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Assessing Wind Erosion Forces: Directions and Relative Magnitudes[1]

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ABSTRACT

Wind erosion force vectors were computed from data of frequency of occurrence of directions by windspeed groups based on wind erosion being proportional to windspeed cubed times the duration of the wind. The vectors were obtained by evaluating $\Sigma\ \overline{U}_i^3\ f_i$ for each of the 16 principal directions where $\overline{U}_i^3$ is the cubed mean windspeed within the ith speed group and f_i is percentage of total observations that occur in the speed group and direction under consideration.

The wind erosion force vectors were used to compute monthly magnitudes of the total wind erosion forces and direction where the ratio of the wind erosion forces parallel and perpendicular to that direction is a maximum. The computed direction indicates proper orientation of a wind barrier for maximum barrier protection. The magnitude of the ratio gives the preponderance of wind erosion forces in the direction of maximum wind erosion forces. The magnitude of the total wind erosion forces indicates the potential need for protection against the erosion forces.

In planning ways and means to reduce the hazard of soil erosion by wind, one needs to know (i) the capacity of the wind to cause erosion on unprotected soils, (ii) prevailing wind erosion direction or direction of maximum wind erosion forces, (iii) preponderance of wind erosion forces in the direction of maximum wind erosion forces or directional distribution of wind erosion forces, and (iv) how these factors change throughout the year. These factors indicate potential need for wind erosion protection, proper orientation of a suitable barrier to reduce the effect of the wind erosion forces, and relative merits of proper orientation of a barrier, respectively.

This paper presents a method of analyzing wind data

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to assess the capacity of a wind to cause erosion, prevailing wind erosion direction, and preponderance of wind erosion forces in the prevailing wind erosion direction.

ANALYSIS

One general use of the term "force" is that of denoting an operating agency (7). It is further defined as the capacity to persuade (8). These definitions of force are incorporated in the definition of wind erosion forces. They are defined as the capacity of a wind (the operating agency) to cause or persuade soil movement.

When wind erosion forces are acting on a highly erodible soil, soil movement will occur in proportion to the magnitude of the wind erosion forces. Whereas if the wind erosion forces are operating on soil that is extremely resistant to wind erosion, only a small amount of soil movement will occur.

The analysis is based on the principle that the capacity of a wind to cause soil movement is proportional to windspeed cubed times the duration of the wind.

Several investigators (1, 3, 9) found that when windspeed was greater than that required barely to move the soil, the rate of soil movement was directly proportional to friction velocity cubed. The friction velocity, U_*, is related to velocity profile as expressed by

$$U_* = \frac{U_z}{5.75 \log z/k} \quad [1]$$

where U_z is the windspeed at height z. Over a specified type of surface and height z, z and k are constant (1, 4). Therefore, U_*, is proportional to U_z and rate of soil movement is proportional to the windspeed cubed after the windspeed attains some minimum or threshold speed required to initiate soil movement.

Threshold speeds were reported by Chepil (2) to range from 13 to 30 miles/hour at 1-foot height depending on the previous history of the field. A threshold speed of about 11 miles/hour at 30 cm was indicated for the conditions of another investigation (3). Malina (6) reported data of O'Brien and Rindlaub in which the amount of sand transported was proportional to windspeed cubed after the windspeed reached a "critical velocity" of 13.4 feet/sec (9.1 miles/hour).

Wind data are commonly reported in climatological records by speed groups. One common division is between 12 and 13 miles/hour. This speed corresponds closely to what has been reported as the minimum windspeed required to initiate soil movement. Therefore, windspeeds 12 miles/hour and less are considered nonerosive and were not used in the computations of wind erosion forces in this study.

Magnitude of Wind Erosion Forces

The magnitude of a wind erosion force vector, r_j, is obtained by summing, for all speed groups with windspeeds greater than 12 miles/hour, the product of mean windspeed cubed and a duration factor for a specified direction as expressed by equation [2].

$$r_j = \sum_{i=1}^{n} \bar{U}_i^3 f_i \quad [2]$$

where $\bar{U}_i^3$ is the mean windspeed within the ith speed group. f_i is a duration factor which is expressed as the percentage of the total observations that occur in the ith direction within the ith speed group. The sub j's indicate direction and take on values from 0 to 15, inclusive, representing the 16 principal compass directions. They are numbered counterclockwise, starting with east, which is arbitrarily taken as the initial side of the coordinate system. Hence, $r_{j=0}$ and $r_{j=1}$ are wind erosion force vectors pointing east and east-northeast, respectively.

The sum of the magnitudes of the wind erosion force vectors for all directions gives the total magnitude of wind erosion forces for the location and is expressed by equation [3]. The value obtained by evaluating equation [3] for some location indicates the relative capacity of the wind to cause soil blowing at the particular location.

$$F_T = \sum_{j=0}^{15} \sum_{i=1}^{n} \bar{U}_{ij}^3 f_{ij} \, . \quad [3]$$

If we divide equation [2] by equation [3], we get equation [4]

$$r'_j = \frac{\sum_{i=1}^{n} \bar{U}_i^3 f_i}{\sum_{j=0}^{15} \sum_{i=1}^{n} \bar{U}_{ij}^3 f_{ij}} \quad [4]$$

which expresses wind erosion force vectors as relative values and where the sum of the r'_j's from j=0 to 15 is unity. The mean value for r'_j is 0.0625.

Parallel and Perpendicular Wind Erosion Forces

The magnitude of erosion forces parallel to a particular direction can be obtained from the wind erosion force vectors. If p is an imaginary straight line intersecting at the origin of a polar coordinate system and ϕ_j is the angle between r_j and the imaginary line p, the amount of erosion forces caused by r_j that occur parallel to p is $r_j \cos \phi_j$.

The total wind erosion forces parallel to p are

$$\sum_{j=0}^{15} r_j \left|\cos\phi_j\right| = r_0 \left|\cos\phi_0\right| + r_1 \left|\cos\phi_1\right| + \ldots + r_{15} \left|\cos\phi_{15}\right| . \quad [5]$$

All values of the trigonometric functions are taken as positive in this analysis as indicated by the absolute value signs. Otherwise wind erosion force vectors in opposite directions would subtract from each other.

Angle ϕ is a function of the orientation of p and of the angular distance between consecutive r_j. The relationship is defined by

$$\phi_j = j \times 22.5 - \theta \quad [6]$$

where θ is the angle between p and the initial side.

The total wind erosion forces parallel to p as a function of the orientation of p is

$$F_{\parallel} = \sum_{j=0}^{15} r_j \left|\cos(j \times 22.5 - \theta)\right| . \quad [7]$$

Similarly, the sum of the wind erosion forces perpendicular to p is

$$F_{\perp} = \sum_{j=0}^{15} r_j \left|\sin(j \times 22.5 - \theta)\right| . \quad [8]$$

When p is oriented so that equation [7] is maximum, p represents a line through which the greatest amount of wind erosion forces occur, the direction of maximum wind erosion forces.

To find the orientation of p when equation [7] is maximum is cumbersome. Two methods may be used; each is tedious. The calculus method for finding maxima and minima may be used. For this method, values of θ are found by successive approximation when $\Sigma r_j \sin (j \times 22.5 - \theta)$ is zero. One could then judiciously select the θ, where $\Sigma r_j \sin (j \times 22.5 - \theta)$ is zero, that corresponds to absolute maximum for $\Sigma r_j \cos (j \times 22.5 - \theta)$.

The other method is to select several values for θ so that p will sweep through the region where $\Sigma r_j |\cos (j \times 22.5 - \theta)|$ maximum will occur and compute $\Sigma r_j |\cos (j \times 22.5 - \theta)|$ for each θ; select the region where $\Sigma r_j |\cos (j \times 22.5 - \theta)|$ is greatest and repeat. This process may be repeated until the desired accuracy is obtained for the value of θ when $\Sigma r_j |\cos (j \times 22.5 - \theta)|$ is maximum.

The second method described for finding the direction of maximum wind erosion forces is better than the first. The first derivative of $\Sigma r_j |\cos (j \times 22.5 - \theta)|$ is a discontinuous function. Several zero points may occur; one must be able to ascertain the maximum from a relative maximum. By comparing values for $\Sigma r_j |\cos (j \times 22.5 - \theta)|$, one can easily select the largest.

The Maximum-Minimum Ratio for Barrier Orientation

When considering orientation of barriers for protection against wind erosion forces, one needs to consider the wind erosion forces that will occur parallel to the barrier as well as those that occur perpendicular.

Since the direction of minimum wind erosion forces is not always perpendicular to the direction of maximum wind erosion forces, to orient wind barriers perpendicular to the direction of maximum wind erosion forces will not guarantee that the parallel wind erosion forces be a minimum, nor will it indicate the relative magnitudes of the wind erosion forces perpendicular to each other.

A useful parameter is the ratio of the wind erosion forces parallel to line p to those perpendicular to line p.

Obtaining an orientation of line p so that this ratio, symbolized R, is maximum, tends to maximize wind erosion forces parallel to p and also minimize wind forces perpendicular to p. The direction of parallel-maximum and perpendicular-minimum may deviate some from the direction of maximum wind erosion forces but it is an improved guide for orientation of wind barriers.

The greater the value of R maximum, the greater the prevalence of the prevailing wind erosion direction. A value for R maximum of 1.0 indicates no prevailing wind erosion direction and a wind barrier would be equally effective in any direction. Whereas, an R maximum of 2.0 indicates a prevailing wind erosion direction with wind erosion forces twice as great parallel as perpendicular to prevailing wind erosion direction.

The ratio is computed by dividing equation [7] by equation [8]

$$R = \frac{\sum_{j=0}^{15} r_j \left|\cos(j \times 22.5 - \theta)\right|}{\sum_{j=0}^{15} r_j \left|\sin(j \times 22.5 - \theta)\right|} \quad . \qquad [9]$$

The greatest value for R, symbolized R_m, is found in the same manner as is direction of maximum wind erosion forces. The orientation of p when R is maximum is called direction of parallel-maximum perpendicular-minimum and is symbolized θ_R. θ_R may also be considered as being the prevailing wind erosion direction. R_m indicates the preponderance of wind erosion forces in the prevailing wind erosion direction.

The relative magnitude of wind erosion forces parallel to p at θ_R from opposite directions can be evaluated by equations [10] and [11]

$$F_{\parallel}+ = \frac{\Sigma r_j \cos(j \times 22.5 - \theta)}{\sum_{j=0}^{15} r_j \left|\cos(j \times 22.5 - \theta)\right|} \qquad [10]$$

$$F_{\parallel}- = \frac{\Sigma r_j \cos(j \times 22.5 - \theta)}{\sum_{j=0}^{15} r_j \left|\cos(j \times 22.5 - \theta)\right|} \qquad [11]$$

where for the numerators of equations [10] and [11] $r_j \cos(j \times 22.5 - \theta)$ is summed for all r_j within $\pm$ 90 degrees of θ and from +90 to +270 degrees, respectively. $F_{\parallel}+$ will be positive and $F_{\parallel}-$ negative. The sum of the absolute values of $F_{\parallel}+$ and $F_{\parallel}-$ is unity.

RESULTS AND DISCUSSION

The data of frequency of occurrence, directions by windspeed groups were obtained from records of the US Weather Bureau and the Air Weather Service, Department of the Air Force. Periods covered by the records ranged from 5 to 11 years for the locations used in this analysis.

Magnitude of wind erosion forces, direction of parallel-maximum perpendicular-minimum wind erosion forces, maximum ratio of parallel to perpendicular wind erosion forces, and relative amounts of parallel wind erosion forces from opposite directions were obtained by the methods described above for sample locations in the Great Plains (Albuquerque, N. M.; Great Falls, Mont.; Midland, Texas; and Salina, Kans.).

The magnitudes of the wind erosion forces are presented on a monthly basis in Fig. 1. The strongest wind erosion forces for Albuquerque, Midland, and Salina occur in the spring. However, erosive winds are greater in the winter months for Great Falls. The wind erosion forces for Great Falls are much greater than for the other three locations.

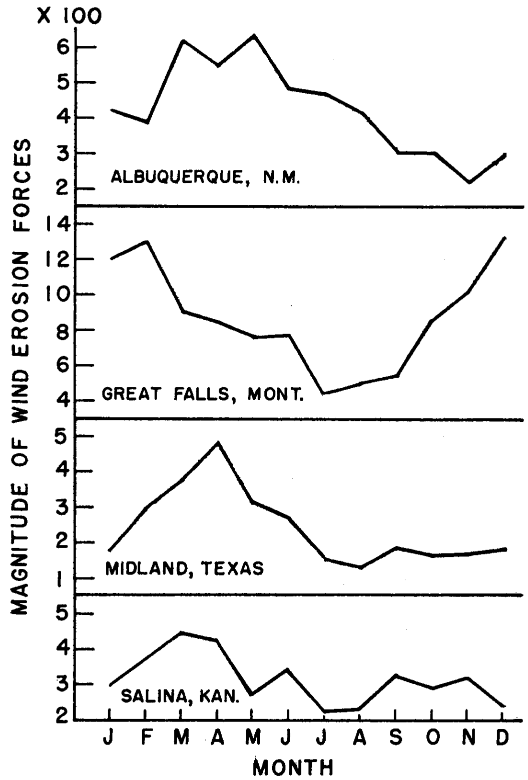

Fig. 1—Monthly magnitudes of wind erosion forces for the locations indicated.

The mean windspeed for a particular locality may be misleading as an index for the erosive potential of the wind. Erosive influence of the wind increases as the cube of the windspeed. Doubling windspeed causes an eight-fold increase in erosion potential. Theoretically, a 40-mile-per-hour wind of 1 hour's duration is equivalent to a 20-mile-per-hour wind of 8 hours' duration. The average windspeeds (annual) for Midland and Albuquerque were 9.7 and 9.0 miles/hour, respectively. Although Midland had a higher average windspeed, the wind erosion forces as calculated by equation [4] for Midland were lower; 210 compared with 445 for Albuquerque.

The maximum ratio of parallel to perpendicular wind erosion forces is shown in Figure 2. The smallest value of the ratio was 1.06 at Midland for April. This indicates that a wind barrier would be, for all practical purposes, equally effective at any orientation. April is also the month of strongest wind erosion forces (Fig. 1).

The greatest value for R maximum occurred in Great Falls where the wind erosion forces parallel to the direction indicated in Fig. 2 were 3.6 times as great as the perpendicular wind erosion forces. December was also the month of strongest wind erosion forces (Fig. 1).

The length of line on either side of the dot in Fig. 2 indicates the relative amounts of the parallel wind erosion forces from opposite directions. A dot one-third of the distance up on a line pointed in the N-S direction indi-

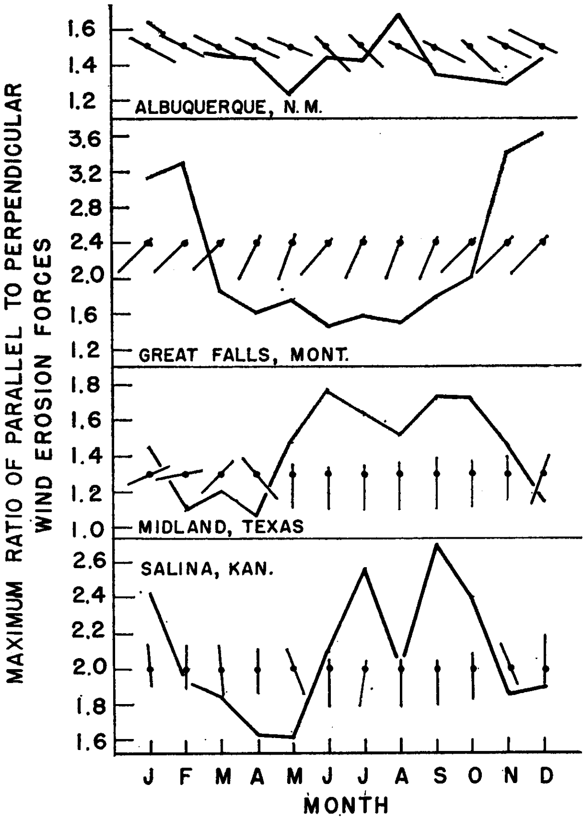

Fig. 2—The maximum ratio of parallel to perpendicular wind erosion forces and the relative amounts of parallel forces from opposite directions indicated by the position of the dot in the line pointing in the prevailing wind erosion direction.

cates that one-third of the wind erosion forces parallel to N-S are from the south and two-thirds are from the north.

The lines with a dot in them in Fig. 2 are pointed in the direction in which the ratio of wind erosion forces parallel to wind erosion forces perpendicular is maximum. The results agree very closely with the graphical method of Chepil et al. (5) of determining prevailing wind erosion direction for Great Falls and Salina but differ by 22 and 14 degrees, respectively, for Albuquerque and Midland.

Wind barriers cannot always be oriented for maximum protection. Therefore, it is useful to know something of the consequence of orienting the barrier at some alternative direction. Fig. 3 gives the Ratio R of parallel to perpendicular forces as a function of the orientation of the barrier.

R_m and θ_R are 1.38 and 155 degrees, respectively. For protection against wind erosion forces the optimum barrier orientation is perpendicular to θ_R, 65 or 245 degrees. At this orientation the wind erosion forces that occur penpendicular to the barrier are 1.38 times the magnitude of wind erosion forces occurring parallel to the barrier.

It may not be physically feasible to orient the barrier

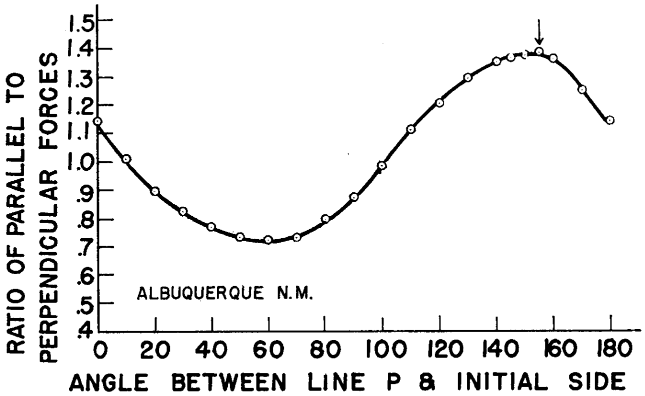

Fig. 3—Ratio of parallel to perpendicular forces as a function of orientation (annual data).

for optimum protection. Suppose that because of the physical layout of the field a barrier could more conveniently be oriented ± 25 degrees from the optimum. R is not symmetrical about R_m and a barrier would give more protection oriented perpendicular to R_m —25 degrees than perpendicular to R_m +25 degrees. At R_m +25 degrees and R_m —25 degrees, R is 1.14 and 1.29, respectively.

Because of the field layout it may be desirable to orient barriers only in N-S or E-W direction. In this example (Fig. 3) it would be better to orient the barrier in the N-S than E-W direction. For a barrier oriented in the N-S direction, R has a value of 1.15. The value of 1.15 indicates only a slight preponderance of wind erosion forces perpendicular to the proposed barrier.

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