES REQUIRED TO PROVIDE EQUAL WIND-EROSION PROTECTION (CFVR); EQUATION [2].

Crop	Plant population, stalks/ha	Residue weight,* kg/ha	Ratio to wheat
Wheat	2,471,000	492	1.0
Sorghum	123,600	2,737	5.5
Corn	61,800	4,293	8.7

*Assumes standing stalks only with bare intervening surface, all erodible soil particles, CFVR = 3.97, stalk diameters of 0.278, 1.77, and 2.54 cm for wheat, sorghum, and corn, respectively, with corresponding stalk densities of 0.157, 0.137, and 0.15 g/cm^3.

TABLE 5. CRITICAL FRICTION-VELOCITY RATIOS $(u_*/u_{*t})_s$ BELOW WHICH NO SIGNIFICANT EROSION WOULD OCCUR FOR STANDING STUBBLE AND SELECTED AMOUNTS OF SOIL CLODDINESS (C).

Crop*	Population, stalks/ha	Height, cm	C, % > 1.0 mm	$(u_*/u_{*t})_s$†
Wheat	3,706,500	25.4	0	5.98
Wheat	3,706,500	25.4	10	6.24
Wheat	3,706,500	25.4	25	6.77
Wheat	3,706,500	25.4	50	8.19
Sorghum	107,600	40.64	0	2.84
Sorghum	107,600	40.64	10	3.10
Sorghum	107,600	40.64	25	3.63
Sorghum	107,600	40.64	50	5.05
Corn	61,800	45.72	0	2.74
Corn	61,800	45.72	10	3.00
Corn	61,800	45.72	25	3.53
Corn	61,800	45.72	50	4.95

*Stalk diameters of 0.278, 1.77, and 2.54 cm for wheat, grain sorghum, and corn, respectively.

†Computed from equation [4].

Soil cloddiness adds a significant amount of protection to that provided by standing crop residues (Table 5). For example, 50 percent of aggregates greater than 1.0 mm diameter would provide the same protection as would 107,600 stalks/ha of standing grain sorghum 21.2 cm tall (equation [2]).

As an example for determining total soil removal, consider grain sorghum stubble with $H = 45.72$ cm; $L_y = L_x = 30.48$ cm; $D = 1.77$ cm, and $C = 0$. From equation [4], $(u_*/u_{*t})_s = 3.006$. Let $(u_*/u_{*t})_e = 3.100$; thus, $H_e = 48.63$ cm, and $H_\Delta = 2.91$ cm. Then, from equation [5], $Q_T = 2.90\ \gamma_B$ g/cm³ (or 290 γ_B mt/ha). The bulk density, γ_B ranges from about 1.1 for clays to 1.5 for sands; thus, $Q_T = 435$ mt/ha if the soil is sand (as implied from $C = 0$). Additional protection from stubble must be limited to some realistic depth of soil removal, perhaps 2 to 5 cm, or the entire stalk may be uprooted during erosion.

To demonstrate the utility of equation [4] and illustrate the protective role of soil aggregates, consider the sorghum stubble data in the previous example and assume a loamy sand with 10 percent aggregates greater than 1.0 mm ($C = 10$). From equation [4], $(u_*/u_{*t})_s = 3.268$. Because $(u_*/u_{*t})_s$ is larger than $(u_*/u_{*t})_e$, no soil would erode for the selected value of $(u_*/u_{*t})_e$. Consequently, the outlined procedures may be used to answer these questions: Will soil erode? What will be the total amount of soil eroded for a given wind-soil-stubble condition?

SUMMARY

Using a wind tunnel, we studied the protection for erodible soil particles provided by simulated standing-stubble height, size, spacing, and orientation.

The amount of protection was expressed in terms of dimensionless parameters characterizing the flow (wind), particles, and stubble properties. We called the dimensionless dependent variable $(u_*/u_{*t})_s$ the critical friction-velocity (CFVR) because, if it was exceeded, the soil began to erode—the larger the ratio, the greater the wind-erosion protection. For typical plant populations, stalks uniformly spaced or in rows normal to wind direction had CFVR's 1.4 to 2.0 times larger than those of stalks in rows parallel with wind.

Results indicated that on a weight basis, at common plant populations, 5.5 times more standing grain sorghum stubble and 8.7 times more standing corn stubble that wheat stubble were needed to provide the same wind-erosion protection (CFVR).

From others' work, we determined the protective role of nonerodible aggregates and incorporated their results into our equation for standing stubble so that we could consider the combined effect of stubble and nonerodible aggregates.

Finally, a procedure was outlined for determining the total amount of soil eroded by wind for a given soil-stubble condition.

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