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THE PHYSICS OF WIND EROSION AND ITS CONTROL[1]

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Page

Notation

Basic dimensions of terms used are indicated in parenthesis by dimensional symbols m, l, t, and f, denoting mass, length, time, and weight or

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force, respectively. Units of English or metric system are given after the dimensional symbols. Pages where each term is used first also are listed. Log values in this review are all to base 10, unless otherwise indicated.

Symbol		*Page*
a, b, c	Empirical constants, coefficients, or exponents in various equations; their values differ in different equations (dimensionless)	220, 262, 262
A	Proportion of fractions > 0.84 mm. (as determined by standard dry seiving) in a soil (dimensionless); per cent	292
A_v	Weight of soil abraded per unit weight of abrader blown by wind of velocity v (dimensionless)	251
A_r	Aerodynamic surface roughness (l); cm., in.	219
B	Percentage of nonerodible clods > 0.84 mm. in diameter in a soil (dimensionless); per cent	263
C	Local climatic factor in the wind erosion equation (dimensionless); per cent	292
C_a	Dust concentration at 6 feet above ground (f/l^3); mg./cu. ft.	246
C_m	Total dust load in the atmosphere up to 1 mile high (f/l^3); tons/cu. mi.	247
C_z	Dust concentration at height z (f/l^3); mg./cu. ft.	246
c.g.	Center of gravity (dimensionless)	223
D	Diameter of a soil particle or grain (l); cm., mm.	224
D_e	Equivalent diameter of a soil particle or grain (l); cm., mm.	245
D_b	Distance (along prevailing wind erosion direction) of full protection from wind erosion afforded by a surface barrier adjoining a field (l); ft.	292
D_f	Distance across a field (along prevailing wind erosion direction) (l); ft.	292
D_s	Distance between surface wind barriers (l); ft.	271
D_h	Zero displacement height—a vertical displacement of a wind velocity gradient by vegetation or other roughness elements of the ground surface (l); cm., in.	218
E	Potential average amount of erosion or soil loss by wind ($f/l^2/t$); tons/acre/annum	294
η	Ratio of mean drag and lift per unit area on the whole soil bed to mean drag and lift per unit area on the top grain moved by wind (dimensionless)	224
ϕ	Angle of repose of a grain on the ground with respect to the mean drag level of the wind (degrees)	224
F_c	Threshold drag on the top grain on a soil bed (f); dynes	223
F'_c	Threshold drag per unit horizontal area occupied by the top grain on a soil bed (f/l^2); dynes/sq. cm.	224
F_s	Mechanical stability of a surface soil crust (dimensionless); per cent	292
G	Percentage of clay in the soil (dimensionless); per cent	262
g	Acceleration of gravity (l/t^2); cm./sec./sec., ft./sec./sec.	224
H	Height of wind barrier or projection on the ground surface (l); ft., in., cm.	271
I_w	Soil erodibility index. It is equal to X_2/X_1 in which X_1 is the quantity eroded from an area not exceeding 30 feet in length along wind erosion direction when the soil contains 60 per cent of clods > 0.84 mm. in	

Symbol		*Page*
	diameter, and X_2 is the quantity eroded under the same set of conditions and time from soil containing any other proportion of clods $>$ 0.84 mm. in diameter (dimensionless)	246
I	Soil erodibility (potential average annual soil loss from an unsheltered, wide, and isolated field with a smooth, bare, and noncrusted surface under climatic conditions like those at Garden City, Kansas ($f/l^2/t$); tons/acre/annum	292
k	Height above Z_0 where the forward average wind velocity above a noneroding surface is zero (l); cm., in.	217
k'	Height above Z_0 where wind velocity above an eroding surface is constant no matter how strongly the wind blows (l); cm., in.	222
K	Soil surface roughness expressed as ridge roughness equivalent (l); in., cm.	292
K_0	Orientation of vegetative cover factor in the wind erosion equation (dimensionless)	292
K_t	Total surface roughness. It is equal to $D_h + A_r$ (l); cm., in.	219
L	Equivalent field width in the wind erosion equation (l); ft.	292
L_c	Lift on the top grain on the ground at the threshold drag F_c on the grain (l); dynes	223
M_e	Equivalent moisture—a ratio of water content of a soil to water content at 15 atmosphere percentage (dimensionless)	237
M	Average moisture of a soil surface	292
N	Number of numbers in a statistical analysis (dimensionless)	232
ν	Kinematic viscosity of air (l^2/t); sq. cm./sec.	238
$\overline{P}$	Mean pressure of lift and drag on the top grain on the ground (f/l^2); dynes/cm.^{2}	226
P-E	Effective precipitation of Thornthwaite (1931) (dimensionless)	234
q	Rate of soil flow (weight of soil moved past a unit width normal to direction of flow and of unlimited height, per unit time) ($f/l/t$); g./cm./sec.	245
Q	Maximum wind velocity for a specified unit of time (l/t); cm./sec., mi./hr.	233
Q_a	Average of the maximum wind velocities for a specific continuous period (l/t); cm./sec., mi./hr.	233
Q_m	Wind velocity equaled or exceeded on an average of once in t years, called recurrence interval (l/t); cm/sec., mi./hr.	232
Q'	Three-year running average wind velocity (l/t); cm./sec., mi./hr.	233
r	Resistance of discrete soil grains against the force of wind, due to cohesion of water film on the surface of the grains. Like wind drag, it is expressed in units of force acting parallel with the ground per unit area of the ground (f/l^2); dynes/sq. cm.	250
R	Quantity (oven-dry weight times 1.2) of vegetative cover per unit area of ground (f/l^2); lb./acre	292
ρ	Density (weight per unit volume) of air (f/l^3); g./cc.	220
ρ/g	Mass density of air (m/l^3); g./cm.^{2}/sec./sec.	220
ρ'	Difference between the density (weight per unit volume) of soil grain and air, known as immersed density of the grain (f/l^3); g./cc.	224
ρ_e	Density (weight per unit volume) of dry erodible soil grains (f/l^3); g./cc.	237

Symbol		Page
ρ_u	Density (weight per unit volume) of dry nonerodible soil aggregates (f/l^3); g./cc.	273
S	Kind of vegetative cover factor in the wind erosion equation (dimensionless)	292
σ	Standard deviation (expressed in same units that the population to which it refers is expressed)	226
t	Recurrence interval of a specific climatic event (t); years	232
T	Turbulence factor—a ratio of "maximum" to mean drag and lift on the top grain on the ground, assuming the ratio to be equal for both drag and lift. It is taken as $(\bar{P} + 3\sigma)/\bar{P}$ (dimensionless)	224
$\bar{\tau}$	Mean wind drag per unit horizontal area of the ground surface (f/l^2); dynes/sq. cm.	220
τ_c	Threshold drag per unit horizontal area of the ground surface, where τ_c is uniform (f/l^2); dynes/sq. cm.	224
$\bar{\tau}_c$	Mean threshold drag per unit horizontal area of the entire ground surface (f/l^2); dynes/sq. cm.	225
V	Equivalent quantity of vegetative cover in the wind erosion equation (f/l^2); lb./acre	292
V_d	Daytime visibility distance of a dusty atmosphere (l); mi.	246
V_*	Drag velocity above a noneroding ground surface (l/t); cm./sec., mi./hr.	218
V'_*	Drag velocity above an eroding ground surface (l/t); cm./sec., mi./hr.	222
V_{*t}	Threshold drag velocity, i.e., minimal drag velocity required to initiate soil movement (l/t); cm./sec., mi./hr.	242
V_t	Wind velocity at height k' above an eroding surface (l/t); cm./sec., mi./hr.	222
v	Wind velocity (l/t); cm./sec., mi./hr.	251
v_t	Threshold wind velocity, i.e., minimal velocity at some specified height z required to initiate soil movement (l/t); cm./sec., mi./hr.	243
v_z	Wind velocity v at height z (l/t); cm./sec., mi./hr.	218
X	Quantity of soil material removable by wind (of specified drag velocity) from the surface of not more than 30 feet of ground along wind erosion direction (f/l^2); tons/acre	245
y	An expression in the Gumbel (1941, 1945) equation indicating frequencies of rain or windstorms of various intensities at a given location. It is equal to $\log_e[-\log_e(1 - 1/t)]$ with t expressed in years	233
Y	Percentage of water-stable particles < 0.02 mm. and > 0.84 mm. in diameter as determined by wet sieving of soil (dimensionless); per cent	263
Z_0	Mean aerodynamic surface—a surface above which the turbulent air flow is unrestricted or "free" compared with restricted, sometimes laminar flow (as though vegetation) below Z_0 (dimensionless)	217
z	Height above Z_0 (l); cm., in., ft.	218

I. Introduction

In many countries throughout the world, wind erosion has depleted the fertility of the soil, and in some it has transformed the fertile soils into sandy deserts. Substantial portions of central Asia, the Middle

East, and North Africa were once fertile lands supporting prosperous populations, but through improper land use and soil exhaustion they changed to their present barren state. The downfall of ancient civilizations such as those of Greece and Rome is a story of depletion of grasslands and forests, soil erosion, and soil ruin.

In North America, relatively little wind erosion occurred while land was under natural vegetation. It accelerated after man began to overgraze and overcultivate the land. It became worse in the Great Plains, the semiarid and subhumid area that extends almost from the Mississippi River to the Rocky Mountains and from the Gulf of Mexico into the Prairie Provinces of Canada.

The first, and probably the last, serious wind erosion in the Great Plains occurred during the 1930's. The general realization of the great economic losses caused by wind erosion during that period helped to stimulate serious attention to its basic causes, effects, and remedies. Soil surveys of the Great Plains were initiated to aid in stabilizing agriculture in that area. Emergency wind erosion control programs were established and administered by the various States and by Federal agencies. Special wind tunnels were developed and used to study the wind erosion problem continually, not just when it occurred in the field. Numerous papers and bulletins were published on wind erosion and control. The publications on the subject, though voluminous, have been fragmentary and somewhat lost in the literature of argiculture and related fields. This review is the first attempt to bring the research information together into an analysis of the subject as a whole.

The subject deals with movement and abrasion of soil by wind. Movement is initiated when the pressure of the wind against the surface soil grains overcomes the force of gravity on the grains. The grains are moved along the surface of the ground in a series of jumps known as saltation. The higher the grains jump, the more energy they derive from the wind. The concentration (number per unit volume) of saltating grains increases with distance downwind till, if the eroding field is large enough, it becomes the maximum that a wind of a particular velocity can sustain. The impacts of the saltating grains initiate movement of larger and denser grains and of smaller dust particles. The saltating grains collide against massive materials and other grains and cause disintegration of all involved. The disintegrated units exhibit different degrees of mobility and sort into different erosion products, such as lag sands, lag gravels, dunes, and deposited dust (loess).

Wind erosion occurs only when soil grains capable of being moved in saltation are present in the soil. Comparatively few saltating grains jump higher than a few feet above the ground. Over 90 per cent generally do not rise higher than 1 foot. Therefore, wind erosion is essentially a surface phenomenon extending to saltation height. Dust clouds are merely the result of movement in saltation.

The above-mentioned processes and products of wind erosion constitute only part of the physics of wind erosion and its control. The subject includes the intricate processes and conditions that cause erosion and the counteracting processes and conditions that suppress it. The severity of wind erosion depends on equilibrium conditions between soil, vegetation, and climate. Wind erosion is accelerated by processes that cause surface soil structural disintegration and depletion of vegetative cover. Conversely, wind erosion is hindered by stabilization processes such as soil consolidation and aggregation and by vegetation and vegetative residue developing on the surface. The speed or intensity of all the processes fluctuates considerably with vagaries of the weather and with various land uses.

The subject includes causes, effects, and remedies of wind erosion. Processes of soil destabilization, soil erosion, and soil stabilization must be understood to design effective and lasting methods of wind erosion control.

To design suitable methods of wind erosion control, soil conservationists must know the conditions that influence wind erosion and how to evaluate the relative significance of each condition. Procedures have been developed to supply them with the so-called wind erosion equation which can be used to estimate the potential amount of wind erosion from measured conditions of the field. Conversely, the equation may be used to estimate the conditions needed to reduce wind erosion to any degree. The procedures are outlined briefly in Section VII of this review.

II. The Surface Wind

A. Drag Velocity and Drag on Noneroded Surfaces

Wind structure near the ground directly influences the movement of soil by wind. A wind strong enough to produce soil movement is always *turbulent*; that is, its flow is characterized by eddies moving at variable velocities and in all directions. The average forward velocity, generally regarded as velocity, of a turbulent wind near the ground increases with height according to an exponential law. Zero velocity is somewhere above the average roughness elements of the surface. The taller the roughness elements of the ground, or the taller and less air-permeable the vegetative cover, the higher level at which zero velocity is found. From this level upward, the velocity increases very rapidly at first, then less rapidly as we go up, as shown on the left-hand side of Fig. 1.

The change in velocity with height is known as the *velocity gradient.* It will be noted from the left-hand side of Fig. 1 that the estimated zero velocity is at height $Z_0 + k$ in which Z_0 is the so-called aerodynamic *surface* and k is height above Z_0 where the velocity is zero. Usually k is so limited that $Z_0 + k$ is approximately the same as Z_0 when plotted on an arithmetic scale as shown on the left-hand side of Fig. 1.

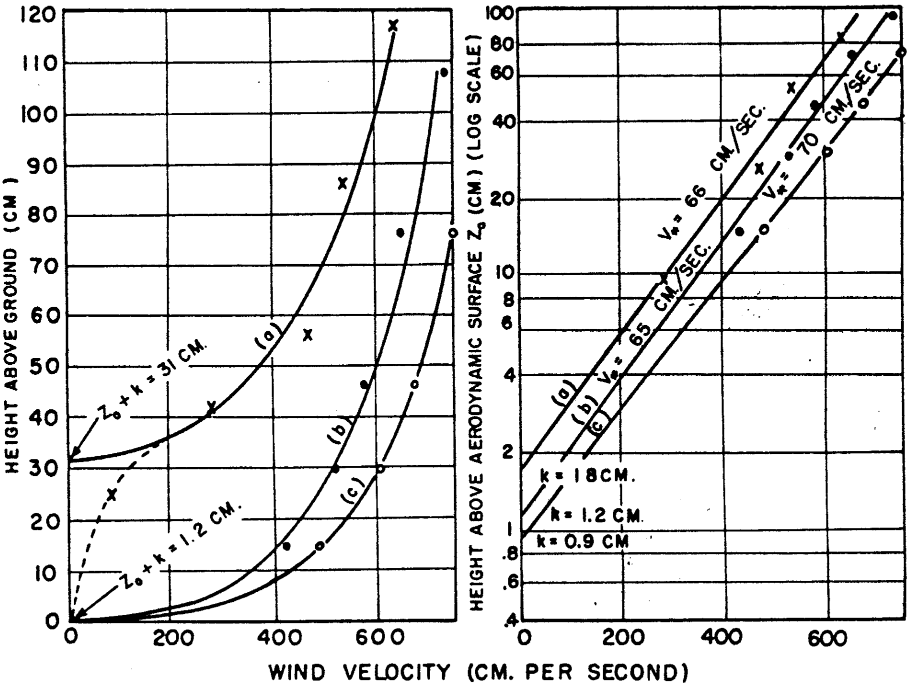

FIG. 1. Wind velocity distribution determined simultaneously and, therefore, for the same wind above (*a*) sorghum stubble with maximum height of 53 cm. no matter how strong the wind blew and (*b*) growing wheat which was 5 cm. high when no wind blew and lower when it did. The velocity distribution for a different wind but the same surface as in (*b*) is shown by curve (*c*). (Unpublished data of Chepil and Siddoway.)

It is important to note that the aerodynamic surface Z_0 is often quite indistinct. It is estimated by plotting (on an arithmetic scale) the velocity *above* the surface projections against the *height above the average ground surface* and *projecting* the curve, thus obtained, to the ordinate (at which velocity is actually or presumably zero, as shown by continuous line on the left-hand side of Fig. 1). The velocity at height $Z_0 + k$ is in fact zero if the surface is impervious, such as the ground surface. Over a porous vegetation-covered surface, however, the velocity at Z_0 is somewhat greater than zero, indicating that some air movement is taking place through the vegetation (shown by discontinuous line on the left-hand side of Fig. 1, curve (*a*). The height Z_0 roughly separates the two types of air flow near vegetation-covered surfaces—the relatively fast-moving, so-called "free flow" above the vegetation and the slow-moving, so-called "restricted flow" below the tops of vegetation. Z_0, as determined, usually is found somewhat below the maximum height of vegetation or vegetative residue. Thus, for sorghum stubble having a maximum height of 53 cm., the estimated Z_0 was about 31 cm., as shown on the left-hand side of Fig. 1. For growing wheat 5 cm. high, Z_0 was found to be nearly at the ground surface, probably because young wheat bends considerably in the wind and is quite porous.

When wind velocity within the free-flowing, fully turbulent zone up to about 5 feet (1.6 meters) above the surface projections, is plotted against the log of *height above the mean aerodynamic surface,* the velocity curve is a straight line (as shown on the right-hand side of Fig. 1). This shows that velocity v at any height z above the mean aerodynamic surface Z_0 conforms with the Prandtl (Brunt, 1944) and von Karman (1934) equation

$$v_z = 5.75 V_* \log \frac{z}{k} \tag{1}$$

in which V_* is the so-called *drag velocity* and k is the height above the mean aerodynamic surface Z_0, at which height the wind velocity is zero, or presumably zero. The rougher the aerodynamic surface, the greater is the value of k, so that k may be considered as an index of the *aerodynamic surface roughness.* Neither the aerodynamic surface roughness nor height k has any relationship to the height of vegetation or other roughness elements of the surface, but only to the variation in height, density, or spacing, flexibility, and other characteristics. Height of Z_0 above the average ground surface, on the other hand, is determined primarily by the height of vegetation. The distance between Z_0 and the average level of the ground surface is the vertical displacement of the velocity gradient by the vegetation or other roughness elements of the surface and often is referred to as the *zero displacement height* D_h (Fig. 2). Geiger (1957) calls it the *roughness height.*

For restricted-flow zone below the tops of vegetation or other roughness elements of the surface, no simple velocity-versus-height relationship has been found.

Transposing Eq. (1) for free-flow zone

$$V_* = \frac{v_z}{5.75 \log \dfrac{z}{k}} \qquad (2)$$

The drag velocity, V_*, is an index of the rate of increase of velocity with the log of height. The stronger the wind the greater the drag velocity, but for a given inflexible surface the values of Z_0 and k remain the same no matter how strong the wind blows (Fig. 1). Moreover, the drag velocity up to at least 5 feet above the surface projections for a

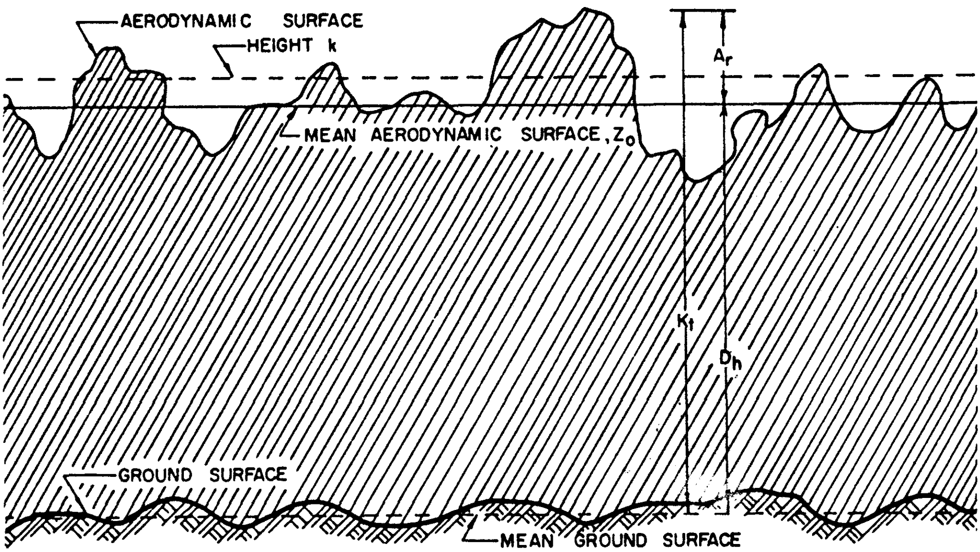

FIG. 2. Diagrammatic representation of the relative positions of the ground and vegetative roughness elements above the ground (marked by slanting lines). $K_t = D_h + A_r$ in which K_t is total surface roughness, D_h is the zero displacement height, and A_r is the aerodynamic surface roughness.

given wind in a given geographic region remains the same no matter what type or how rough the surface. The drag velocity within 5 feet above the aerodynamic surface Z_0 therefore can be used as an index of the general atmospheric wind force. The velocity alone at any given height is meaningless unless the values of Z_0 and k are known.

For many years the power law of Hellmann (1915), as reported by Geiger (1957), has been used to characterize the distribution of wind velocity with height above the ground. More recently, however, the exponential law of Prandtl (Brunt, 1944) and von Karman (1934) has been accepted as more nearly describing the velocity distribution near the ground. The power equation might be valid for heights greater than 5 feet, but below 5 feet and for fully turbulent flow as would occur when wind erosion is in progress, the exponential law of Prandtl and von Karman is generally valid. For such flow, air temperature differences with height above ground vanish, but the increase of velocity with log of height is its primary characteristic.

For rough pipes and relatively smooth soil surfaces it was found by von Karman (1934), Nikuradse (Rouse, 1950), and Zingg (1953a) that

$$\bar{\tau} = \rho \, (V_*)^2 \tag{3}$$

where $\bar{\tau}$ is the mean wind drag per unit horizontal area of the ground surface and ρ is the density of air, that is, the weight per unit volume of air (about 0.0012 g./cm.^{3}). If V_* is expressed in cm./sec., then $\bar{\tau}$ is in dynes/cm.^{2}. The force $\bar{\tau}$ is dynamic, acting generally in the direction of flow. Like wind velocity, it fluctuates greatly in all directions.

For rough, vegetation-covered surfaces, Sheppard (1947), and Chepil and Siddoway (Table I) found that the mean drag, $\bar{\tau}$, for a given natural wind varies significantly with surface roughness. The rougher the surface, the greater is the drag. Typical data presented in Table I show that Eq. (3), developed from experiments with rough pipes, cannot be used to compute the surface drag over soil and vegetation-covered surfaces. Roughness of pipes did not exceed 1.5 mm., but that of vegetation-covered surfaces was much greater, as shown in Fig. 1. Consequently, for vegetation-covered surfaces, Eq. (3) must be modified to

TABLE I

Measured Drag on Field Surfaces of Different Degrees of Roughness[a]

Time period (variable)	Sorghum stubble 20 inches high (dynes/cm.^{2})	Growing wheat 9 inches high (dynes/cm.^{2})
1	4.9	2.5
2	14.3	7.9
3	9.0	6.6
4	6.9	5.5
5	8.2	4.5
Average	8.7	5.4

[a] Unpublished data of Chepil and Siddoway.

$$\bar{\tau} = a\rho \, (V_*)^2 \tag{4}$$

in which a is a drag coefficient which varies with aerodynamic surface roughness as influenced by type and height of vegetation.

It should not be construed from Table I that because a rough surface takes up a greater drag, it is more erodible than a smooth one. This might be true if a rough soil surface were composed only of erodible fractions, but if the roughness elements are composed of nonerodible clods and erodible fractions, as they usually are, the erodible fractions are moved down and trapped in the depressions and the clods then take up most of the drag. Conversely, if the soil is covered with anchored vegetation or vegetative residue, much of the drag is taken up by the vegetative matter and only the residual drag is taken up by the soil.

B. Effect of Soil Movement on the Surface Wind

Over an eroding soil surface the velocity gradient was found by Bagnold (1936) and Chepil and Milne (1941a) to undergo a considerable change to which Eq. (1) of Prandtl and von Karman does not apply. They showed that sand and soil movement in saltation reduces the momentum and, therefore, the surface velocity of the wind, as shown

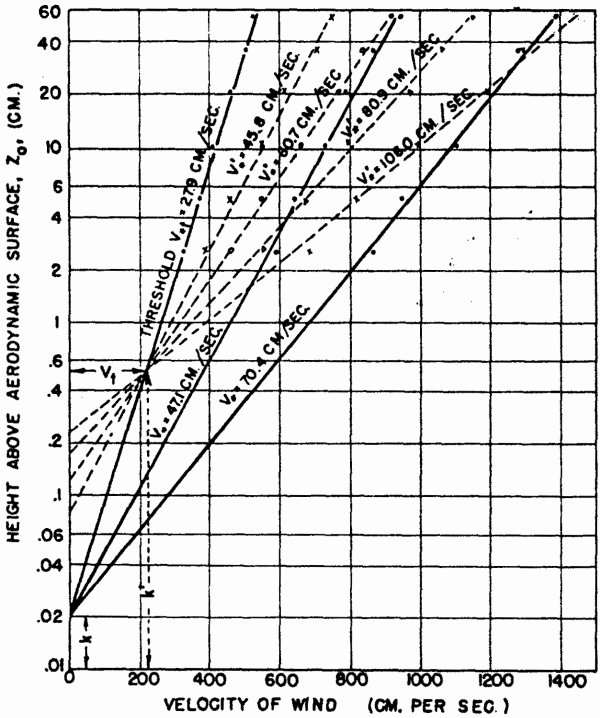

FIG. 3. Wind velocity gradients over an eroding and noneroding surface in a portable field tunnel. Broken lines denote gradients over an eroding surface, and continuous lines over the same surface "fixed" with a fine spray of water. $V_t = 4.8$ mph. or 214 cm./sec., $k = 0.02$ cm., and $k' = 0.5$ cm. (Chepil, 1941.)

in Fig. 3. The solid lines of Fig. 3 indicate typical wind gradients over a "fixed" surface over which no soil movement took place, and the dashed lines indicate the velocity gradients when soil movement was in progress. The surface was fixed by spraying it with water. The drag velocity curves over a fixed surface confrom with Eq. (1). An eroding soil surface, on the other hand, reduces wind velocities to considerable height; consequently, new drag velocity curves are established, all of which have a common velocity at height $Z_0 + k'$ as shown in Fig. 3. The new wind velocity distributions conform with the Eq. (5)

$$v_z = 5.75\, V_*' \log \frac{z}{k'} + V_t \qquad (5)$$

in which V_*' is a drag velocity above an eroding surface, k' is height (above Z_0) to which all drag velocity curves V_*' converge, and V_t is velocity at height k'. V_t remains constant no matter how strong the wind blows. Therefore,

$$V_*' = \frac{v_z - V_t}{5.75 \log \frac{z}{k'}} \qquad (6)$$

It will be evident from Eq. (5) and Fig. 3 that the higher the drag velocity V_*', that is, the stronger the wind blows, the lower is the velocity below height k'. This seemingly illogical condition apparently is due to greater concentration of saltating soil grains with strong winds, which tends to lower the wind velocity below height k'. Height k' was found to be considerably below the average height of saltation. Field measurements by Chepil and Milne (1941a) indicated, too, that the lowering of wind velocity due to soil movement varies directly with soil erodibility; that is, the more erodible the soil the greater the concentration of moving soil grains and the greater is the reduction of wind velocity near the ground.

III. Equilibrium Forces on Soil Grains

A. Forces at Threshold of Soil Movement

A moving fluid such as air or water exerts three types of pressure on a soil grain resting on the ground (Einstein and El-Samni, 1949; Ippen and Verma, 1953; Chepil, 1959b). One is a positive pressure against that part of the grain facing into the direction of fluid motion. This pressure results from the impact of the fluid against the grain and is called the *impact* or *velocity pressure*. The velocity pressure causing the initiation of movement of a soil grain varies directly as the square of the fluid velocity, and its magnitude is the force per unit of cross-sectional area of the grain normal to the direction of fluid motion.

The second type is a negative pressure on the lee side of the grain, known as *viscosity pressure.* Its magnitude depends on the fluid's coefficient of viscosity, density, and velocity.

The third type of pressure is a negative pressure on the top, as compared to the bottom, of the grain, caused by the Bernoulli effect. The Bernoulli law states that wherever the fluid velocity is speeded up, as at the top of the soil grain, the pressure (measured transverse to the general direction of fluid motion) is reduced. This is called the *static, isotropic,* or *internal pressure.*

The impact or velocity pressure on a soil grain lying on the ground is known as *form drag,* and the pressure due to viscous shear in the fluid close to the surface of the soil grain is called *skin friction drag.* The sum of the two forces is the *total drag.* Separation of the two kinds of drag appears unnecessary in determining the equilibrium forces on the soil grain. The total drag in this review is referred to as *drag.* The drag, F_c, on the top grain at the threshold of its movement is due to the pressure difference against its windward and leeward sides. The arrow marked by F_c in Fig. 4 indicates the general direction and the average level at which it acts.

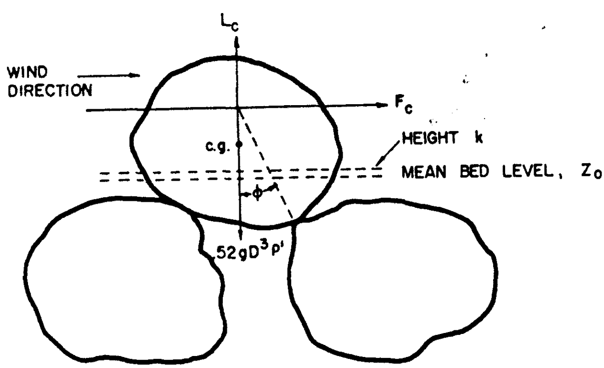

FIG. 4. Forces of lift, drag, and gravity acting on a soil grain in a windstream at the threshold of movement of the grain. Net moment opposing F_c is $(0.52\, gD^3\rho' - L_c) \tan \phi$ for a spherical grain (Chepil, 1959b).

A decrease in static pressure at the top of the grain as compared to that at the bottom causes a *lift* on the grain. It is determined by, but is not the same as, the pressure difference against the top and the bottom halves of the grain. The arrow marked L_c in Fig. 4 indicates the general direction in which it acts. It acts through the center of gravity, c.g.

The minimum mean drag and lift forces, known as the threshold drag and lift, required to move the top soil grains by wind are influenced by the diameter, shape, and immersed density of the grains; by the angle of repose ϕ of the grains with respect to the mean drag level of the wind; by the closeness of packing η of top grains on the sediment bed; and by the impulses of wind turbulence T associated with drag and lift (Jeffries, 1929; White, 1940; Kalinske, 1943; Einstein and El-Samni, 1949; Chepil, 1958).

From Fig. 4, the threshold drag F_c acting on a spherical grain is

$$F_c = (0.52\, gD^3\rho' - L_c) \tan \phi \tag{7}$$

in which g is the acceleration due to gravity, D is the diameter of the grain, ρ' is the immersed density of the grain, and ϕ is the angle of repose of the grain with respect to the average drag level of the fluid. In this equation the expression $0.52\, gD^3\rho'$ is the immersed weight of the spherical grain. From experiments, Chepil (1959b) found that L_c is equal to about 0.75 F_c for any size of spherical elements, such as soil grains on the surface, and for any wind velocity within the range required to move different sizes of soil grains. Therefore, by substitution, transposing, and factoring, Eq. (7) becomes

$$F_c = 0.52\, gD^3\rho' \tan \phi/(1 + 0.75 \tan \phi) \tag{8}$$

Equation (8) indicates the threshold drag F_c required to move the top grain of diameter D. But the threshold drag F'_c per unit cross-sectional *horizontal area* occupied by the grain is equal to $F_c/0.7854D^2$ in which $0.7854D^2$ is the largest cross-sectional horizontal area occupied by the spherical grain. Then, by substitution and simplification (Chepil, 1959b)

$$F'_c = 0.66\, gD\rho' \tan \phi/(1 + 0.75 \tan \phi) \tag{9}$$

Drag and lift per unit horizontal area occupied by the topmost grains are much higher than drag and lift per unit area on the whole bed, because the topmost grains which take up most of the drag and lift occupy only a portion of the bed area. If η is the ratio of drag and lift on the whole bed to drag and lift on the topmost grain moved by the fluid, then Eq. (9) becomes

$$\tau_c = 0.66\, gD\rho' \tan \phi\eta/(1 + 0.75 \tan \phi) \tag{10}$$

in which τ_c is the threshold drag per unit horizontal area of the whole bed.

Equation (10) is applicable to wind of uniform velocity. Since the airstream of a velocity required to move the top soil grains is not uniform, movement of the grains is facilitated by the maximum lift and drag impulses of turbulent flow. Therefore, for turbulent flow, Eq. (10) should be modified to

$$\bar{\tau}_c = 0.66\, gD\rho' \tan \phi\eta/(1 + 0.75 \tan \phi)T \qquad (11)$$

in which $\bar{\tau}_c$ is the mean threshold drag per unit horizontal area of the whole soil bed and T is the ratio of maximum to mean lift and drag on the soil grain exerted by the turbulent wind.

By estimating wind velocities at different heights above the mean level of the sediment beds, Chepil (1959b) found that the drag on the topmost grains on the bed acts at an average level of about one-third of the grain diameter below the top of these grains. On the basis of these experiments, he found that the angle of repose ϕ of the topmost grains with respect to the mean level of drag is about 24 degrees. Therefore, tan ϕ is equal to about 0.45.

Assuming that all the drag is taken up by the topmost grains on a bed, White (1940) determined the coefficient η by counting the grains lying on top of the bed, computing the largest horizontal cross-sectional area of the grains, and dividing this area by the total horizontal area of the bed. He found that coefficient η, so determined, had a value of about 0.1. However, exact determination of the coefficient in this manner is impossible since all sorts of gradations between complete exposure and virtually complete embedding of the surface grains occur. Chepil (1959b) therefore determined the coefficient from actual measurements of pressure on topmost spherical bodies, such as soil grains, and from drag on the whole surface computed from the threshold drag velocity of the wind in accordance with Eq. (3). He found that the coefficient determined from those two conditions has a value of about 0.2.

In studying the motion of sediment particles in water, Ippen and Verma (1953) concluded, "Nothing is known in detail as yet concerning the turbulent pressure fluctuations near the bed." Lack of such knowledge was largely due to lack of suitable instruments for measuring turbulence. Chepil and Siddoway (1959), therefore, devised a strain gage anemometer for this purpose. Analysis of oscillograms obtained with this instrument, and shown by example in Fig. 5, indicated that pressure of both lift and drag at a level of the topmost grains is distributed statistically according to a somewhat skewed normal error law. Hence, from a statistical standpoint, the maximum pressure of lift and drag has no definite limit and, therefore, the ratio of maximum to mean cannot be given.

The standard deviation, however, completely describes the spread of pressure of lift and drag around the mean. Analysis showed that the standard deviation of the pressure distributions varies directly with the drag velocity of the wind and that the ratio of mean pressure to standard deviation is nearly constant at the position of the topmost grains of a size range eroded by wind. Nearly all, or 99.73 per cent, of the pressure range is included within $\overline{P} \pm 3\sigma$ in which $\overline{P}$ is the mean pressure of drag

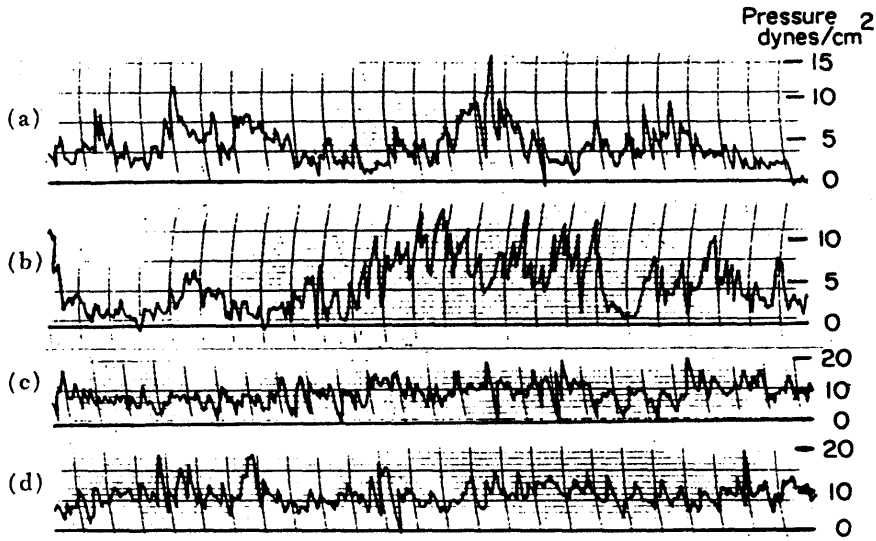

FIG. 5. Oscillograph records of pressure of drag and lift on spherical gravel at bed level for a drag velocity of 47 cm. per second: (a) Drag on 3.2-mm. gravel, (b) drag on 6.4-mm. gravel, (c) lift on 3.2-mm. gravel, (d) lift on 6.4-mm. gravel. Time interval, 1 second (Chepil, 1959b).

and lift and σ is the standard deviation of the pressure around its mean. The turbulence factor, T, therefore, was taken as $(\overline{P} + 3\sigma)/\overline{P}$ which assumes that the "maximum" pressure is $\overline{P} + 3\sigma$. On the basis of this assumption, the turbulence factor for both lift and drag at the position of the topmost grains on a soil bed was found to be approximately 2.5.

Oscillograms of Fig. 5 show that the smallest-scale cycles of pressure, although irregular as to both magnitude and duration of occurrence, have a period of about 1/80 to 1/120 second. Duration of this primary period varied little with all wind velocities used. Pressures equal to or greater than $\overline{P} +$ 3σ for lift and drag occurred two to three times per second, depending somewhat on drag velocity of the wind.

Assuming that tan $\phi = 0.45$, $\eta = 0.2$, and $T = 2.5$, Chepil (1959b) computed, on the basis of Eq. (11), the mean threshold drag $\overline{\tau}_c$ for various sizes and immersed densities (differences in bulk density between the grain and the air) of soil and sand grains and compared them with the actual mean threshold drag determined by wind tunnel tests. The threshold drag determined in a tunnel agreed reasonably well with the threshold drag computed in accordance with Eq. (11), as shown in Table II. This seems to confirm the general validity of Eq. (11) and the approximate values of the parameters that it embodies.

TABLE II
Concordance of Computed with Actual Threshold Drag for Soil Grains[a]

Minimum grain diameter D (cm.)	Immersed grain density ϱ'	Computed threshold drag (dynes/cm.^{2})	Actual threshold drag (dynes/cm.^{2})
0.015	2.65	0.69	0.59
0.025	2.65	1.16	0.85
0.030	2.65	1.39	1.11
0.042	2.65	1.95	1.60
0.059	2.65	2.74	2.32
0.010	2.09	0.37	0.27
0.015	1.96	0.51	0.35
0.018	1.94	0.61	0.48
0.025	1.91	0.84	0.69
0.042	1.91	1.40	1.08
0.059	1.80	1.86	1.51
0.084	1.78	2.62	2.33
0.119	1.74	3.63	3.59
0.200	1.65	5.78	5.15
0.336	1.52	8.94	10.30
0.475	1.55	12.90	14.00

[a] Data from Chepil (1959b).

B. Forces during Soil Entrainment

Lift and drag on soil grains change rapidly as the grains move up from the surface of the ground. Lift decreases with height and becomes hardly detectable a few grain diameter heights above the ground. This height is considerably less than the height to which many grains rise in saltation. The greater the ground roughness and drag velocity of the wind, and therefore the steeper the velocity gradient, the higher lift extends. Lift is caused, apparently, by a steep wind velocity gradient near the ground.

Drag, on the other hand, increases with height just as wind velocity increases with height, and apparently is due mainly to the direct pressure of the wind against the grain.

A diagrammatic representation of lift and drag on a small sphere, such as a soil grain, is given in Fig. 6. It is shown that lift in this case almost ceased to exist at about 2.5 cm. height. Drag on the sphere, on the other hand, continued to increase all the way up to the height of measurement, just as velocity increased with height.

The drag on the grains is generally much greater than the lift. After being shot into the air, the grains rise to various heights, and because

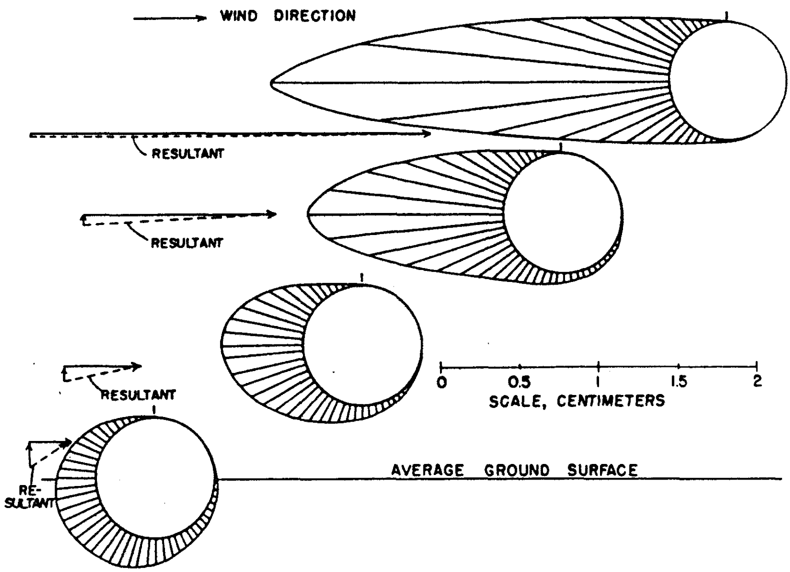

FIG. 6. Pattern of approximate pressure differences between position 1 on top of the sphere and other positions on the sphere at various heights in a windstream. Length of lines in the shaded areas outside the circular line (sphere) denotes the relative differences in air pressures. The sphere is 0.8 cm. in diameter and the drag velocity is 98 cm. per second (Chepil, 1961).

of the force of gravity, fall at an accelerating velocity. There is at the same time a horizontal acceleration of the falling grain due to the force of drag. The downward and forward accelerations are proportioned uniformly so that the inclined path of the falling grain is almost a straight line. However, the average force of drag is much greater than the force of gravity, and therefore the angle of descent is only about 6 to 12 degrees from the horizontal. If the ground were perfectly smooth and there were no lift, the angle of ascent (expressed as deviation from the horizontal) should be the same as of descent. However, grains in saltation rise vertically or nearly so.

From measurements of pressure on suspended spheres, such as soil grains, Chepil (1961) concluded that the essentially vertical rise must be due in some measure to the presence of lift near the ground but that lift alone could not possibly be the sole factor involved. Another factor, apparently, is the surface obstructions from which the saltating grains rebound (Fig. 7). The obstructions are usually spherical or nearly spherical soil aggregates or other grains resting on or creeping along the ground. The topmost grains that compose the eroding surface occupy on the average about 0.1 of the total surface and therefore are spaced about three diameters apart (White, 1940), as shown in Fig. 7. The saltating grains descend at an average angle of about 9 degrees from the

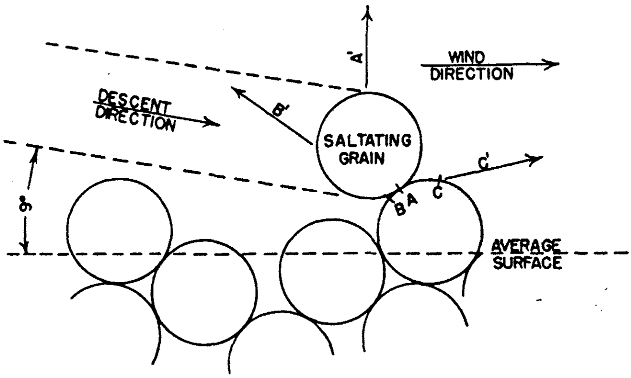

Fig. 7. Diagrammatic representation of a saltating grain striking a stationary grain at an average impact point *A* and rebounding in a vertical direction *A'*. Possible extreme points of impact are *B* and *C* with rebound directions *B'* and *C'* (Chepil, 1961).

horizontal, strike the top portions of spherical ground objects, and then rebound predominantly in a vertical or nearly vertical direction. Because of the particular angle of descent and configurations of the ground surface, as shown diagrammatically in Fig. 7, the rebounds should be generally vertical even if lift did not exist. Lift merely contributes to the vertical rise of soil grains. The vertical momentum of saltating grains carries some of them upward and above the zone of lift.

IV. The Cycle of Wind Erosion

All the processes of soil stabilization, destabilization, and wind erosion, including conditions resulting from those processes, may be termed the cycle of wind erosion (Chepil, 1961). This cycle is a part of the much broader cycle of weathering, which is defined as all physical and chemical changes produced in rock and soil materials by the elements of the weather and which result in disintegration, decomposition, movement, and sorting of the materials (Polynov, 1937).

Each process associated with the cycle of wind erosion yields a specific product and each product leads to or causes another process.

All the processes go only in one direction, and therefore form a cycle as shown in Fig. 8.

The cycle of wind erosion is characterized by a continual transition among the different processes and their associated products or resulting conditions. The cycle may be viewed as an equilibrium between soil

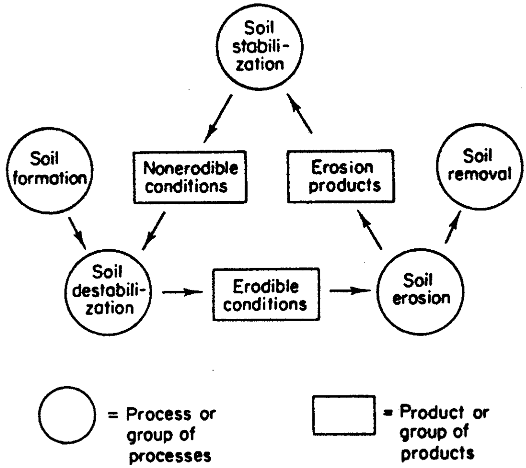

FIG. 8. The cycle of wind erosion (Chepil, 1962c).

stabilization processes on the one hand and soil destabilization processes on the other. Always associated with soil destabilization processes are the processes of soil erosion and their resulting products or conditions.

The conditions resulting from soil destabilization, erosion, and stabilization cannot be defined explicitly because they vary greatly with the intensity of the processes that produce them. Therefore, what is an erodible condition under one set of climatic or weather processes may not constitute an erodible or an equally erodible condition under another.

The processes and products associated with the cycle of wind erosion embody the causes, effects, and remedies of wind erosion and may be listed as follows.

PROCESSES	PRODUCTS OR CONDITIONS
Soil destabilization processes—basic causes of erosion	*Primary causes of erosion*
Climatic causes	
High wind velocity and turbulence	Increased surface wind velocity
Low precipitation	Erodible soil conditions
High temperature	Dry, small, loose, and light soil grains
Soil structural breakdown	
Soil weathering	Erodible surface conditions
Improper and excessive cultivation	Smooth, bare, unsheltered, large, and improperly oriented fields

Erosion processes—effects of basic causes	*Products and conditions resulting from erosion*
Initiation of soil movement	
Soil transportation	
Movement by saltation	
Movement by surface creep	
Movement by suspension	
Avalanching	Expanded eroding area
Detrusion	Progressively smoother and more erodible conditions to leeward of eroding area
Sorting	Residual soil materials
	Lag sands and gravels
	Dunes
	Loess
Abrasion	
Breakdown of soil structure	Increased quantity of erodible soil fractions
Destruction of vegetation	Loose and bare soil conditions
Soil stabilization processes—remedies of erosion	*Conditions resulting from stabilization*
Soil deposition (stilling of erosion)	Nonerodible soil conditions
Sedimentation	Moist and firm surface soil
Trapping	Soil aggregates large and dense enough not to be moved by wind
Soil consolidation and aggregation	Nonerodible surface conditions
Proper tillage and cropping practices	Rough and covered surface
Revegetation	Surface sheltered by barriers
Proper tillage and cropping practices	Restricted width of erosion-susceptible field
Proper field orientation and management	Broad sides of field or field strip oriented at right angles to prevailing wind direction
Climatic and weather influences	
Decreased wind velocity and turbulence	Reduced surface wind velocity
Increased precipitation	
Decreased temperature	

Associated with the cycle of wind erosion are the processes of soil formation and soil removal (Fig. 8). The primary objective of the soil conservationists is to modify the processes that affect soil removal so that the rate of soil removal does not exceed the rate of soil formation.

A. Soil Destabilization and Stabilization Processes

The opposing processes of soil destabilization and stabilization form an equilibrium; therefore, it is convenient to discuss them together.

Soil destabilization processes may be considered as the basic causes of wind erosion, whereas the products or conditions resulting from these processes may be termed the primary causes.

The basic causes of accelerated wind erosion are associated with the equilibrium between climate, soil, and vegetation. Accelerated wind erosion in many parts of the world developed after man began to interfere unduly with the natural equilibrium between climatic, soil, and vegetative environment (Sears, 1935). Burning, overgrazing, and overcultivation have been the chief means of disturbing this equilibrium. The problem of excessive wind erosion, therefore, is associated principally with the way the farmer uses his land (Bennett, 1939).

Relatively little wind erosion occurs on grassland or woodland, but even here overgrazing and overclearing often cause accelerated erosion by wind and water. Accelerated erosion occurs chiefly on cultivated land.

The equilibrium between climate, soil, and vegetation embodies the following opposing processes: (1) increased vs. decreased wind velocity, temperature, and precipitation, (2) soil loosening and deaggregation vs. soil consolidation and aggregation, and (3) devegetation vs. revegetation.

1. Increased vs. Decreased Wind Velocity, Temperature, and Precipitation

Extended periods of low precipitation, high temperature, and high wind velocity often contribute to the severity of wind erosion (Bennett, 1939; Zingg, 1953b, 1954).

Wind erosion becomes progressively more serious as the sequence of dry years continues; this is so because conditions become progressively more erodible. Conversely, the severity of wind erosion was found to diminish only after the return of at least two consecutive years of favorable moisture and vegetative growth (Zingg, 1953b).

Great variations in precipitation, temperature, and wind velocity exist in continental climates throughout the world. These variations are controlled generally by the normal probability law, just as are floods. Gumbel (1941, 1945) and Potter (1949) devised a workable method for determining the probability of occurrence of different flood magnitudes. Zingg (1949, 1950) has applied this method to analysis of intensity-frequency of occurrence of winds of various velocities in different regions. The method is based on a relationship

$$Q_m = Q_a + \sigma(0.7797y - 0.45005) \qquad (12)$$

where Q_m = wind velocity equaled or exceeded on the average of once in t years, where t is termed the recurrence interval, i.e., time in years.

Q_a = average of the maximum wind velocities, Q, in miles per hour for a specified continuous period.

σ = standard deviation of maximum wind velocities for a specific continuous period, or

$$\sigma = \sqrt{\frac{N}{N-1}\left(\frac{\Sigma Q^2}{N} - Q_a{}^2\right)}$$ where Q is maximum wind velocities for a specific continuous period (based on one event for each specified unit of time).

$$y = \log_e\left[-\log_e\left(1 - \frac{1}{t}\right)\right].$$

N = number of events for a period of record (number of numbers in the analysis).

Chepil *et al.* (1962) applied the method of Gumbel and Potter to analyze the intensity-frequency of a combination of major climatic conditions that influence wind erosion. An example of normal distribution of climatic conditions that influence wind erosion is given in Fig. 9.

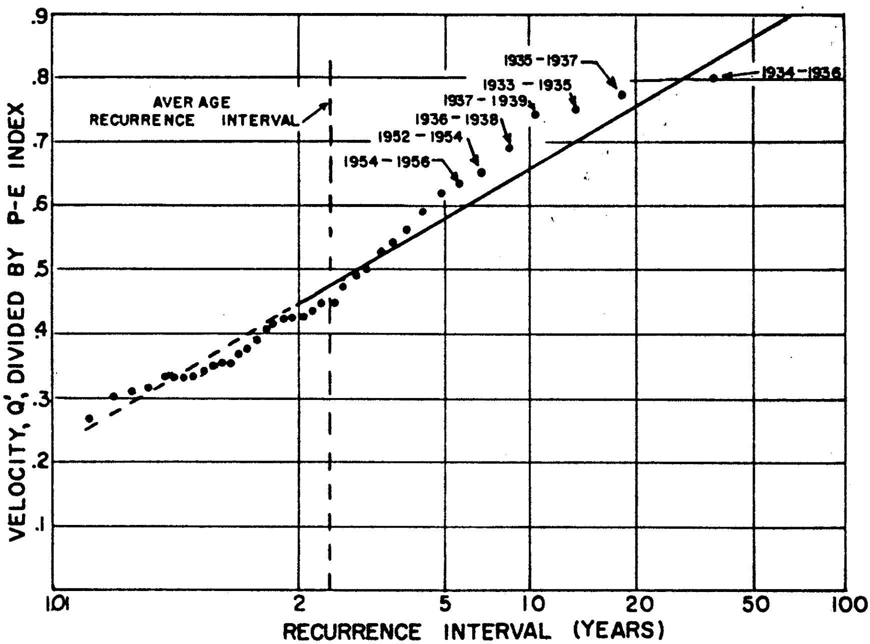

FIG. 9. Intensity-frequency data for three-year running average of wind velocity Q', corrected to that at 30-foot height, divided by the three-year average of P-E index at the Branch Agricultural Experiment Station, Garden City, Kansas, for 1920 through 1960 (Chepil *et al.*, 1962).

These climatic conditions include a three-year running average of wind velocity, Q, which affects wind erosion directly, and a three-year running average of P-E index of Thornthwaite (1931), which affects wind erosion inversely (Chepil *et al.*, 1962). The P-E index is an index of soil moisture and is influenced by monthly precipitation and temperature.

A three-year running average was taken because it is known (Zingg, 1953b) that wind erosion generally becomes most or least intense after two or three consecutive years of drought or adequate moisture, respectively. All values of the wind erosion climatic factor (Q'/P-E) falling on a straight line on the $\log_{10}$ probability scale of Fig. 9 would fit the normal curve perfectly. A longer period of record no doubt would have produced a better fit. Figure 9 indicates that during the period of record beginning in 1920, the most severe climatic conditions that influenced wind erosion at Garden City, Kansas, occurred in the 1930's, and slightly less severe conditions in the 1950's. Wind erosion was actually most severe in the 1930's and next to most severe in the 1950's, thereby substantiating the validity of the wind erosion climatic factor as an index of severity of wind erosion, other factors remaining the same.

The general frequency of occurrence of periods of high wind and temperature and low precipitation can be predicted from past records for any given location, but unfortunately the time when these periods will occur cannot be predicted. Owing to these climatic variations, occasionally some wind erosion will occur in severely affected regions even under virgin conditions. With sufficient resourcefulness, however, man can modify the intensity of wind erosion so that it is insignificant in amount.

Atmospheric turbulence also contributes to the severity of wind erosion. It tends to increase the velocity near the earth's surface and therefore to increase the frictional force on the ground (von Karman, 1934). Parkinson (1936) observed that the presence of dust storms in central United States generally is associated with instability, or turbulence, of the air masses. Over these, man presently has no control.

2. *Soil Loosening and Deaggregation vs. Soil Consolidation and Aggregation*

In some regions subject to frost, the spring season is potentially the most hazardous from the standpoint of wind erosion. Frost action on moist soils during the winter tends to loosen and break down soil clods, therefore increasing the erodibility by wind. In the summer an increase in cementing substances somewhat dispersible in water tends to cement the soil mass, to increase the proportion of nonerodible clods, and to decrease the erodibility by wind.

Excessive and improper tillage often causes excessive soil loosening and pulverization and increases the hazards from erosion by wind (Woodruff and Chepil, 1956; Woodruff *et al.*, 1957). Suitable tillage in regions where wind erosion is a hazard is necessary, especially to kill weeds and to conserve moisture. Moisture must be conserved to reduce the risks from wind erosion. Therefore, proper tillage and cropping practices are required if weeds are to be controlled, moisture conserved, and erosion curtailed.

Wetting by rain, compaction, and activities of soil microorganisms greatly influence soil consolidation and aggregation and, consequently, erodibility by wind (McCalla, 1950; Chepil, 1956, 1958). On the other hand, repeated wetting and drying, and especially freezing and thawing, of the surface soil tend to soften and disintegrate the surface crust and aggregates and to enhance wind erosion. Because of these counteracting processes, maximum degree of soil consolidation and aggregation occurs usually below the depth of 3 to 4 inches (Chepil, 1954b). Tillage to bring the consolidated soil material (clods) to the surface reduces erosion by wind if the vegetative cover buried is negligible. However, the effects of tillage are temporary because the forces of the weather tend to break the clods to sizes small enough to be moved by wind (Chepil, 1954b). As the clods at the surface are broken down, clods below the surface are being formed, making repeated tillage necessary in maintaining a cloddy surface indefinitely.

3. *Devegetation vs. Revegetation*

The most important basic cause of wind erosion is depletion or destruction of vegetation or vegetative residue on the land. Drought, at times, reduces or stops vegetative growth, but drought alone is seldom the cause of severe wind erosion. For example, little erosion occurred in semiarid regions of North America during drought periods when the land was protected by natural vegetation, but serious extensive erosion occurred during the drought periods after man began to burn and overgraze the vegetation and later to bury it by excessive and improper cultivation (Sears, 1935; Jacks and Whyte, 1939; Malin, 1946). Vegetation must thrive and keep pace with soil weathering, cultivation, decomposition, and other denudation processes if wind erosion is to be kept in check.

B. Conditions Resulting from Destabilization and Stabilization Processes

The above-mentioned processes associated with climate, weather, and human activities tend to create conditions that increase or decrease wind erosion (Chepil, 1958). They are equilibrium conditions, like the processes that produce them. They are as follows:

1. Increased vs. decreased surface wind velocity
2. Dry vs. moist soil particles
3. Light vs. heavy soil particles
4. Loose vs. consolidated soil particles
5. Smooth vs. rough surface
6. Bare vs. covered soil surface
7. Unsheltered vs. sheltered soil surface
8. Large vs. small eroding field
9. Improperly vs. properly oriented fields, crop strips, crop rows

1. *Increased vs. Decreased Surface Wind Velocity*

Although atmospheric turbulence tends to increase the surface velocity of the wind and contributes greatly to movement of soil and snow by wind, control of this has not been possible. It has been possible, however, to slow down the surface velocity and therefore to reduce wind erosion by roughening the surface and by establishing windbreaks and barriers in the path of the wind (Woodruff, 1954; Woodruff and Chepil, 1956; Woodruff *et al.*, 1957). These and other principles of wind erosion control will be discussed in Section VI of this review.

2. *Dry vs. Moist Soil Particles*

Only dry soil particles are readily moved by wind. Soil particles that have been oven-dried and those that have been air-dried are about equally erodible by wind. Damp and moist soil particles, due to cohesion of the water films, are virtually stable. The force of cohesion between erodible soil particles varies directly with moisture content. Seldom is

TABLE III
Influence of Equivalent Moisture, M_e, of a Silt Loam Soil on the Rate of Soil Erosion Under Different Wind Velocities at 6-Inch Height[a]

Equivalent moisture	Rate of soil erosion under 20-m.p.h. velocity (mg./cm. width/sec.)	26-m.p.h. velocity (mg./cm. width/sec.)	32-m.p.h. velocity (mg./cm. width/sec.)
0.01	315	605	820
0.25	295	630	780
0.29	235	590	710
0.34	230	540	640
0.71	68	290	390
1.03	2	49	40

[a] Data from Chepil (1956).

a natural wind strong enough to overcome the cohesive force of moisture at about 15-atmosphere percentage, which corresponds approximately to per cent water at permanent wilting point of plants. A relatively great increase in wind velocity is required to produce movement of discrete soil grains when their moisture content is increased slightly above the 15-atmosphere percentage. The 15-atmosphere percentage has an equivalent moisture, M_e, of 1 (Table III). The equivalent moisture is a ratio of the water content in question to water content at 15-atmosphere percentage. It is equal to w/w' in which w is the amount of water held by the soil grains and w' is the amount of water held by the same soil at a 15-atmosphere percentage.

3. *Light vs. Heavy Soil Particles*

Lighter particles are more erodible than heavier ones, but only if the diameter of the particles is greater than about 0.1 mm. Both size and density determine the weight, and therefore the erodibility, of the individual particles. Size is designated usually by diameter as determined by dry sieving. Density is defined as the weight in grams per cubic centimeter volume of a discrete soil grain or aggregate, including any air spaces within the grain or aggregate. It is convenient to express size and density together by what is known as *equivalent diameter*. Equivalent diameter is approximately equal to $\rho_e D/2.65$ in which ρ_e is the bulk density of the erodible soil particles and D is their diameter as determined by dry sieving.

The most erodible particles of 2.65 density are about 0.1 mm. in diameter. They require the minimal drag velocity, known as *threshold drag velocity* (designated as V_{*t}) of about 15 cm. per second to initiate movement. This is equivalent to about a 10-mile-per-hour wind velocity at 1 foot above a smoothed soil surface. Sizes greater and smaller than 0.1 mm. equivalent diameter are less erodible by wind. The dividing point between erodible and nonerodible particles is not distinct for it varies with the drag velocity of the wind, the equivalent size range of erodible particles, and the proportion of so-called erodible and nonerodible fractions. Relatively few particles greater than 0.5 mm. in equivalent diameter are moved by common erosive winds, although a few up to 2 mm. equivalent diameter may be moved by exceedingly high winds. For most mineral soils, the 0.5 mm. equivalent diameter of a soil grain corresponds to about 0.84 mm. actual diameter. The 0.84 mm. is one of the sizes in the sieve series of the United States Bureau of Standards. This size of square sieve openings has been used, therefore, to separate the so-called erodible from the nonerodible soil fractions (Chepil and Bisal, 1943; Chepil, 1952).

Soil clods or aggregates that are just large enough not to be moved by wind are most effective in protecting the erodible soil particles (Chepil, 1958). This is because a unit volume of the smallest clods has the greatest surface for protecting the erodible particles. Density of the nonerodible fractions has no direct bearing on erodibility (Chepil, 1958). Only their size and to some degree their shape are the determining factors.

Dust particles, especially those less than 0.02 mm. in diameter, are highly resistant to movement by direct force of wind. Moreover, they hinder the movement of the larger particles mixed with them. The more fine dust present in the wind-eroded soil, the greater is the threshold drag velocity of the wind required to initiate soil movement. Loose particles smaller than 0.01 mm., if not mixed with coarser particles and if placed in a bed that is thoroughly smoothed, are not moved even by an exceedingly strong wind.

The high resistance of the fine dust particles to movement by wind is partly due to cohesion among the particles. More particularly, when the bed is thoroughly smoothed, the particles are too small to protrude above the viscous, nonturbulent layer of air, known as the *laminar layer,* close to the surface. It is known (Goldstein, 1938) that particles of height D would be submerged in the laminar layer as long as the Reynolds number of the form $V{\cdot}D/\nu$ is less than 3.5. The kinematic viscosity, ν, for air is approximately 0.15. If, on the other hand, the Reynolds number is greater than 3.5, the particles behave as obstructions in the path of the wind, throw off eddies to their lee sides, and disrupt the laminar layer.

Under a force of wind equal to or greater than that required barely to move fine dust particles, the particles will disrupt the laminar layer if they are greater than 0.05 mm. in diameter (Chepil, 1945b). If the surface composed of dust particles is roughened to a degree where the surface projections are at least 0.05 mm. in height, movement of the particles takes place under a relatively low velocity of wind. In such cases the projections composed of many dust particles clinging together are broken off and moved bodily by the wind. Movement ceases as soon as the projections are leveled down to less than 0.05 mm. in height. Under field conditions the surface roughness elements usually are much greater than 0.05 mm. The dust particles cling to the larger grains, and therefore are moved readily with them.

4. *Loose vs. Consolidated Soil Particles*

The most erodible soil condition exhibits no cohesion among the individual soil particles and aggregates. This condition is brought about by stirring or tilling the soil in a dry condition. Wetting a loose soil bed followed by drying produces a certain degree of cementation (consolidation) among the various individual particles and aggregates and tends to reduce erodibility by wind (Chepil, 1958). The degree of cementation is greatest at the surface of the ground, especially if the ground is exposed to impacts of raindrops (Fig. 10). On the other hand,

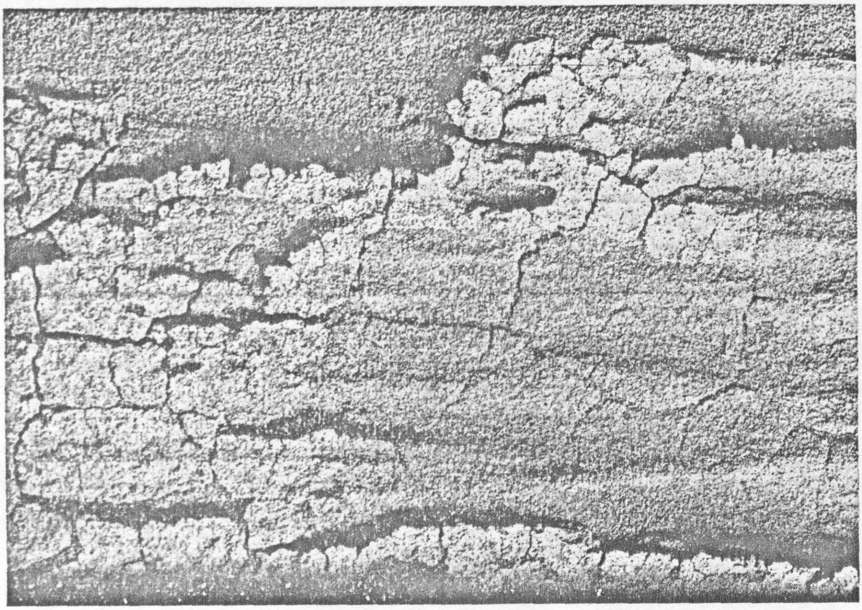

FIG. 10. Surface crust on clay soil partly destroyed by abrasion with dune sand for 5 minutes with a wind velocity of 28 miles per hour at 1-foot height, exposing a more erodible soil beneath (Chepil, 1958).

frost action, tillage of dry soil, and abrasive force of windblown sand and soil particles all tend to loosen the bond between individual soil particles and aggregates and to increase the erodibility by wind.

5. *Smooth vs. Rough Surface*

A smooth soil surface is generally more erodible by wind than is a rough one (Table IV). This is because it is less effective in slowing down the velocity of wind near the ground. A smooth surface reduces wind turbulence, but whatever effect the decreased turbulence has in reducing wind erodibility usually does not compensate entirely for the increased surface velocity (Chepil and Milne, 1914b).

Roughening is not always effective in reducing wind erosion. If the soil is composed mostly of erodible fractions, roughening the surface does little good because the roughness elements continue to erode with the wind. But if the roughness elements, such as ridges, are composed of erodible and nonerodible fractions (as they usually are) the erodible fractions move from the ridges into the furrows where they are trapped, and the ridges soon become stabilized with a mantle of soil aggregates too large to be moved by the wind.

TABLE IV
Initial Rates of Erosion (Soil Flow) over Rough and Smooth Surfaces of Hatton Fine Sandy Loam under Different Wind Velocities[a,b]

Wind velocity at 12-inch height (m.p.h.)	Rate of soil flow on	
	Smooth surface (g./cm. width/sec.)	Rough surface (g./cm. width/sec.)
17	0.32	0.10
22	0.88	0.19
30	2.10	0.70

[a] Data from Chepil and Milne (1941b).
[b] Rough surface was composed of ridges 2.5 inches high, 9 inches apart, at right angles to wind direction.

The aerodynamic surface roughness, A_r, (Fig. 2) described in Section II, A, is only one element of surface roughness that influences wind erosion. The other element, which is far more influential in reducing wind erosion, is the zero displacement height, D_h. Between the ground surface and height D_h the air is usually stagnant or is slow-moving and often laminar (Geiger, 1957). The aerodynamic surface roughness plus the zero displacement height is the *total surface roughness,* which, in this review, is referred to simply as *surface roughness.* The greater the surface roughness, the lower is the wind velocity against the ground and the lower is the rate of erosion.

6. *Bare vs. Covered Soil Surface*

The greatest frequency and magnitude of wind erosion occur on soils that have been partly or completely denuded of vegetation or vegetative cover. Bare, aggregated soils may exhibit resistance to erosion, but generally temporarily, because aggregates exposed to the weather usually disintegrate to erodible particles (Slater and Hopp, 1951; Chepil, 1954b). Covers other than vegetative also reduce or eliminate wind erosion if they are sufficiently resistant and durable against the force of wind. Those include various dust palliatives such as asphaltic, resinous, and latex films, gravel pavements, and chemical dust binders.

Virtually all vegetative covers include both elements of roughness and cover and tend to reduce wind erosion on both counts. Pound for pound, a standing crop or stubble is more effective in controlling wind erosion than is flattened vegetation because it has greater total roughness. Pound for pound, a tall crop or stubble is more effective than a short one for the same reason (Chepil, 1944). On the other hand, fine vegetation or vegetative matter (such as wheat stubble) is a more effective cover than coarse (such as sorghum stubble) because it has a greater protective surface. Grass affords one of the best protective covers because it is finer than most cultivated crops, has a relatively great protective surface both above and below the surface of the ground, and is well anchored. Grass that is easily bent by wind is less effective in controlling erosion than grass that is not. More details on the relative effectiveness of different kinds and orientations of vegetative matter will be given under Section VI, A.

7. *Unsheltered vs. Sheltered Soil Surface*

A surface may be bare and the soil finely divided, yet the soil may not be eroded if it is sufficiently sheltered from the force of wind. Sheltering is afforded on the lee sides of natural wind barriers such as shrubs, trees, hills, or mountains, or by artificial wind barriers such as walls, picket fences, hedges, crop strips, and crop rows. The extent and degree of sheltering afforded by the barriers vary with their spacing, height, width, shape, and air penetrability (Bodrov, 1935; Bates, 1944; Woodruff, 1954; Staple and Lehane, 1955; Caborn, 1957).

8. *Large vs. Small Eroding Area*

The larger the unprotected field, the more it is erodible by wind, up to a certain limit. This is because the rate of soil movement (flow) increases with distance downwind across the wind-eroded field or adjoining fields until it reaches a maximum that a wind of a given velocity can sustain (Chepil and Milne, 1941a; Chepil, 1957c). Several contiguous erodible fields are in effect as erodible as if they were one. Sometimes whole communities become as one eroding field—a condition that makes wind erosion control an exceedingly difficult problem.

9. *Improperly vs. Properly Oriented Fields, Crop Strips, and Crop Rows*

Because the rate of soil flow increases with distance along the prevailing wind erosion direction, it follows that fields or field strips with their broad sides at right angles to, and their narrow sides parallel with, the prevailing wind will have the minimum overall rate of erosion (Chepil, 1957c). Field orientation is of little consequence where erosive winds blow equally from all directions. Under such conditions, small, nearly square fields are less subject to wind erosion and will trap the greatest amount of snow.

Orientation of crop rows with respect to prevailing wind direction is even more important than orientation of unprotected fields (Zingg *et al.*, 1952). This is because crop rows are usually so close together that sheltering of the soil by the rows rather than reducing soil avalanching becomes a dominant influence. When rows are oriented as nearly as possible at right angles to prevailing erosive wind, the soil is better protected from the wind and more snow is accumulated in the sheltered areas.

C. Soil Erosion and Its Resulting Conditions

1. *Initiation of Soil Movement*

If the wind is increased gradually, a velocity is reached that starts the most erodible grains in motion. This velocity is known as the *minimal fluid threshold velocity*. A further increase in velocity causes heavier (denser or larger) grains to be set in motion. Further increases cause movement of still heavier grains. Ultimately, for soils containing only erodible fractions a velocity is reached which is just high enough to move all sizes. This velocity is known as the *maximal fluid threshold velocity* (Chepil, 1945b). Usually soils are composed of erodible and nonerodible fractions, so that no velocity is available that will remove all the fractions. For such soils no maximal fluid threshold velocity exists.

The first type of movement of soil grains is in a series of jumps known as *saltation* (Fig. 11). The higher the grains jump, the more energy they derive from the wind.

The impacts from the most erodible grains moving in saltation cause the movement of the larger, denser, and smaller particles. In the field, knolls, ridges, and other more exposed or more erodible spots first start to erode. Once erosion has started, it spreads fanwise to leeward and the bombarding action of the particles in saltation causes the movement of other particles. The threshold velocity under the bombarding action from the most exposed and most erodible grains is known as the *impact threshold velocity* (Bagnold, 1943). Both the fluid and the impact threshold velocities are the same for the most erodible grains, but the impact threshold velocity becomes increasingly lower than the fluid threshold for grains of increasingly greater size and density.

The fluid and impact threshold drag velocities for dry grains greater than 0.1 mm. in diameter vary as the square root of the product of equivalent diameter of the grain and the density relationship of the fluid and the grain (Bagnold, 1943). This square root law may be expressed by

$$V_{*t} = a\sqrt{\frac{\rho'}{\rho} gD} \qquad (13)$$

in which D is the diameter of the grain, g the gravity constant, ρ' is the immersed density of the grain, ρ is the density of the fluid, and a is a coefficient whose value depends on the range of equivalent size of particles present on the eroding surface and on whether movement is

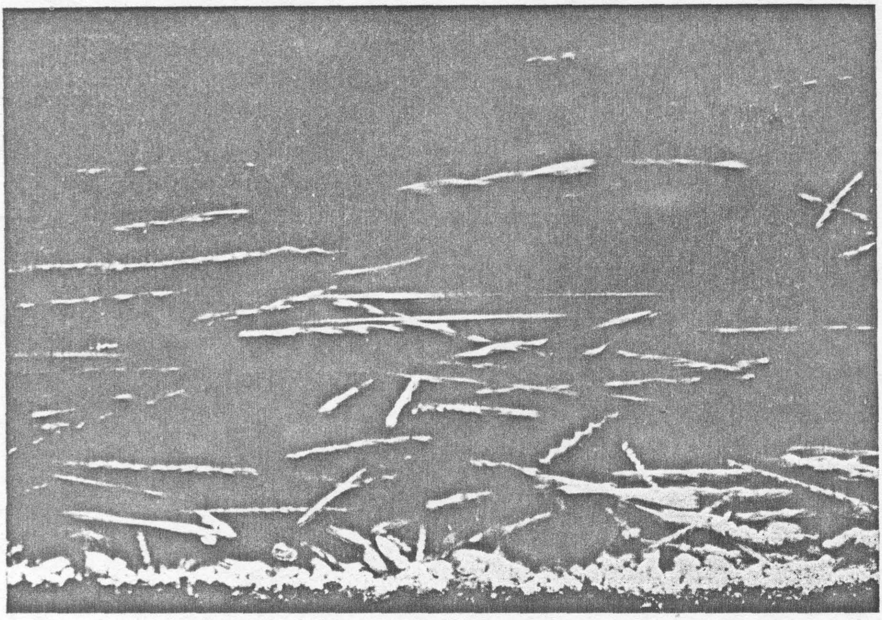

FIG. 11. Photograph of paths of wind-blown soil particles moved primarily in saltation. Wind direction is from left to right. The photographed area is 1 inch high and 1.5 inches wide. Exposure is 1/200 of a second. Under magnification the paths appear as distinct spirals, indicating that particles spin as they fly through the air. The rate of spinning ranges from 1,200 to 60,000 revolutions per minute.

initiated by direct pressure of wind or by pressure and bombardment from the most exposed and most erodible grains.

The relation between the threshold velocity v_t at any height z, equivalent diameter of the soil particles, and the roughness of the surface as exemplified by the value of k can be expressed by

$$v_t = 5.75\, a \sqrt{\frac{\rho'}{\rho} gD} \log \frac{z}{k} \qquad (14)$$

As shown from Eq. (14), the greater the value of k, which varies with roughness of surface, the lower the velocity (at some fixed height) required to move the particles. This relation applies only to a condition where the roughness elements are the soil fractions moved by the wind. It means that the larger the erodible particles or the higher they are perched on a rough surface, the higher they will protrude into the airstream and the greater the force of wind that would contribute to their movement, other factors being equal. On the other hand, where the roughness elements or the surface projections or barriers are nonerodible, the threshold law expressed by Eqs. (13) and (14) still applies, but the value of coefficient a is increased considerably. Under such a condition much of the surface drag is dissipated against the nonerodible fractions and only the residual drag contributes to the movement of erodible particles.

If the soil material is composed only of erodible particles of a limited size range, such as an increment of $\sqrt{2}$ commonly obtained by dry sieving, the value of coefficient a of Eqs. (13) and (14) based on centimeter-gram-second units is equal to about 0.1 for particles greater than 0.1 mm. in equivalent diameter. However, natural soil materials have a much wider range in size of fractions and therefore are associated with values of coefficient a larger and smaller than 0.1. If a soil, such as a commonly occurring dune material, is composed only of erodible fractions ranging from the largest down to the smallest erodible particles, the value of coefficient a of Eqs. (13) and (14) is only about 0.085. For such materials the threshold drag velocity varies as the square root of the average equivalent diameter of all the component particles (Chepil, 1958). Thus, the threshold drag velocity for a mixture of different equivalent sizes of erodible particles is lower than that required to erode only the largest of the particles. Movement of the larger particles is facilitated by bombardment received from the smaller particles moving in saltation.

2. *Soil Movement*

Movement in saltation causes two other types of movement—the rolling and sliding of coarser grains along the surface of the ground, known as *surface creep,* and the floating of fine dust particles through the air, known as *suspension.* The presence of coarse grains and fine dust particles in the soil hinders the movement in saltation (Chepil, 1958). Coarse grains hinder the movement by sheltering the finer, more erodible grains from the wind. Dust hinders the movement by cohering to the grains and to other dust particles. Dust is readily kicked up by grains moving in saltation in the same manner as dust is kicked up by traveling vehicles, animals, etc. Once kicked up in the air, dust particles can be lifted high in the atmosphere by upward velocity of eddies of erosive wind. The upward eddies of erosive wind have a velocity of at least 2 or 3 miles per hour, sufficient to lift silt and some very fine sand to an indefinite height. Dust clouds often extend 2 and 3 miles high and are the most visible and therefore the most dramatic aspects of "dust storms."

The proportion of the three types of soil movement varies greatly for different soils. In the cases examined, between 50 and 75 per cent of the weight of the soil was carried in saltation, 3 to 40 per cent in suspension, and 5 to 25 per cent in surface creep (Chepil, 1945a).

a. Rate of soil movement. If the wind velocity is greater than that required barely to move the soil grains, then, according to Bagnold (1943) for dune sands and Chepil (1945c) for dry soils

$$q = a\sqrt{D_e}\,\frac{\rho}{g}\,(V_*')^3 \tag{15}$$

in which q is the rate of soil movement (total weight of soil material moved past a unit width normal to the direction of movement and of unlimited height per unit time). Equation (15) shows that the rate of soil movement varies directly as the cube of the drag velocity V'_* and as the square root of the average equivalent diameter D_e of the soil particles moved by wind. The coefficient a varies greatly with different conditions. It varies with the size distribution of the erodible particles (Chepil, 1941; Bagnold, 1943), the proportion of fine dust particles present in the mixture (Chepil, 1941, 1945c), the proportion and size of nonerodible fractions (Chepil, 1941, 1950b), position in the field (Chepil and Milne, 1941a), and the amount of moisture in the soil (Chepil, 1956). All these factors, and perhaps many more, affect the rate of soil movement and hence the value of coefficient a. Equation (15) applies equally well to movement in saltation, suspension, and surface creep (Chepil, 1945a).

b. Quantity of erodible soil. The rate of movement of cultivated soils is seldom constant; it changes with the surface conditions of the soil, which, in turn, change with the duration of exposure to the wind and with the erosional history of the field. For that reason the weight of soil material removable from the surface by the wind under some conditions is a more accurate measure of erodibility of dry cultivated soils than the rate of soil removal. The weight of soil material X that is removable from a given area by the wind may be expressed in terms of drag velocity of the wind by

$$X = a\,(V_*')^5 \tag{16}$$

where the coefficient a varies with many factors.

The quantity of erodible soil for a given drag velocity varies in great measure with the degree of soil abrasion as influenced by the characteristic length of the eroded area. For that reason it is better to express erodibility in dimensionless form applicable to any size of eroding area, direction of wind, or units of measure by

$$I_w = a(V_*')^5 \tag{17}$$

In Eq. (17) I_w is the soil erodibility index, which is equal to X_2/X_1 where X_1 is the weight of soil material removable per unit area from a "small" area, such as in a wind tunnel, where the soil contains 60 per cent of clods greater than 0.84 mm. and X_2 is weight removable under the same set of conditions from soil containing any other proportion of clods greater than 0.84 mm. in diameter. "Small" area has a width not exceeding 30 feet along the direction of the wind (Chepil and Woodruff, 1959).

c. Dust concentration and visibility. The concentration of dust (weight of dust in unit volume of air) was found by Chepil and Woodruff (1957) to vary with height in accordance with an empirical power equation of the form

$$C_z = \frac{a}{z^b} \tag{18}$$

in which C_z is concentration of dust at height z above ground and a and b are constants. Constant a varies with the intensity of erosion and b is approximately equal to 0.28. Equation (18) agrees reasonably well with the basic formula of Schmidt as reported by Vanoni (1946) in his experiments with water.

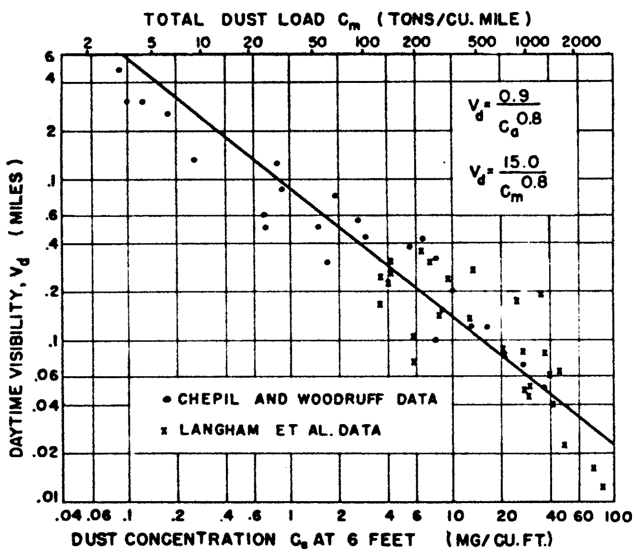

FIG. 12. Relation between daytime visibility and dust load and concentration (Chepil and Woodruff, 1957).

A quick estimate of an approximate total quantity of dust load suspended in the lower atmosphere can be obtained from daytime visibility data of Chepil and Woodruff (1957) and Langham *et al.* (1938), using Fig. 12. The total dust load C_m refers to the square mile against the earth's surface and 1 mile high. Dust clouds have been observed to extend up to more than 2 miles in height. The dust concentration above the 1-mile height may be estimated for any intensity of erosion by assuming the relationship given in Eq. (18). Such an estimate would be only approximate.

3. *Avalanching*

On an unprotected eroding field, the rate of soil flow is zero on the windward edge and increases with distance to leeward until, if the field is large enough, the flow becomes the maximum that a wind of a particular velocity can sustain. The acceleration of soil flow with distance downwind over an unprotected field is known as *soil avalanching* (Chepil, 1957c).

Maximum rate of flow is approximately the same for all soils and is about equal to that of dune sand. However, most fields are not large enough for development of maximum rate of soil flow.

The distance required for soil flow to reach a maximum on a given soil is the same for any erosive wind. It varies only and inversely with erodibility of a field surface. That is, the more erodible the surface, the shorter the distance in which maximum flow is reached (Table V).

TABLE V
Relation between Wind Tunnel Erodibility of a Field Surface and Distance for Soil Flow to Reach a Maximum[a]

Wind tunnel erodibility, I_w (dimensionless)	Distance in the field for soil flow to reach a maximum (feet)
920.0	180
300.0	300
50.0	1,100
39.0	1,600
19.0	2,200
7.5	3,900
6.1	4,100
5.1	5,200

[a] Data from Chepil (1959a).

Any factor that influences the erodibility of the field surface influences the rate of soil avalanching. The lower the proportion of nonerodible soil clods or the less the amount of crop residue, the greater is the erodibility of a field surface, the higher is the rate of soil avalanching and the narrower the field or field strips have to be to keep the rate of erosion down to some tolerable rate.

4. *Sorting*

The wind moves the finer and lighter particles faster than the coarser and denser ones (Udden, 1898; Fly, 1935; Moss, 1935; Daniel, 1936, Chepil, 1957a). The finer the eroded particles the greater is their speed, height, and distance of travel. The finer particles have greater mobility despite the fact they are less erodible.

The wind separates the soil into several distinct grades as follows:

(a) *Residual soil materials*: Nonerodible clods and massive rock materials that remain in place.

(b) *Lag sands, lag gravels,* and *lag soil aggregates*: Semierodible grains that have been moved primarily by surface creep.

(c) *Sand* and *clay dunes*: Accumulations of highly erodible grains that have been moved primarily in saltation.

(d) *Loess*: Dust lifted off the ground by saltation and carried high in the air and deposited in uniform layers both near and far from dunes. Dust is carried in true suspension. The composition of freshly deposited dust is like the composition of the loess laid down in the Pleistocene age (Swineford and Frye, 1945; Péwé, 1951; Warn and Cox, 1951; Chepil, 1957b). Huge deposits of loess in many regions of the world show the great importance of wind as a geologic mover of dust.

There are no distinct demarcations of size between the various grades of wind-sorted materials. The size limits of one grade overlap considerably with size limits of another grade (Chepil, 1957b).

In some cases, wind erosion virtually removes the surface soil (Zingg, 1954; Chepil, 1957a,b). *This nonselective removal* by wind is associated primarily with loess which was already sorted and deposited from the atmosphere during past geologic eras.

Another type of soil removal is *selective removal.* It occurs on soils developed from glacial till, residual material, mountain outwash, and sandy soils of various origins. On these soils the wind tends to remove the silt and clay and to leave the sands and gravels behind. This process often causes the surface soil to become progressively more sandy and therefore more erodible and less productive.

5. *Abrasion*

Abrasion by impacts of particles transported along the surface by wind is an important phase of the wind erosion process on all soils (Chepil, 1945d).

Soils usually are covered with a thin crust that is somewhat resistant to wind erosion. As soon as some soil particles are loosened and moved by wind, their abrasion against the surface causes the crust to disintegrate and exposes a more highly erodible soil (Fig. 12). Also, the nonerodible clods gradually break under impacts of saltating grains. The longer erosion continues, the greater is the quantity of erodible material formed by abrasion and the higher the rate of soil flow. The materials detached from clods and surface crust by abrasion accumulate on the leeward side of fields or, if they are fine, are carried far through the atmosphere.

Abrasion caused by wind-blown soil grains is also extremely injurious to plants. For example, yield of winter wheat forage at maturity was reduced 78 per cent and of grain 86 per cent after only one 10-minute exposure of young plants to soil movement caused by a 28-mile-per-hour wind at 6-inch height (Woodruff, 1956). The greater the intensity and the more prolonged the soil movement, the greater is the destruction of vegetation on the lee of an eroding area. By the same token, the lower the rate of erosion, the more vegetation tends to cover and stabilize the soil. The equilibrium between climatic environment, soil conditions, and vegetative growth shifts continually with the seasons and with the way man uses his land.

V. Soil Properties That Influence Wind Erosion

Chepil (1958) found that soil properties or conditions that influence wind erosion directly may be grouped into the following four categories:

(a) Stability of soil against erosion as influenced by cohesive and dispersive forces of water and raindrops.

(b) State of soil structure, such as size, shape, and density of erodible and nonerodible soil fractions.

(c) Stability of soil structure against breakdown by mechanical agents, such as tillage, abrasion from windblown materials, and direct force of wind.

(d) Stability of soil structure against breakdown by natural causes, such as wetting and drying and freezing and thawing.

The above-mentioned properties are known as the primary properties because they influence erodibility directly. Most of them in turn are influenced by basic factors inherited by or imparted to the soil. Until the influence of the primary soil properties or conditions is thoroughly understood and expressed, it will be difficult or impossible to evaluate the importance of the basic soil factors that affect the primary properties and erodibility by wind. The basic factors will be discussed in Section V, E, 1–4.

The most important primary soil conditions that influence wind erosion have been described in Section IV, B, 2–4. In this section, we shall indicate where these conditions exist in the soil, how they are created, and how best they may be maintained.

A. Cohesive and Dispersive Forces of Water and Raindrops

Soil erodibility by wind is a function of the cohesive force of the adsorbed water films surrounding the discrete soil particles. The resistance, r, due to cohesion of the water films among the discrete soil grains and to the force of gravity on the grains, must be overcome by the wind before erosion can occur. The values of resistance, r, were found to be equal to $6(M_e)^2$ where M_e is the equivalent moisture.

Since for "smooth" soil surfaces (with surface roughness elements not exceeding 1 inch in height) V'_* is equal to $\sqrt{\bar{\tau}/\rho}$, the rate of movement of moistened erodible particles on such surfaces, utilizing Eq. (15), may be expressed by

$$q = a\sqrt{D_e}\,\frac{\rho}{g}\left(\frac{\bar{\tau} - r}{\rho}\right)^{1.5} \tag{19}$$

and the relative quantity of moistened soil material removable from a limited area before soil movement ceases, utilizing Eq. (17), may be expressed by

$$I_w = a\left(\frac{\bar{\tau} - r}{\rho}\right)^{2.5} \tag{20}$$

Equations (19) and (20) apply only to conditions where moisture has been added to originally loose, dry soils. They do not apply to soils that have been moistened and then dried to various degrees, thereby causing a substantial degree of cementation of the originally discrete soil fractions—a cementation due to shrinkage of the water films on fine particles by drying.

Wetting and drying cause little cementation of drifted soil materials, such as those accumulated in drifts by wind, but they cause considerable cementation of most other soil materials. The drifted materials that cover much of the surface of eroded fields are composed essentially of water-stable grains devoid of fine dust particles required to bind them together. Only the impacts from a few grains moving in saltation are needed to separate the water-stable grains and to start them again in motion by the wind.

On the other hand, when a loose soil other than drifted material is wetted and dried, the fine particles tend to bind the whole soil body to form a somewhat compact mass more resistant to wind than was the originally loose soil. Then, too, a surface crust almost invariably is formed, owing to impacts of raindrops on the ground. Except at the immediate surface, the primary (water-stable) aggregates and the secondary aggregates, or clods, usually undergo little transformation by individual wetting from rain and drying. A greater change occurs in the degree of compactness and cementation among the various recognizable aggregates. This type of cementation has an important influence on erodibility by wind, but the degree of cementation generally is too weak to be detectable by wet or dry sieving. Thus, wet or dry sieving, or elutriation in water or air, does not measure directly some important phases of soil structural stability that influence the erodibility by wind. In addition to the above-mentioned conventional methods of structural analysis, other methods must be used if erodibility is to be determined fully. One of these methods is a direct measure of stability, or resistance, of the various structural units to breakdown by abrasion from windborne soil particles, as will be described next.

B. Mechanical Stability and Abradability of Soil Structural Units

Resistance of a dry soil to breakdown by mechanical agents, such as tillage, force of wind, or abrasion from windborne materials, is known as *mechanical stability*. It is due to coherence of the soil particles. Mechanical stability has been determined conveniently by dry sieving and repeated dry sieving on a rotary sieve (Chepil, 1951). Mechanical stability of the various phases of field structure is a relative measure of the resistance to disintegration by abrasion to which the soil is subjected when it is eroded by wind.

The relative resistance of the soil to abrasion by windborne soil particles has been expressed as the *coefficient of abrasion* (Chepil, 1955a). It is the quantity of soil material abraded off a soil aggregate per unit weight of abrader blown against the aggregate by a 25-mile-per-hour windstream. Since the amount of abrasion varies as the square of wind velocity, the coefficient of abrasion a can be expressed by the equation

$$a = A_v \left(\frac{25}{v}\right)^2 \tag{21}$$

in which A_v is the weight abraded per unit weight of abrader blown at wind velocity v expressed in miles per hour. The coefficient of abrasion (abradability) of the different structural units of the soil varies inversely with their mechanical stability, as determined by repeated dry sieving (Table VI). Furthermore, *modulus of rupture*, a measure of cohesive strength of soil briquets as determined by the method of Richards (1953), varies inversely with the coefficient of abrasion and inversely with the diameter of mechanical soil particles from which a briquet is formed.

Owing to abrasion, soil structure breaks down progressively as wind

TABLE VI
Relation between the Coefficient of Abrasion and Mechanical Stability of Different Phases of Field Structure of Soil[a]

Phase of field structure	Soil class	Coefficient of abrasion	Mechanical stability (%)
Consolidated fraction < 0.42 mm. from fresh drifts	Sandy loam	2.94	3.0
	Silt loam	1.92	8.8
	Silty clay loam	2.03	5.0
	Clay	2.45	4.6
Consolidated fraction < 0.42 mm. from residual soils	Sandy loam	1.48	17.0
	Silt loam	0.61	28.1
	Silty clay loam	1.14	27.3
	Clay	1.25	17.4
Consolidated residual soils	Sandy loam	0.46	40.8
	Silt loam	0.14	54.4
	Silty clay loam	0.23	65.4
	Clay	0.32	56.0
Clods ¼ to ½ inch diameter from residual soils	Sandy loam	0.011	83.8
	Silt loam	0.003	91.7
	Silty clay loam	0.005	90.6
	Clay	0.002	92.8

[a] Data from Chepil (1958).

erosion continues. The amount of breakdown depends on mechanical stability of the structural units. Initiation of perceptible soil movement for the first time in the field generally requires a much higher drag velocity than for succeeding windstorms, since the soil usually is covered with a transient surface crust that is initially resistant to wind erosion. As soon as some soil particles are loosened and moved by wind, their abrasive action against the surface causes the crust to disintegrate and expose a more highly erodible soil (Fig. 10). Then, too, the nonerodible clods gradually become broken down by impacts of saltating grains. The erodible fractions are being sorted continually from the less erodible fractions and usually are piled in hummocks in the vicinity of the eroded area. The longer erosion continues, the more erodible material accumulates on the leeward side of an isolated field and the lower is the velocity of wind required to initiate erosion.

Therefore, a range of threshold drag velocity for any soil depends on the previous erosional history of the field. This range varies from the original threshold velocity of the previously noneroded field to the threshold velocity of dry dune materials. The lowest threshold velocity for a dry dune material is about 13 miles per hour 1 foot above smooth ground (Chepil, 1945b). The highest threshold velocity for a previously noneroded soil is indefinite; some fields do not erode no matter how high the natural wind.

Surface soil, such as exists in the field after wetting and drying, is not homogenous, although often it appears to be so. It is composed of various types of structural units cemented together in varying degrees (Chepil, 1953b). The strength of cementation and, consequently, the abradability when the soil is dry vary greatly for different soils and different structural units of the soil. Two types of soil cements seem to be responsible for consolidation of the soil in different structural units: (1) water-insoluble and (2) water-soluble or water-dispersible. These cements appear to be responsible for the following types of structural units with distinct degrees of mechanical stability and abradability by wind: (1) primary (water-stable) aggregates; (2) secondary aggregates, dry aggregates, or clods; (3) fine materials among the secondary aggregates; and (4) the surface crust. These phases of field structure in cultivated soils are shown in Fig. 13. Each secondary aggregate in Fig. 13 is designated by a line surrounding a number of primary aggregates, of which the secondary aggregate is composed.

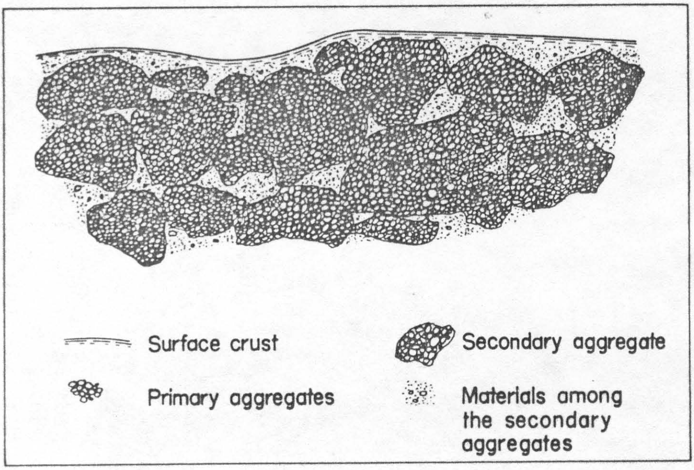

Fig. 13. Diagrammatic representation of structure of cultivated soil after wetting by rain and drying (Chepil, 1953b).

1. *Water-Stable Aggregates*

These primary aggregates, which seldom exceed 1 mm. in diameter in cultivated dryland soils, are held together by water-insoluble cements composed of clay particles and irreversible or slowly reversible inorganic and organic colloids (McCalla, 1950). The water-stable granules possess high strength of coherence and stability against the disintegrating forces of the weather (Chepil, 1951, 1953a, 1954a). Since they are the most stable structural units of the soil, they represent the units into which the secondary aggregates ultimately disintegrate, both by forces of weather and by abrasive action of wind-eroded soil particles. The water-stable aggregates are readily separated from the other soil fractions by the wind and usually are accumulated in drifts or mounds within and outside the eroded fields. Particles finer than the water-stable aggregates are removed in the form of dust, while the coarser fractions (clods, gravel, and rocks) remain behind as residual soil materials.

The drifted particles are principally individual water-stable aggregates or discrete sand grains. The drifted sand grains and clay aggregates exhibit the greatest mechanical stability, whereas those of intermediate texture exhibit a somewhat lower mechanical stability (Table VII). Without appreciable quantities of fine dust, the windblown grains tend to remain as discrete units, giving the soil materials a characteristically

TABLE VII
Mechanical Stability of Different Structural Units and of Fine Materials among the Structural Units of Wind-Eroded and Residual Soil Materials[a]

	Mechanical stability			
Structural units	Sandy loam (%)	Silt loam (%)	Silty clay loam (%)	Clay (%)
Particles > 0.42 mm. from fresh drifts (chiefly water-stable)	97.6	95.5	95.0	97.0
Dry aggregates or clods > 0.42 mm. obtained by dry sieving	83.8	91.7	90.6	93.8
Surface crust ⅛- to ¼-inch thick on residual soil	60.2	73.3	69.3	58.5
Particles < 0.42 mm. from residual soils after consolidation[b]	17.0	28.1	27.3	17.4
Particles < 0.42 mm. from fresh drifts after consolidation[b]	3.0	8.8	5.0	4.6

[a] Data from Chepil (1958).

[b] Consolidation was accomplished by spraying the dry soil material in a column 2 inches high with 1 inch of water, followed by drying.

mellow structure commonly referred to as "good tilth." An ideal structure from the standpoint of resistance to erosion by wind and of other desirable features is a soil that has a substantial proportion of water-stable aggregates greater than 1 mm. in diameter. Any treatment that would achieve this condition would aid greatly in establishing lasting resistance to wind erosion. Presently, dryland soils are virtually devoid of water-stable aggregates large enough to resist movement by wind. Their resistance to wind erosion has been enhanced by formation of secondary aggregates known commonly as clods.

2. *Secondary Aggregates or Clods*

Secondary aggregates are next in order of mechanical stability, depending on soil class, depth, and tillage treatment. They are held together in a dry state primarily by water-dispersible cements acting under pressure from depth and time. The cements are composed mainly of water-dispersible particles smaller than 0.02 mm. in diameter (Table VIII). When these fine particles are removed by repeated decantation

TABLE VIII
Relation between Dry Clod Formation and Percentage of Particles < 0.02 mm. Dispersed in Water[a]

Soil material and treatment	Soil textural class	Particles < 0.02 mm. dispersed in water (%)	Clods > 0.42 mm. after dry sieving (%)
Dry sieve fraction < 0.42 mm., consolidated[b]	Sandy loam	10.2	17.0
	Silt loam	19.3	28.1
	Silty clay loam	18.2	27.3
	Clay	9.8	17.4
Dry sieve, fraction < 0.42 mm. from which particles < 0.05 mm. were removed by shaking and repeated decantation in water, and then consolidated[b]	Sandy loam	0	0
	Silt loam	0	0
	Silty clay loam	0	.09
	Clay	0	.23

[a] Data from Chepil (1958).
[b] Consolidation was accomplished by spraying dry soil material in a column 2 inches high with 1 inch of water, followed by drying.

after shaking in water, the water-stable aggregates to which the clods disintegrate after being shaken in water are much like sand grains in that they fail to cohere to each other after a layer of them has dried (Chepil, 1958). Fine water-dispersible particles are necessary to bind the water-stable aggregates together to form clods.

Many clods maintain their identity for some time after repeated wetting and drying in the field. Individual rains have little influence on the form or compactness of clods below the surface, even after they lose their visible identity after the soil is wetted and dried. Only within a narrow zone of the immediate surface where the soil mass assumes a structure distinctly different from that below do the clods become appreciably disintegrated by impact of raindrops. Abrasive tests have indicated that after repeated wetting and drying the clods become merely embedded in the fine, loosely consolidated portion of the soil. The strength of cementation between the clods is generally much lower than within the clods; this is why blocks of soil abrade unevenly when exposed to impacts of windborne soil grains. In some extreme cases, however, a surface soil may become completely cemented into a single, seemingly homogeneous mass.

3. *Materials among the Clods*

The cohesive forces that exist among the clods after the soil has been wetted and dried vary greatly, as within the clods, depending on the number and the nature of wettings, on the depth and consequent pressure exerted against the soil, and on the physical-chemical nature of the soil. The degree of cementation that holds the clods together after the soil has been wetted and dried is due in large measure to the quantity of particles of the size of silt and clay dispersible in water (Chepil, 1958). Wetting apparently causes either some water-soluble or water-dispersible cements to become released from the originally discrete structural units; on drying, the cements cause a certain degree of cementation between the units. The greater the quantity of fine particles dispersible by water, the greater the degree of cementation among the structural units and the greater is the resistance of the soil to breakdown by mechanical forces after it has been wetted and dried.

Pressure likewise increases the cementation among the clods and other structural units. The greater the depth, the greater the pressure exerted on the soil and the greater the degree of cementation and mechanical stability among the structural units, until the whole soil mass, at a certain depth, may become strongly cemented together. This condition often is referred to as a massive structure. Tillage breaks the massive structure to various sizes of blocks referred to as clods. Tillage, if suitable, may bring the clods to the surface to resist erosion by wind.

The fine particles that tend to cement the clods and other structural units together are composed of silt, clay, and various materials of organic and inorganic origin. Dispersed silt, although usually not considered as a soil cement, acts as a weak cement of sufficient strength to resist considerably the force of wind (Chepil, 1955a). Silt particles are dispersed by water much more readily than clay particles. The presence of large quantities of dispersed silt particles in a soil appears to cause the formation of a compact, massive structure, which, while quite resistant to wind erosion, may present a serious structural problem otherwise. Bradfield and Jamison (1938) concluded that hard and intractable soils were usually those largely composed of fine silt having a single-grain structure when dispersed in water.

4. *The Surface Crust*

Because of impacts of rain, the soil material at the surface becomes more dispersed than the soil below. On drying, the dispersed soil forms a thin surface crust that is more compact and mechanically stable than some parts of the soil below. The crust often does not exceed one-sixteenth inch in thickness, but occasionally it may reach a thickness of one-fourth inch or more. The crust is easily recognizable by its dense, platy structure. This type of structure becomes less distinct with depth, until it merges with the soil below.

Medium-textured soils containing a high proportion of silt are most subject to dispersion in water and, therefore, these soils produce the thickest and most compact crust (Table IX). This property contributes to the usually high resistance of the medium-textured soils to erosion by wind. Sandy soils generally are less subject to surface crust formation, because they do not contain a high proportion of silt and clay. That property contributes considerably to the high erodibility of sandy soils

TABLE IX
Relation between Mechanical Stability of the Surface Crust and Percentage of Particles < 0.02 mm. Dispersible in Water[a]

Soil textural class	Soil material	Mechanical stability of crust (%)	Particles < 0.02 mm. dispersed in water (%)
Sandy loam	Drifted	44.7	6.2
	Residual	60.2	10.4
Silt loam	Drifted	60.8	10.2
	Residual	73.2	16.8
Silty clay loam	Drifted	59.7	10.4
	Residual	69.3	15.4
Clay	Drifted	38.1	4.9
	Residual	58.5	9.6

[a] Data from Chepil (1958).

by wind. Clay soils are highly variable with respect to wind erosion. Those that contain a high proportion of fine water-dispersible particles tend to puddle and resist erosion by wind. On the other hand, some clays are not subject to a high degree of dispersion; consequently, the surface crust and the clods tend to remain as fine granules, some of which are moved readily by wind.

Rain often carries some of the finely dispersed and water-soluble cementing materials downward, leaving the coarser particles, such as sand or water-stable aggregates, at the top. Some of these coarser particles remain loose on the surface and often contribute to the initial stage of wind erosion. Being on the surface, they dry rapidly. Consequently, these coarser particles may be moved by wind soon after a rain, even before the drying of the surface has become apparent. Abrasion from these particles tends to wear down the surface crust, to hasten the drying of the surface, and to accelerate the soil movement as long as the wind that is strong enough to move the soil material continues. Small showers often tend to smooth the soil surface, to loosen some of the surface particles, and, if the field is large, to accelerate rather than alleviate soil movement by wind.

On many soils the rate of soil movement is slow at the beginning, but it accelerates as the surface crust is worn through and a weakly consolidated soil beneath it is exposed to the wind (Chepil, 1953b, 1957c). The nature of the surface crust and its relation to erosion by wind perhaps can be interpreted best from its appearance as it is destroyed by abrasion with dune sand (Fig. 10). The surface crust proved completely stable under the same wind of 28 miles per hour without the abrader.

5. *Order of Mechanical Stability and Abradability*

Susceptibility of the soil to abrasion by impacts from windborne soil material varies inversely with its mechanical stability (Table VI). The order of mechanical stability from highest to lowest, and hence the order of abradability from lowest to highest, for the different structural units in a dry state is as follows: (1) water-stable aggregates, (2) secondary aggregates or clods, (3) surface crust, and (4) fine materials among the clods cemented together and to the clods after the soil has been wetted and dried. The last of the structural units at some depth below the surface may possess mechanical stability and abradability approaching that of clods. Mechanical stability tends to reduce wind erosion by resisting the breakdown of nonerodible units to smaller erodible particles.

C. Relative Importance of State and Stability of Soil Structure

Erodibility of the soil depends on (1) size, shape, and density of the structural units, and (2) mechanical stability of the structural units. The first may be referred to as the state of structure, and the latter as the stability of structure. Both phases of structure are measurable by elutriation, dry sieving, and repeated dry sieving. The relative importance of the state and stability of dry structure with respect to erodibility by wind varies with the area of the field, the roughness of the surface, and many other factors. If the area of the field is small, the amount of abrasion from erosion is small and erodibility of the field is determined primarily by the state of structure, or specifically by the proportion of discrete granules small enough to be moved by wind. If, on the other hand, the field is large, mechanical stability of the structural units is the more important factor. In such case, if the soil structural units lack mechanical stability, the presence of even a small quantity of loose, erodible material on the surface is usually sufficient for substantial disintegration of the structural units by abrasion from windborne material and for consequent intense erosion of the loosely cemented soil (Chepil, 1951).

The relative importance of the state and stability of structure of different soils is shown in Table X, based on wind-tunnel tests. A surface crust formed by spraying the soil with water and then drying (condition b) reduced greatly the quantity of soil material eroded by wind. However, when the soil that was wetted and dried was subjected to impacts of soil particles blown in from the outside (condition c), the crust soon was worn through, the rate of soil removal was increased considerably, and erosion continued as long as the stream of sand passed over the soil. The amounts of erosion occurring under condition b are comparable to those obtained in small, isolated fields where abrasion is limited; the amounts of erosion occurring under condition c, on the other hand, are applicable to those on the leeward sides of large, open fields where the intensity of abrasion from eroded particles is relatively great.

D. Seasonal Influences on Soil Structure and Erodibility

Biological activities and alternating wetting and drying and freezing and thawing have a strong influence on soil structural conditions and erodibility (Peele, 1940, 1941; McCalla, 1942, 1945, 1950; Martin, 1946). The structural conditions and erodibility fluctuate in accordance with the varying influences of the seasons.

Soil cloddiness and mechanical stability of clods are decreased and erodibility increased in winter in cases where the soil is moistened at

TABLE X

The Influence of State of Structure and Stability of Structure on Erodibility of Soil by Wind[a]

Soil class	Clods > 0.5 mm. equivalent diameter (%)	Degree of cementation between the clods after consolidation (%)	Amount or rate of soil erosion[b]		
			Condition a (tons/acre)	Condition b (tons/acre)	Condition c (tons/acre/min.)
Sandy loam	39.8	17.0	3.4	0.4	13.0
Silt loam	32.3	28.1	4.5	.2	5.6
Silty clay loam	42.1	27.3	2.9	.3	9.4
Clay	12.1	17.4	9.5	3.4	11.0

[a] Data from Chepil (1958).

[b] Conditions:

a—Exposure to wind of well-mixed, loose, and dry soils till movement ceased.

b—Exposure to wind after consolidating the soil by spraying with 1 inch of water and drying. Exposed till movement ceased.

c—Exposure to wind and a stream of windborne sand after consolidating the soil. Rate of sand flow was 1,000 g. per minute per 8-inch width.

least occasionally (Table XI). Also, the changes are greatest at or near the surface of the ground and least, if any, at a 6-inch depth.

The changes in cloddiness and stability of clods with depth vary with the seasons and with soil texture. The effects of tillage are temporary, because the forces of the weather, especially freezing and thawing of moist soil during the winter, tend to break the clods to sizes small enough to be moved by wind. As the clods at the surface are broken

TABLE XI
Influence of Seasons on Some Phases of Soil Structure and Wind Erodibility at Various Depths[a,b]

Depth (inches)	Season	Clods > 0.84 mm. (%)	Mechanical stability of clods (%)	Amount eroded in tunnel until movement ceased (tons/acre)
0 to 1	Fall	65.0	87.8	0.40
	Spring	46.7	72.7	1.50
1 to 3	Fall	71.9	87.8	0.24
	Spring	58.1	80.0	0.80
3 to 6	Fall	80.5	88.8	0.06
	Spring	80.5	90.6	0.09

[a] Data from Chepil (1954b).
[b] Averages for Cass loam during a three-year period at Manhattan, Kansas.

down, however, clods below the surface are being formed. Hence, repeated tillage of a proper type is useful in maintaining a cloddy surface indefinitely. The degree of cloddiness that can be maintained varies with the nature of the soil and with the depth and nature of tillage.

E. Basic Soil Factors

The basic soil factors affect wind erosion indirectly. The most important of these are soil texture, water-stable structure, organic matter, soil microorganisms and various products of organic matter decomposition, moisture as it influences wind erosion indirectly, calcium carbonate, water-soluble salts, and nature of the soil colloids. Some of these factors, such as soil moisture, affect erodibility directly by affecting the resistance to the forces of erosion and indirectly by influencing the state of structure such as size, shape, and density of the water-stable aggregates and clods.

1. *Soil Texture*

The relationship between the soil erodibility index I_w and the amount of clay, on the average, conforms with the equation

$$I_w = aG^b c^G \tag{22}$$

in which G is percentage (by weight) of clay in the soil and a, b, and c are constants (Chepil, 1952).

In general, the higher the proportion of silt (0.002 to 0.05 mm.) in the soil, the higher the percentage of nonerodible clods and the lower the soil erodibility. On the other hand, the higher the proportion of sand (0.05 to 0.5 mm.) in the soil, the lower the percentage of nonerodible clods and the higher the erodibility. These relations do not apply to all soil classes, nor especially to the finer textured soils. This is because clay, rather than silt or sand, is a predominant factor influencing erodibility by wind. Nevertheless, silt is a factor that tends to decrease, whereas sand tends to increase, the erodibility. In all soil textures, erodibility is inversely associated with the proportion of nonerodible clods as determined by rotary dry sieving.

Sand grains have little or no cohesive property, are readily loosened by force of impact of windborne materials, and execpt for the coarse grains 0.5 to 1 mm. in diameter, are easily carried by wind. Silt and clay, on the other hand, cohere after wetting and drying, and therefore seldom exist as individual particles but act as binding agents in the formation of nonerodible clods. The relative effectiveness of silt and clay as binding agents depends somewhat on their proportion to each other and to the sand fraction. The first 5 per cent of silt or clay mixed with sand is about equally effective in creating cloddiness, but the quality of the clods is different. Those formed with clay and sand are harder and less subject to abrasion by windborne sand than those formed from silt and sand. For proportions greater than 5 per cent and up to 100 per cent the silt fraction creates more clods, but the clods are softer and more readily abraded than those formed from clay and sand. The greatest proportion of nonerodible clods exhibiting a high degree of mechanical stability and low abradability is obtained in soils having from 20 to 30 per cent of clay, 40 to 50 per cent of silt, and 20 to 40 per cent of sand (Chepil, 1955a).

2. *Water-Stable Structure*

The effects of water-stable aggregates and fine water-dispersible particles on the state and stability of soil clods and on erodibility by wind were discussed in Section V, B, 1–3. This section is devoted only to the influence of the total water-stable structure on soil cloddiness and erodibility by wind.

Russell (1938) in his review on soil structure referred to the water-stable particles (as conventionally determined by sedimentation, elutriation, or sieving of soil in water) as the building blocks of field structure of soils. Some of these particles are primary particles of sand, silt, and clay and some are water-stable aggregates, often referred to as primary aggregates. Few primary particles or aggregates exist individually in soils. They usually are grouped into secondary aggregates commonly referred to as clods (Fig. 13).

Chepil (1943) indicated that both coarse (> 0.42 mm.) and fine (< 0.02 mm.) water-stable particles increase cloddiness and decrease erodibility by wind. He (Chepil, 1953a) further indicated that each unit per cent change in water-stable particles > 0.84 mm. influences the proportion of nonerodible clods and erodibility about equally (Table XII). The relations between the dry nonerodible clods *B*, > 0.84 mm.

TABLE XII

Relation of Water-Stable Structure to Dry Soil Structure and Erodibility by Wind[a]

Soil class	Number of fields	Water-stable fractions > 0.84 mm. (%)	Water-stable fractions < 0.02 mm. (%)	Clods > 0.84 mm. (%)	Amount eroded in tunnel[b] (tons/acre)
Sand	3	4.8	1.7	8.3	49.8
Loamy sand	12	3.8	3.0	6.9	29.4
Sandy loam	13	3.0	10.0	36.6	5.4
Loam	25	3.2	13.8	44.4	2.2
Silt loam	35	3.0	17.8	48.6	1.9
Clay loam	5	4.5	14.0	43.6	1.5
Silty clay loam	10	5.2	14.4	49.4	1.2
Silty clay	1	3.9	10.8	19.2	3.4
Clay	8	1.9	10.8	20.2	6.7

[a] Data from Chepil (1953a).

[b] Drag velocity of wind, 61 cm. per second.

in diameter, and the water-stable fractions conform with the simple arithmetic equation

$$B = a(Y - b) \tag{23}$$

in which Y is the percentage of water-stable fractions < 0.02 and > 0.84 mm. in a soil and a and b are constants. For the first inch of soil, a and b were found to have a value of 3 and 4, respectively. The constants change with depth in soil, probably due to changes in soil compaction. The coefficient of correlation between the percentage of nonerodible clods B and the water-stable fractions < 0.02 mm. and > 0.84 mm. computed from the 112 cases shown in Table XII is 0.70. This is very highly significant, since the required value for significance at the 1 per cent level for 112 cases (Table XII) is 0.26.

The relation between the soil erodibility index I_w and the percentage of water-stable fractions < 0.02 mm. and > 0.84 mm. is exponential and conforms with the equation

$$I_w = ab^{-Y} \tag{24}$$

in which a and b are equal to 1000 and 1.35, respectively. The coefficient of correlation between the log of erodibility and the percentage of water-stable fractions < 0.02 mm. and > 0.84 mm. is 0.72. This correlation is highly significant, as for Eq. (23).

Chepil (1953a) found that the water-stable fractions < 0.02 mm. and < 0.84 mm. may vary together with or independently of each other. No single-value property, such as percentage of water-stable aggregates above or below a certain size, can be used, therefore, as an indicator of erodibility by wind. The whole size distribution of water-stable fractions must be taken into account.

3. *Organic Matter*

General observations in Canada have indicated that high organic matter content of soil is conducive to high fertility and good tilth but facilitates erosion by wind (Hopkins, 1935; Hopkins *et al.*, 1946). Preliminary experiments undertaken to verify these observations showed that wheat straw in the process of decomposition increased soil cloddiness and decreased erodibility by wind (Canada Department of Agriculture, 1949). These trends were reversed after the straw was decomposed. When samples of soil were brought together under identical climatic conditions and treatment, the black soils containing a relatively high content of decomposed organic matter (humus), contained more wind-erodible fractions than did the brown and the chestnut soils, and were more susceptible to wind erosion.

Chepil (1955b) noted from field experiments on some soils of the Great Plains of the United States that during the time of rapid decomposition of vegetative matter the proportion of coarse water-stable aggregates > 0.84 mm. in diameter increased, the content of fine water-stable particles < 0.02 mm. decreased, soil cloddiness by percentage of nonerodible dry soil aggregates > 0.84 mm. increased, and erodibility, as determined by wind tunnel tests, decreased (Table XIII). The greater the quantity of vegetative matter added to soils, the more pronounced were these effects initially. When additions of vegetation to soils were stopped, these effects gradually diminished, disappeared in about a year or two depending on the quantity of vegetative matter initially added, and then shifted in reverse and remained in reverse for at least 2 to 5 years depending on the original amount of vegetative matter added. The more vegetative matter added, the longer these effects lasted. Four years after additions of vegetative materials were stopped, all of the nine widely different soil types tested showed a significantly lower degree of soil cloddiness and higher erodibility by wind.

TABLE XIII
Influence of Decomposing and Decomposed Vegetative Matter on Soil Structure and Erodibility by Wind[a]

Amount vegetative matter added (%)	Water-stable particles > 0.84 mm. (%)	Water-stable particles < 0.02 mm. (%)	Clods > 0.84 mm. (%)	Relative amount of erosion in wind tunnel (%)
Vegetative matter still decomposing (0.5 year after adding)				
0	1.4	16.3	38.1	100
1	2.0	13.2	39.1	90
6	5.1	11.3	43.7	79
L.S.D. 1% level	1.2	1.7	6.7	N.S.
L.S.D. 5% level	0.9	1.3	5.1	N.S.
Vegetative matter decomposed (4 years after adding)				
0	0.9	11.5	48.8	100
1	0.8	10.9	47.6	118
6	1.2	9.4	42.4	282
L.S.D. 1% level	0.3	1.5	3.7	180
L.S.D. 5% level	0.2	1.1	2.8	136

[a] Data from Chepil (1955b).

The above-mentioned results substantiate, in general, results of numerous previous studies on the effects of decomposition of vegetative matter on soil aggregation and deaggregation. The literature reveals that numerous cementing substances produced by soil microörganisms as they attack the vegetative matter bind soil particles to form aggregates. The cementing substances may be divided into these major categories: (a) lyophyloc and lyophobic colloids consisting of decomposition products of plant residues (Myers, 1937; McCalla, 1945); (b) the microorganisms themselves and their secretory products such as mucus, slime, or gum (Peele, 1940; Martin, 1942; McCalla, 1950); and (c) polysaccharides synthesized by some microorganisms (McCalla, 1945; Martin, 1946).

The aggregating effects of the initial products of decomposition are temporary (Browning, 1944; McCalla, 1945). Aggregation declines as the products are destroyed by other microorganisms (Martin, 1942). Incorporating the vegetative matter into the soil is not as important as leaving it on the surface, where it decomposes less rapidly and, therefore, continues to replenish the cementing products for much longer periods (Havis, 1943; McCalla, 1945). Improved aggregation persists long after the bacterial population has declined (Peele, 1941) but remains only as long as the initial decomposition products exist (McCalla, 1950). The products concentrate in and around the water-stable soil aggregates (Hide and Metzger, 1939).

Although many initial cementing substances persist in the soil only a short time, others like the polysaccharides persist for long periods. It is likely that their persistence is due to combination with the mineral soil constituents that render them resistant to decomposition (Martin, 1946). In such a combination they probably contribute to the more water-stable soil structure.

Increases in soil aggregation are not discernible until after decomposition of vegetative matter has begun. The aggregating effects apparently are due to the products of decomposition and not particularly to the binding action of vegetative fibers in the soil. These sticky products of decomposition increase the size of both the water-stable aggregates and the dry (secondary) aggregates, or clods. These products are not entirely water-soluble; otherwise water-stable aggregates would not be formed. Many of the water-stable aggregates formed by decomposition of the vegetative matter are large enough to resist wind erosion.

Gradually, the initial cementing materials lose their sticky property or are destroyed and replaced by secondary materials. Mechanical forces of expansion and contraction of the soil by wetting and drying and especially by freezing and thawing apparently cause the secondary cements to break up and the coarse primary and secondary aggregates to disintegrate to a more or less granulated condition. The secondary cements are more brittle and cause more granulation than do the initial products. The granules are essentially water stable. They form a friable, mellow soil which is more erodible by wind.

High organic matter levels are essential to maintenance of soil fertility, and high soil fertility must be maintained to produce more vegetative matter. Continual additions of vegetative matter to the soil should tend to produce some wind-resistant aggregates and should tend to counterbalance excessive granulation and increased wind erodibility caused by the secondary products of decomposition. On the basis of information derived from studies on this subject, the benefits obtained from the primary products of decomposition in augmenting resistance of soil to wind erosion are small compared to the detrimental effects from the secondary products of decomposition collectively known as "humus." However, a high humus content of the soil must be maintained *despite* these detrimental effects, because the beneficial effects of humus in augmenting soil fertility far exceed the detrimental effects. Greater benefits to control erosion, no doubt, would be derived by leaving as much living or dead vegetative matter as possible anchored on top of the ground to protect the soil surface from wind. Thus, vegetative cover, not just organic matter, is the key to effective soil stabilization and conservation.

4. *Calcium Carbonate*

Hopkins (1935) observed in Canada that soils high in free calcium carbonate ($CaCO_3$), or lime, and organic matter have been eroded severely by wind. Hardt (1936) concluded from his investigations of muck soils in Bavaria that the high content of lime, particularly in the clay fraction, appreciably increases erodibility by wind, but that organic matter, or humus, has little influence on erodibility of those soils.

Chepil (1954a) carried out extensive field studies on the influence of powdered, precipitated $CaCO_3$ and decomposed organic matter (humus) on soil structure and wind erodibility of some soils of the central United States. For all soil textures tested, except loamy sand, addition of precipitated $CaCO_3$ to soils in the field decreased soil cloddiness and mechanical stability of clods and increased erodibility by wind, as shown by example in Table XIV. The differences in erodibility produced by adding different quantities of $CaCO_3$ were generally highly significant. Except for loamy sand, the greatest effects were obtained with about 3 per cent of $CaCO_3$. Amounts greater and smaller than this had somewhat lesser effects.

On loamy sand, the more $CaCO_3$ added, the greater was the increase in soil cloddiness and mechanical stability of clods and the decrease in erodibility by wind. This soil class is exceedingly erodible by wind, and adding even as much as 10 per cent of $CaCO_3$ left it in a condition still much more erodible than any of the other treated and untreated soils. It is expected that results with sand would have been similar to those with loamy sand.

The foregoing results remained about the same for 5 years after treatment, when the experiment was terminated. It is apparent that effects from lime last as long as lime remains in the surface soil.

Results obtained with high-lime and low-lime soils of similar texture and similar content of organic matter substantiated the results obtained by additions of lime to soils (Chepil, 1954a). Erodibility by wind apparently was unaffected where the free lime content did not exceed 0.3 per cent.

Adding $CaCO_3$ to soils had virtually no effect on the size distribution of water-stable aggregates except to increase the proportion of water-stable particles < 0.02 mm. in diameter. Analysis of particle size distribution of the lime itself indicated that the increases in this fraction in soil were due to the lime particles added rather than to dispersion of the soil. However, when the soil contained a high proportion of humus, addition of lime decreased the proportion of water-stable particles < 0.02 mm. in diameter (Canada Department of Agriculture, 1943). Apparently the lime tended to aggregate the fine discrete particles < 0.02 mm., but only in the presence of humus. Reduction of these fine particles decreased soil cloddiness and erodibility by wind, as already indicated in Section E, 3; hence the highest erodibility was recorded for soils containing the highest quantity of both $CaCO_3$ and humus (Table XV).

TABLE XIV

Effect of Calcium Carbonate on Soil Structure and Erodibility by Wind[a]

Soil type	Amount of $CaCO_3$ added (%)	Water-stable aggregates > 0.84 mm. (%)	Water-stable aggregates < 0.02 mm. (%)	Clods > 0.84 mm. (%)	Mechanical stability of clods (%)	Amount eroded in wind tunnel[b] (tons/acre)
Hastings,	0	1.7	24.4	68.6	87.6	0.27
Keith, and	1	1.9	24.1	64.3	81.4	0.50
Baca silt	3	1.8	24.2	59.4	84.0	0.57
loams	10	1.9	28.9	65.7	88.2	0.32
Dalhart	0	0.9	13.4	57.7	83.5	0.62
fine	1	1.2	11.8	52.8	82.2	0.86
sandy	3	1.0	13.6	51.6	80.4	1.00
loam	10	0.9	18.6	55.3	83.2	0.63
Pratt	0	1.2	3.9	11.0	31.2	16.40
loamy	1	0.8	3.5	13.5	31.4	14.00
fine	3	1.6	5.7	20.5	49.7	7.00
sand	10	0.9	10.5	39.4	68.1	2.10

[a] Data from Chepil (1954a).

[b] From a 5-foot-long tray and with a drag velocity of 61 cm. per second.

The effects of precipitated $CaCO_3$ on sand and loamy sand are similar in some respects to the effects of quartz silt. Probably this is because the crystals in precipitated $CaCO_3$ when shaken in water are predominantly of the size of silt. Silt is a mild cementing agent and is partly responsible for the formation of fragile secondary aggregates or clods. As shown by Chepil (1955a), small initial amounts of silt are very effective in reducing erodibility of sand. Addition of 10 per cent $CaCO_3$ to Pratt loamy fine sand raised the proportion of water-stable particles of the size of silt and clay from 3.9 to 10.5 per cent and reduced erodibility from 16.4 to 2.1 tons per acre (Table XIV). This reduction in erodibility was virtually the same as that produced by adding the same proportion of quartz silt.

TABLE XV
Some Properties of Soils 2½ Years after Application of Calcium Carbonate and Ground Wheat Straw[a, b]

Amount and kind of material added	$CaCO_3$ (%)	Organic matter (%)	Clods > 0.84 mm. (%)	Mechanical stability of clods (%)	Amount eroded in wind tunnel[b] (tons/acre)
None	0.67	2.53	65.7	62.6	0.33
3% $CaCO_3$	3.13	2.57	57.0	59.6	0.61
3% $CaCO_3$ and 3% straw	3.41	2.78	44.7	50.6	1.60
10% $CaCO_3$	9.10	2.43	53.8	59.1	0.84
10% $CaCO_3$ and 10% straw	9.08	4.09	35.4	53.1	2.95

[a] Chepil (1954a).
[b] Averages of results obtained with Baca silt loam, Larned sandy loam, and Sutphen clay of the brown, reddish chestnut, and black soil zones, respectively.

On other than sand and loamy sand the action of precipitated $CaCO_3$ is considerably different from that of quartz silt. In soils containing an appreciable proportion of clay, $CaCO_3$ appears to weaken the cementing strength of the clay and causes the clods to soften and granulate. It has little influence on the state of the primary or water-stable aggregates. It primarily weakens the bonds that hold the water-stable aggregates together to form clods. This action is probably basically due to the flocculation phenomenon, which may be observed clearly when precipitated $CaCO_3$ is shaken in water.

Thompson (1952) asserts that the presence in soils of large amounts of calcium, usually present in the form of $CaCO_3$, tends toward the development of a granular soil structure. If the granules are small enough they will be eroded readily by wind. More often than not, granulation of dryland soils tends to induce wind erosion (Hopkins *et al.*, 1946).

In semiarid regions, soils are characterized generally by a layer of $CaCO_3$ accumulation, which normally lies just below the solum. This layer often is brought up to the surface by tillage implements, especially where some of the soil has been removed by erosion. Exposure of the $CaCO_3$ layer increases the hazard of wind erosion. Higher ground, such as a knoll, commonly is eroded to expose this layer. Knolls frequently cause erosion of adjacent lands by serving as focuses from which $CaCO_3$ may be spread. Such areas are a serious erosion hazard to surrounding lands and should be protected specially, as with grass.

In humid regions, applications of lime are required sometimes to correct soil acidity. The amounts of ground limestone applied in such cases range from 2 to 5 tons an acre, according to the degree of soil acidity. As shown from studies by Chepil (1954a), these amounts are too small to have an appreciable effect on soil structure and erodibility by wind. Moreover, the favorable soil moisture conditions in these regions almost preclude the hazard from wind erosion.

VI. Wind Erosion Control

Soil stabilization proceeds under natural conditions or is accomplished by man usually in three major successive stages: (1) trapping of moving soil particles; (2) consolidation and aggregation of trapped soil particles; and (3) revegetation of the surface.

Trapping of eroding soil particles is known as the stilling of erosion. Trapping may be accomplished by roughening the surface, by placing barriers in the path of the wind, or by burying the erodible particles by tillage. Trapping is accomplished naturally by soil crusting resulting from rain followed by a slow but inevitable process of revegetation.

The height to which particles rise in saltation has an important bearing on the most effective methods of stilling wind erosion. This is because saltation is the cause of all other forms of soil movement and is the major cause of soil abrasion. The ratio of height of rise to the horizontal equivalent of grain leap is about 1:7 for rise up to 2 inches, 1:8 for 2 to 4 inches, 1:9 for 4 to 6 inches, and 1:10 for heights above 6 inches. The capacity of stubble or ridged strips to trap particles in saltation is governed by the width of the trap strip and its receptiveness (Chepil, 1945a). The strip should be wide enough so particles will not jump over it and continue their movement, and it should be receptive enough so all the saltating particles that enter it will come to rest. In addition, a trap strip must be wide and high enough to allow sufficient reservoir for trapped soil so that at no time will it fill to its maximum capacity.

Besides the use of trap strips, the whole eroding surface may be roughened or covered with any material that stills erosion.

Methods of stilling wind erosion are known as *emergency methods*

(Woodruff *et al.*, 1957). Their effects are only temporary. Once erosion is stilled, plant cover must be established or plant residues must be maintained for more permanent control.

Both temporary and permanent control of wind erosion employ a single principle, known as the principle of surface barriers and cover. Perhaps the simplest way to explain it is by describing the behavior of bare soils subjected to an erosive wind.

In bare soils containing a mixture of erodible and nonerodible fractions, the quantity of soil removed by wind is limited by the height and number of nonerodible fractions that become exposed on the surface. If these soils are unaffected by encroachment of erodible material from the outside and if the length of the eroded area along the direction of the wind is limited, the removal of erodible fractions continues until the height of the nonerodible fractions that serve as barriers to the wind is increased to a degree that affords complete shelter to the erodible fractions. Movement then ceases (Fig. 14). The time required for movement to cease varies greatly with the soil structural conditions and the length across the field parallel to wind direction. The smaller the size of nonerodible fractions, the higher is the initial rate of soil movement q and the shorter the time required for movement to cease. The higher the proportion of erodible to nonerodible fractions, the higher is the initial rate of soil removal and the longer the time required for movement to cease. Also, the larger the field the greater the time required for removal of erodible fractions.

If the soil contains a large proportion of erodible fractions, few nonerodible clods per unit area of ground become exposed by the wind. The nonerodible clods under such a condition have to reach a considerable height before soil removal will cease. If, on the other hand, the soil contains a small proportion of erodible fractions, many nonerodible clods will be exposed on the surface by the wind and their height when soil movement ceases will be relatively low. The greater the number of clods exposed on the surface, the lower is their height when soil movement ceases.

At a stage when soil removal ceases, the ratio of distance between the nonerodible barriers divided by the height of the barriers remains constant for any proportion and size of nonerodible fractions present in the soil. The ratio is known as the *critical surface barrier ratio.*[2] It is a ratio of distance between the nonerodible surface barriers, D_s, to the height of the barriers, H, that will barely prevent the movement of

[2] Chepil (1950a) originally called this the critical surface roughness constant. The present term is believed to be more generally appropriate.

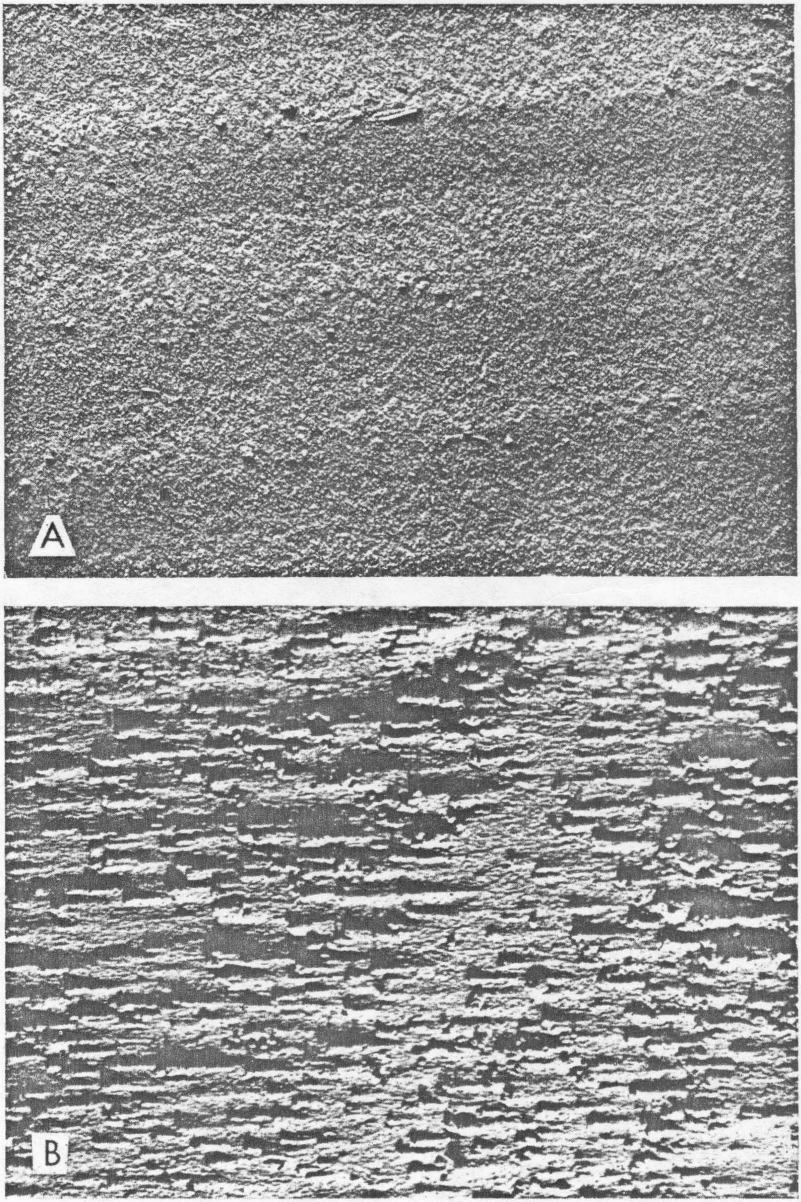

Fig. 14. Appearance of a silt loam composed of 92 per cent nonerodible fractions (A) before exposure to wind, and (B) after exposure for the period required for soil removal to cease. Drag velocity of the wind was 60 cm. per second and wind direction was left to right (Chepil, 1958).

erodible fractions by the wind. It is equal to D_s/H. On cultivated soils this ratio was found to have a value of 4 to 20, depending on the drag velocity of the wind and on the threshold velocity of the erodible soil fractions (Chepil, 1950a). The critical surface barrier ratio of 4 means that the surface barriers of height H will prevent the movement of soil within a distance of 4 H downwind of the barriers. This dominant principle of surface barriers governing the erodibility of bare, cultivated soils can be expressed by

$$I_w = a \frac{\rho_u}{\rho_e} \frac{W_e}{W_u} (V_2 - V_1) \quad (25)$$

in which I_w is the relative quantity (weight) of soil erodible from unit area of ground; e and u are densities (weights per unit volume) of erodible and nonerodible soil fractions, respectively; W_e and W_u are relative weights (in per cent) of erodible and nonerodible soil fractions, respectively; V_1 is volume of nonerodible surface barriers before exposure to wind; V_2 is volume of such barriers (in cc./sq. cm.) after soil movement has ceased, and a is a coefficient which, for the units used, has a value of about 6. If the density of erodible and nonerodible soil fractions is the same, the expression $\rho_u/\rho_e = 1$ and therefore may be dropped out.

The critical surface barrier ratio is in fact an *effective distance* between nonerodible surface barriers (measured in terms of heights of such barriers) required to reduce the quantity of erosion to zero. The effective distance, D_s/H, may be expressed by

$$\frac{D_s}{H} = \frac{a}{V_* - V_{*t}} \quad (26)$$

in which V_* is the drag velocity of the wind, V_{*t} is the minimal drag velocity required to initiate movement of erodible soil particles, and a is a constant which varies with the characteristics of the surface barriers, such as their shape and porosity (air penetrability).

If the nonerodible surface barriers are extremely low, as they would be for fine gravel, a relatively large number of the gravel pieces would be needed to protect the erodible fractions from the wind. The gravel pieces in such cases would protect the erodible fractions more by covering than by sheltering them from the wind. Thus, virtually all nonerodible materials placed on the surface of the ground to control wind erosion have an element of cover in addition to barriers which protect the erodible soil fractions from the wind. The principle of surface barriers and that of cover is therefore inseparable.

The principle of surface barriers and cover that governs the erodibility of cultivated soils is clearly manifested where the eroding area is small. The larger the area the greater the time required for erosion to cease. In fact, in large fields soil removal seldom ceases for a given wind. On the average, about 120 hours of continuous exposure to erosive wind blowing from a single direction would be required to stabilize a one-half-mile length. Erosive winds, however, seldom blow continuously from one direction for such periods. A change in wind direction also would prolong the period required to stabilize a field. Then, too, great quantities of nonerodible fractions in large fields are converted to erodible particles by abrasion from the moving soil particles. The nonerodible surface barriers under such conditions tend to be destroyed and the rate of soil movement tends to accelerate rather than decrease, as is usual in small, isolated fields. The decrease and ultimate cessation of soil movement are possible only if the surface projections or barriers are indestructible by wind erosion. The desert pavement composed of a mantle of nonerodible gravel is one example of virtual indestructibility of a stabilized surface.

The principle of surface barriers and cover extends beyond the surface roughness elements composed of nonerodible soil clods. It extends to almost all elements employed in wind erosion control, such as vegetative covers, soil ridges, windbreaks and wind barriers of various sizes and characteristics, and crop strips. All these elements of wind erosion control are designed to: (a) take up some or all of the wind force so that only the residual force, if any, is taken up by the erodible soil fractions; (b) trap the eroded soil, if any, on the lee or among surface roughness elements or barriers, thereby reducing soil avalanching and intensity of erosion and preventing erosion from spreading to other fields and farms.

A. Vegetative and Other Types of Cover

The importance of vegetative protection on the land cannot be overstressed as it is the one generally applicable method for permanent and effective control. Zingg (1954) in reporting results from studies of different field surfaces stated that different amounts, types, and orientations of residues removed 5 to 99 per cent of the direct wind force from the immediate soil surface.

Natural vegetative covers are perhaps the most effective, easiest, and most economical to maintain in agricultural areas. All the common crops, such as grasses, wheat, sorghum, corn, legumes, and cotton, provide cover of varying degrees of effectiveness where wind erosion is a hazard. In addition to the cover grown in place, crop residues often are placed artificially on the soil to provide temporary cover until permanent vegetation can be established. Chepil *et al.* (1960) reports such applications, if well anchored, to be an effective, economical way to control wind erosion.

Other than nonprocessed vegetative covers are used principally on nonagricultural land where it is not feasible to obtain cover by growing and managing vegetation. Some of the nonvegetative and processed vegetative materials used are gravel and crushed rock, various surface films such as resin-in-water emulsion (petroleum origin), rapid curing cutback asphalt, asphalt-in-water emulsions, starch compounds, latex-in-water emulsion (elastomeric polymer emulsion), by-products of the paper pulp industry, and wood cellulose fiber. These materials may be used as the only cover or as temporary expedients to protect the land while a natural vegetative cover is being established. Highway and military departments are particularly interested in these materials for stabilizing highway shoulders and ditches, ammunition dumps, airfield landing strip shoulders, and other conditions resulting from construction where there is a great need for quick, effective soil stabilization.

The relative effectiveness and the maintenance of different kinds of vegetative and nonvegetative covers will be discussed in this section.

1. *Effectiveness*

Grasses and legumes once they are established are usually most effective because they provide a dense, complete cover. Wheat and other similar small grains are effective after they have passed the crucial 2 or 3 months after planting period. Corn, sorghum, and cotton are only of intermediate effectiveness, principally because they are planted in rows too far apart (24 to 42 inches) to protect the soil.

After the plants have completed their growth and the residue becomes the primary cover, the durability of the residues as measured by the resistance to decay by natural weathering largely determines their effectiveness. Duley (1958) in discussing some of the general characteristics of different kinds of residue indicated that legume residues tend to decay rapidly because they contain high amounts of protein which supply nitrogen for the organisms that promote decay. He found corn and sorghum stalks to be quite durable, especially when on top of the soil. He found wheat and rye straw more resistant to decay than oat straw.

The importance of density and orientation of residue on effectiveness for wind erosion control is well illustrated by results of some recent research by Siddoway (Table XVI). The more erect and the finer and denser the residue, the smaller the amount of erosion.

Gravel and crushed rock of any size > 2 mm., if applied in sufficient quantities, have been found, generally, to provide good wind erosion control. Chepil *et al.* (unpublished data, 1962) also have reported that fine, medium, and coarse gravel spread uniformly at 20, 50, and 100 tons per acre, respectively, adequately controlled wind erosion even on dune sand where no traffic was involved.

TABLE XVI
Average Effects of Kind and Orientation of Crop Residue on Erosion of Sandy Loam Soil by Wind of Uniform Velocity[a]

Quantity of crop residue above soil surface (pounds/acre)	Quantity of soil eroded in a wind tunnel			
	Covered with wheat residue		Covered with sorghum residue	
	Standing, 10 inches high (tons/acre)	Flat (tons/acre)	Standing, 10 inches high (tons/acre)	Flat (tons/acre)
0	16.0	16.0	16.0	16.0
500	2.8	8.5	13.0	14.5
1,000	0.1	2.5	8.1	10.4
2,000	T[b]	0.1	3.9	5.3
3,000	T	T	1.4	2.2
6,000	T	T	T	0.2

[a] Unpublished data from F. H. Siddoway.
[b] T = trace, insignificant.

Most of the other nonvegetative materials stabilize soils against wind erosion by forming a surface film. These materials usually are dispersed in water and sprayed on the soil surface. Chepil (1955c) and Chepil *et al.* (unpublished data, 1962) have indicated the following desirable characteristics for surface films: (1) they should be indispersible in water, durable, yet porous enough to allow percolation of water; (2) they should be weak enough for seedling penetration; (3) they must be able to maintain their sticky property indefinitely when used as permanent wind erosion control covers; and, (4) they must be easy to apply. If excessive dilution with water is required, they lose their effectiveness, and if they must be heated before application, special equipment is needed.

Although none of the group of surface film covers listed here are as effective or as economical as well-anchored vegetative mulch, most provide ample protection to the soil if applied in sufficient quantity. Cutback asphalt is particularly effective. Asphalt and resin emulsions are also quite effective, especially the resin emulsions which have the properties of remaining moist for at least 3 months after application and make clods and soil surface roughness resistant to soil slaking by rain. Some of the latex emulsions are effective but very expensive. Hydrolized starches are relatively ineffective as covers for wind erosion control because they are readily washed away by rain. Unhydrolized starches, on the other hand, are ineffective as surface films. Wood cellulose fiber is reasonably effective if a binder such as asphalt of sufficient amount is mixed with the material.

2. *Maintenance*

Excessive tillage, or tillage with improper implements, and overgrazing are the major causes of vegetative cover reduction on crop and grazing lands. Land management policies which avoid these destructive practices must be adhered to constantly if wind erosion control is to be realized from vegetative covers.

On rangelands, controlled grazing should be practiced at all times. The number of animals per acre should be regulated closely in order to realize maximum use of the grass and still maintain a sufficient amount of vigorous, complete vegetative cover. Supplementary practices should include contour furrowing to reduce runoff, establishment of more productive grass species, application of fertilizers where economics permit, and supplying adequate watering sites preferably on more nonerosive locations to prevent blowouts caused by excessive animal traffic.

Stubble mulching and minimum tillage or plow-plant systems of farming are all excellent methods of maintaining vegetative residues on cropland. Stubble mulching usually is defined as a year-around system of managing plant residues in which all tilling, planting, cultivating, and harvesting operations are performed to keep a sufficient amount of the residue on the surface at all times to provide protection from erosion. The practice requires use of tillage implements which generally undercut the residue without soil inversion (Fig. 15). Several types of implements are available and commonly used for this practice. Research by Anderson (1953, 1961), Siddoway *et al.* (1956), Woodruff and Chepil (1958), and Fenster (1960) has shown that each implement maintains on the surface a slightly different amount of residue. The average range is from 50 to 90 per cent maintained after each operation, but values range from 30 to 115 per cent (Table XVII) depending upon kind of implements, kind, height, and amount of residue, and moisture, texture, and density of soil. Maintenance greater than 100 per cent means that more residue was brought up than buried below the surface.

Stubble mulching, while principally applied to wheat, also can be used in row-crop production. Greb and Black (1962) reported that maximum use of subsurface tillage on sorghum residues in a summer fallow system has preserved from 30 to 45 per cent of the original amount. The minimum tillage or plow-plant system of farming row crops has gained considerable acceptance in recent years. In this sys-

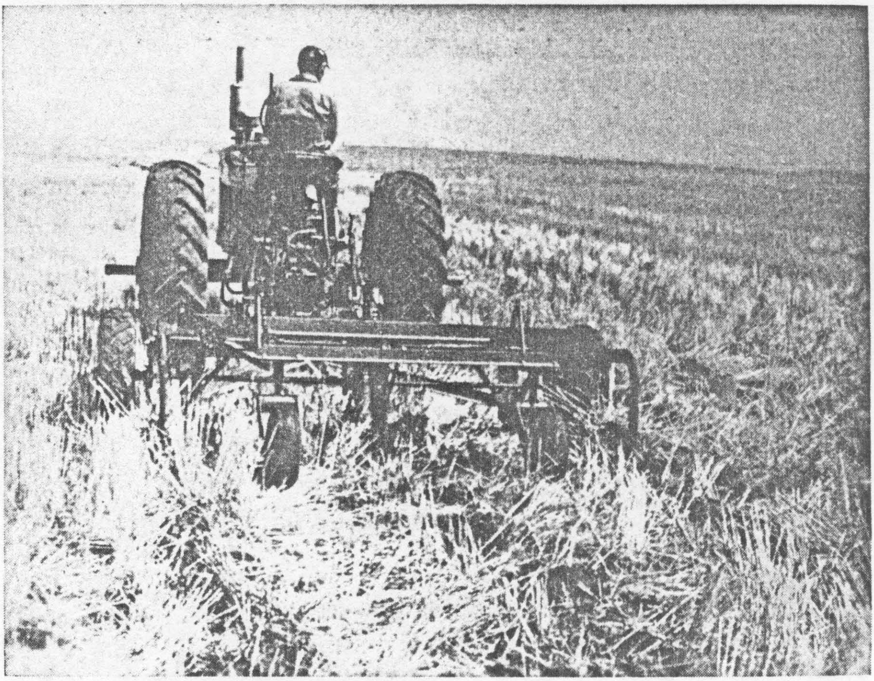

FIG. 15. This rodweeder with small duckfoot shovels leaves as much as 80 per cent of the wheat stubble, mostly standing above the surface.

TABLE XVII
Residue Maintenance with Tillage Implements[a]

Type of implement	Average maintained after each tillage operation (%)	Range maintained (%)
Subsurface implements		
Blades (36 inches or wider)	90	70 to 113
Sweeps (24 to 36 inches)	90	60 to 112
Rodweeders, plain rod	90	80 to 115
Rodweeders, with semi-chisels	85	55 to 105
Mixing implements		
Heavy duty cultivator (16 to 18-inch sweeps)	80	50 to 100
Heavy duty cultivator (2-inch chisels 12 inches apart)	75	—
One-way disk (24 to 26-inch pans)	50	30 to 90
Tandem or offset disks	50	—

[a] Data from Anderson (1953, 1961, 1962), Woodruff and Chepil (1958), and Fenster (1960).

tem, special equipment is used to till, plant, and apply insecticides, herbicides, and fertilizers all in one operation. Subsequent cultivation then is kept to a minimum. Lane and Wittmus (1961) reported that since the system leaves residues on the surface, it provides good wind and water erosion control, requires less labor, lowers tillage costs, and produces slightly higher yields in some areas of Nebraska.

Maintenance problems with organic film covers develop because freezing and thawing and swelling and shrinking of soils break up the film. Chepil (1955c) reported that films can be maintained longer on sand and loamy soils than on clays. They also can be maintained longer on any soil if they are applied uniformly without too much dilution with water, if they do not penetrate into the top soil layer, and if they retain their sticky properties (Chepil *et al.*, unpublished data, 1962). Once films are applied, maintenance consists of keeping all traffic off to avoid breaking the film. Where traffic is involved, use of materials that penetrate the top soil layer is necessary. Gravel and crushed rock afford rather permanent covers; maintenance here consists of avoiding any disturbance of the rock by mechanical action such as tillage and of using herbicides to control vegetative growth where such growth is undesirable.

B. Soil Clods and Ridges

Practical application of the principle of surface barriers and cover is well exemplified by tillage with different implements. The soil surface is made cloddy and rough by: (1) regular tillage processes used to prepare suitable seedbeds and to control weeds for crop productions; and (2) special tillage practices used specifically to bring clay to the surface for possible increased cloddiness and to roughen the land to prevent wind erosion. Roughening the surface is effective only to the extent that the roughness elements are nonerodible. Ridging dune sand for example, is of little value because the ridges on sand are erodible and are soon leveled by the wind.

The role of different tillage implements and operations in creating cloddiness and roughness of the land surface will be discussed in this section.

1. *Regular Tillage*

Much of the regular tillage in semiarid regions where wind erosion is generally most severe is on fallow. Repeated tillage of fallow is needed to kill weeds and thereby conserve soil moisture; however, repeated tillage tends to pulverize the soil and induce wind erosion. In winter wheat areas, pulverization of fallow by repeated tillage is somewhat compensated by the fact that wheat is seeded in fall and, if germination and growth is favorable, provides a vegetative cover the following spring when protection from wind erosion is needed most. But in spring wheat areas, fallow presents a real problem because the only vegetative cover that may be present in spring is residue from a crop grown almost 2 years before. Therefore, fallow in spring wheat areas generally must be tilled early in spring to create a rough, cloddy soil surface before high winds occur.

In winter wheat areas, severe wind erosion often occurs in spring when wheat has failed to make sufficient growth the previous fall. Under such circumstances a farmer is faced with the dilemma of whether to till and stop wind erosion, but kill the wheat, or not to till and hope that wheat will not be completely destroyed by wind.

Row crops such as corn are less susceptible to damage from erosion because of the relative roughness of the land when they are seeded. Other row crops, such as sorghum and cotton, are less susceptible to damage from erosion because of their late planting date when the wind erosion problem is generally past. Cotton stubble has little resistance to wind erosion. It is usually tilled to create a cloddy surface before spring winds occur. Sorghum and corn stubble, if heavy enough, makes an effective vegetative cover and is, therefore, left standing till the windy season is over. If the stubble is too light, it is usually tilled to create the necessary clods. The greater the required cloddiness, the deeper the tillage should be.

It is important in all tillage operations to avoid excessive or frequent tillage, because this can lead only to soil surface smoothing and clod pulverization. Soil moisture at time of tillage has a decided effect on cloddiness. Lyles and Woodruff (1962) have reported that different soils have differing moisture contents at which soil pulverization is most severe, and that more clods are produced if the soil is either extremely dry or extremely moist than if it is at intermediate moisture content.

The type of tillage implement used also has a definite influence on soil cloddiness and surface roughness. Lyles and Woodruff (1962) working with a moldboard plow, a one-way disk, and a subsurface sweep in controlled soil moisture conditions found that influences on cloddiness due to tillage machinery lasted longer than did influences due to soil moisture. They also reported that the moldboard plow produced a rougher, more cloddy surface with higher mechanical stability of clods than did the one-way disk or subsurface sweeps. Tillage implements commonly used in stubble-mulch farming, with the exception of chisel cultivators, usually do not leave a ridged, rough surface. One-way and offset or tandem disks leave a smooth surface. Subsurface sweeps, because they do not disturb the soil surface, do not create a rough, ridged soil surface, but they do create a greater vegetative roughness by allowing the vegetation to remain erect. Small sweeps and chisels produce a more cloddy condition than large sweeps and one-way disks operated at shallow depths. Listers generally provide the maximum cloddiness and surface roughness.

It is important that planting and seeding equipment preserve as much protective residue as possible, keep the soil surface rough and cloddy, and at the same time place the seed in moist, firm soil to promote rapid germination. Major types of planters available for small grains include hoe, single and double disk, deep furrow drills, and seeding attachments on one-ways and cultivators.

For wider spacing of row crops, such as corn, sorghum, and cotton, listers, furrow opener planters, and seeding attachments on cultivators are available. For small grains, the deep furrow disk and hoe drills provide maximum surface ridging, pass through heavy residues easily and concentrate them in the ridges, and place the seed in good moisture (Siddoway *et al.*, 1956; Woodruff and Chepil, 1956; Zingg and Whitfield, 1957; Fenster, 1960; McCalla and Army, 1961). All of the row-crop planting equipment generally leaves a rougher surface than does some of the other small-grain seeding equipment; however, lister planters generally provide the maximum surface roughness and offer excellent protection to small plants.

2. *Special Tillage*

Emergency tillage to provide a rough, cloddy surface is a temporary measure and its only purpose is to create an erosion-resistant soil surface. It is usually a last resort carried out when vegetative cover is depleted by excessive grazing, drought, improper or excessive tillage, or by growing crops that produce little or no residue, or when potentially severe erosive conditions are encountered or expected soon. It should be done before blowing starts rather than after, because soils rapidly become more erodible under abrasion of moving soil particles, thus requiring more drastic measures to prevent further erosion.

Woodruff *et al.* (1957) and Chepil *et al.* (1961) have indicated that various tillage implements can be used as emergency tillage tools. The most common are listers, duckfoot cultivators, and narrow-tooth chisel cultivators. The effectiveness of any of these implements, as measured in terms of the degree of cloddiness and roughness they create, depends to a great extent upon soil moisture, texture, and density. Lyles and Woodruff (1961) found that the cloddiness potential of soils could be increased markedly by increasing density; also, the cloddiness potential of soils with a high clay content is greater than for sandy soils. Speed of travel, depth of tillage, spacing between tillage point carriers, and the type of tillage point also influence the degree of roughness and cloddiness. Intermediate speeds of 3.5 to 4.0 miles per hour usually provide good roughness and cloddiness; such speeds do not throw the tillage layer, which would reduce roughness and pulverize clods (Woodruff *et al.*, 1957).

Emergency tillage should be accomplished at a depth which brings up compact clods, usually 3 to 6 inches. Spacing of lister and chisel points must be governed by severity of erosion and presence or absence of crops. Close spacing with any implement will create a rougher surface than will wide spacing. However, if a crop is involved and there is a possibility of saving part of it, then wide spacings of 48 to 54 inches will provide sufficient roughness for some control and at the same time permit most of the crop to continue growing.

Insofar as type of tillage point is concerned, listers and narrow chisels are most effective. Chepil *et al.* (1961) have indicated that listers produce a high degree of roughness, and in extremely sandy soils where clods can be produced only by deep tillage they are the most effective tools available. Chisel cultivators are more widely used as emergency tillage implements because they require less power and destroy less crop than do listers. They vary in effectiveness, depending on the type of point. Woodruff *et al.* (1957) reported that wedge-shaped heavy duty chisels generally bring up more clods and leave rougher surfaces than do duckfoot shovels or narrow chisels.

Direction of wind with reference to direction of tillage also influences the effectiveness of emergency tillage. It will be more effective if the wind blows across rather than parallel to the ridges. For this reason emergency tillage always should be accomplished perpendicular to the prevailing wind erosion direction.

Deep plowing is another form of special tillage used to bring adequate amounts of clod-forming clay subsoil to the surface, thereby reducing wind erosion. It is accomplished with large moldboard or disk plows. Most of the plowing is done at 24- to 30-inch depths; however, some of the larger moldboard plows are capable of plowing 42 inches deep. Research in Oklahoma by Harper and Brensing (1950) has indicated that clay content of surface soils was increased from 4 per cent to 12 per cent by deep plowing. Chepil *et al.* (unpublished data, 1962) reported that deep plowing increased the clay in the surface soil on an average from 5 to 12 per cent in fields in Texas and Kansas. However, Chepil (1953a) has found that about 27 per cent of clay in the surface soil is required for maximum benefit to control wind erosion. Furthermore, Chepil *et al.* (unpublished data, 1962) concluded that increased ridging and cloddiness resulting from deep plowing of sandy soils are only temporary, particularly if wind erosion occurs. Therefore, it must be supplemented with other suitable control practices.

C. Windbreaks and Wind Barriers

One type of windbreak is a planting of trees or shrubs in 1 to 10 rows to provide a barrier of sufficient height and density to present a formidable obstacle to the wind. Other wind barriers are crops in narrow rows, snowfences, solid wooden or rock walls, and earthen banks.

Windbreaks or wind barriers function as do other surface barriers in providing wind erosion control; i.e., they take up or deflect a sufficient amount of the wind force to lower the wind velocities to the leeward below the threshold required for initiation of soil movement. The effect of any barrier in reducing the rate of soil movement depends on many factors, including wind velocity and direction, and shape, width, height, and porosity of the barrier.

The velocity of the unobstructed wind has an important influence on the effectiveness of a barrier. Nearly all barriers provide maximum percentage reductions in wind velocity at leeward locations near the barrier, with a gradual decrease downwind. These percentage reductions for rigid barriers generally remain constant no matter how hard the wind blows (Woodruff and Zingg, 1952). The percentage reductions for porous, resilient barriers tend to increase slightly with increased velocities (Bates, 1944; Fryrear, unpublished data, 1962). This means that for such barriers the degree of wind erosion control will be greater for low-velocity winds than for high-velocity winds.

The direction of the wind influences both the size and location of the leeward-protected area. The area of protection is greatest for wind blowing at right angles to the barrier length and is smallest or almost nil for wind blowing parallel with barrier direction. It is, therefore, important that a complete system of barriers be provided for protection from winds from all directions, or that cognizance be taken of the prevailing wind direction for a given region, if there is a prevailing direction.

The shape of windbreaks characterizes the outer perimeter, or surface, which is in contact with the airstream. The data of Woodruff and Zingg (1952) have indicated that a streamlined or very abrupt vertical barrier will provide less protection than will a sloped or triangular outer surface. In barriers composed of several rows of growing plants, such as trees, the ultimate shape can be controlled by proper selection of species within the barrier rows.

Porosity is an important factor influencing the effectiveness of a barrier. Dense barriers provide large reductions in velocity for relatively short leeward distances, whereas porous barriers provide smaller reductions in velocity but for more extended leeward distances (Woodruff and Zingg, 1952; Woodruff, 1954; Caborn, 1957). Generally, some porosity is desirable in order to gain extended protection; however, large openings must be controlled, because too much openness causes air jetting with serious erosion in the immediate leeward zone.

Height of barrier is a very important factor influencing effectiveness because it governs the limits of influence. Expressed in multiples of barrier height, the zone of wind velocity reduction on the leeward side of a barrier may extend a distance equal to 40 or 50 times the height of the barrier. Influences to these distances are, however, insignificant in terms of wind erosion control, and if complete control is desired barriers must be spaced at relatively close intervals. Actual effective limits of influence vary with open wind velocity, barrier porosity, and threshold velocities of soils.

Chepil (1949) has reported that willow barriers form a protective influence extending only 6 to 7 heights in some of the highly erodible sandy regions of China. Woodruff and Zingg (1952) in wind tunnel tests indicated that full protection from a 40-mile-per-hour wind velocity was provided only for a distance equal to 9 times the height of the barrier. Woodruff, Fryrear, and Lyles (unpublished data, 1962), presenting data on effective zones for wind erosion protection for various narrow tree windbreaks, have shown the zone to depend on levels of open wind velocity and have indicated an average protected distance of about 12 times the height of the barrier for winds of 40 miles per hour measured at the 50-foot elevation.

Iizuka (1950) has observed that a windbreak which reduced wind velocities to 61, 69, and 77 per cent of that in the open at leeward distances of 10, 20, and 30 times the barrier height, respectively, decreased soil blowing at those distances to 0.14, 18, and 50 per cent of that in the open, respectively. This relatively limited influence of barriers emphasizes the need for complete barrier systems designed to provide extended protection across fields and for use of other supplementary wind erosion control practices.

1. *Tree Windbreaks*

Plantings of trees in middle rows and shrubs in outside rows (Fig. 16) have been made for a number of years in an attempt to reduce wind velocities. This type of windbreak received special emphasis in the 1930's when there was a serious wind erosion problem in the Great Plains region of the United States. Most of the windbreaks planted during that period were wide, 10 rows or more, because it was believed that wide belts were necessary to provide adequate reductions in velocity and for attainment of the so-called forest condition believed to be necessary for propagation and self-preservation of trees. The trend today is toward narrower plantings, i.e., 1-, 2-, 3-, and 5-row barriers, which have been found to be just as effective as wider belts in reducing wind velocities.

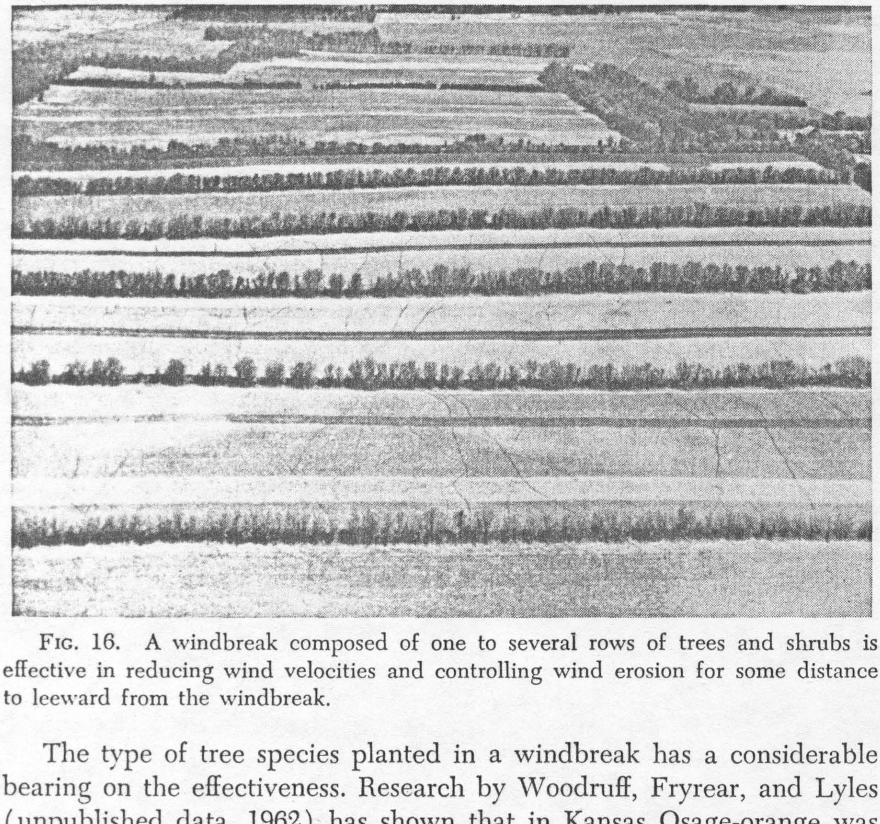

FIG. 16. A windbreak composed of one to several rows of trees and shrubs is effective in reducing wind velocities and controlling wind erosion for some distance to leeward from the windbreak.

The type of tree species planted in a windbreak has a considerable bearing on the effectiveness. Research by Woodruff, Fryrear, and Lyles (unpublished data, 1962) has shown that in Kansas Osage-orange was most effective, followed in order by arborvitae, Siberian elm, cottonwood, and jackpine. The rate of growth of trees also largely governs the extent of protection that can be expected in later years. In general, trees that grow rapidly provide a greater protected length than do the slower gowing trees.

Combinations of different tree and shrub species planted in rows to provide windbreaks vary considerably in their ability to provide protection from wind erosion. The amount of protection is not directly related to the number of rows in the windbreak (Table XVIII). The seasons govern porosity of deciduous species and, therefore, influence the effectiveness of the windbreaks.

Tree windbreaks have very definite limitations as a general method of wind erosion control, not only because of the relatively close spacing required which is objectionable where large machinery is used, but also

TABLE XVIII
Effect of Number of Rows and Season on Amount of Wind Erosion Protection Provided by Tree Windbreaks[a]

Windbreak	Effectiveness index[b]	Protected distance[c] (*H* units)[d]
	Summer conditions	
2-row Mulberry	55.9	18.0
5-row Plum, cedar, mulberry, elm, olive	42.6	15.0
1-row Osage orange	32.4	—
3-row Cedar (2), shrub	30.8	11.0
1-row Siberian elm	27.1	9.5
1-row Jackpine	19.7	—
	Winter conditions	
10-row Cedar (1), deciduous (9)	46.6	—
5-row Plum, elm (2), cedar, honeysuckle	24.9	9.2
1-row Osage orange	24.9	12.0
7-row Ash (2), elm, cottonwood (2), osage orange, coffee	7.2	—

[a] Unpublished data from Woodruff *et al.* (1962).

[b] Effectiveness index is computed by summing the products (velocity-reduction ratio at a given leeward location times the distance of the location from the barrier expressed in *H* units).

[c] Based on 40-mile-per-hour wind at 50-foot height and a 25-mile-per-hour threshold velocity at the 50-foot height.

[d] H = average height of trees in a single-row windbreak and average height of tallest trees in a multiple-row windbreak.

because of the competition they afford adjacent crops for moisture and nutrients. Greb and Black (1961) have reported a direct yield reduction in wheat and sorghum attributed to extraction of soil moisture and nitrate nitrogen by the windbreak as far as its roots extend into a field. They indicate a ratio of root length to tree height of 2.5:1, and that deciduous species are more competitive than conifers. Staple and Lehane (1955) from measurements during five dry years in Canada have indicated that sapping of moisture by caragana windbreaks was not appreciable and extended into the fields a distance equal to about the height of the trees, or 25 feet. The general aridity of the areas where wind erosion control is most needed also limits the use of tree windbreaks as control measures.

2. *Crop Barriers*

Annual crops are frequently interplanted in narrow strips or rows so that one crop provides protection to the other crop (Fig. 17). Sobolev (1947) has reported their use in the U.S.S.R. for preventing wind erosion and trapping drifting snow. Sheng (1961) also reported the use of the

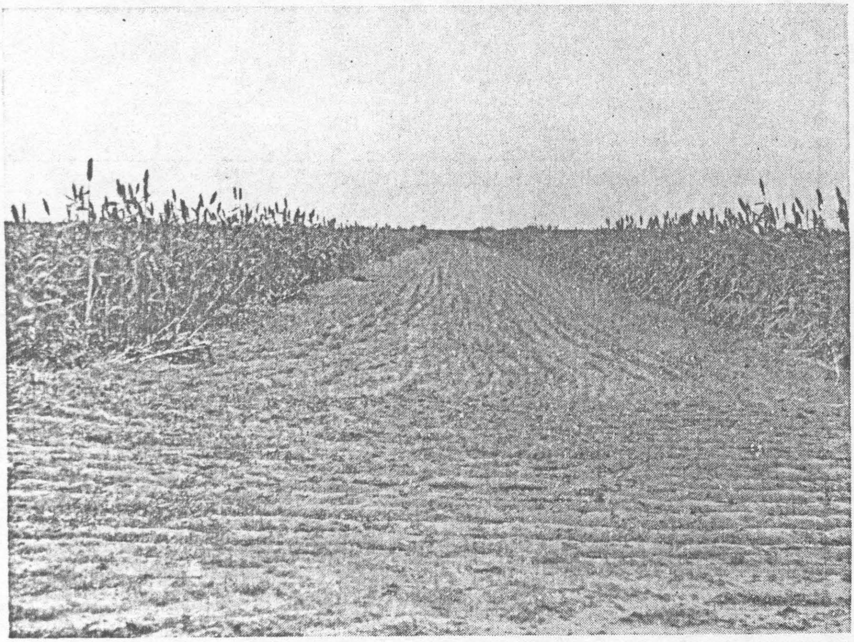

FIG. 17. This picture, taken in early fall, indicates rows of sorghum protecting winter wheat that has just emerged. Sorghum will be harvested for grain, and its stubble will protect the wheat in the crucial wind erosion period next spring.

perennial grass, Miscanthus, planted at 15- to 30-meter intervals in rice fields along the coastal regions of Taiwan. In the United States, crop rows are used frequently for protection of vegetable crops. Schultz and Carlton (1959) reported good protection from wind erosion of asparagus located on peat soils in California by interrow planting of barley. Rows of annual crops also have been used in the Great Plains for a number of years principally to trap snow and shelter new tree plantings (Ferber, 1958). Research designed to measure the effectiveness of annual crop barriers generally has been lacking; however, some recent studies by Fryrear (unpublished, 1962) have provided some information. Results from tests on sudangrass, grain and forage sorghum, broomcorn, sunflowers, castorbeans, crotalaria, and kochia have indicated that some of the crops provide adequate barriers for protection from wind erosion if they are spaced sufficiently close (Table XIX).

TABLE XIX
Effectiveness of Some Annual Crop Barriers for Wind Erosion Control[a]

Crop	Height[b] (feet)	Effectiveness index[c]	Protected distance[d] (feet)
Kochia	3.5	17.0	42.0
Sudangrass	3.0	11.4	22.5
Grain sorghum	2.0	10.7	12.0
Forage sorghum	1.5	7.9	6.0
Broomcorn	4.0	3.9	4.0

[a] Unpublished data from Fryrear (1962).
[b] Harvested height.
[c] Effectiveness index equals sum of products (velocity-reduction ratio at a given leeward location times the distance of the location from the barrier expressed in H units).
[d] Based on 40-mile-per-hour wind at 50-foot height and a 25-mile-per-hour threshold velocity at the 50-foot height.

3. *Artificial Barriers*

Artificial barriers such as snowfences, board walls, bamboo and willow fences, earthen banks, hand-inserted straw rows, and rock walls have been used for wind erosion control on a rather limited scale. Because of high cost of material or of labor required for their construction, their use is restricted generally to applications where high value crops are involved or in areas where overpopulation requires intensive agriculture. Sheng (1961) reports use of hand-inserted straw barriers between rows of sweet potatoes, erection of 2-meter high woven bamboo fences at intervals of 30 to 50 meters, and construction of 2-meter high rock walls at 10- to 20-meter intervals for wind erosion control along the coastal regions of Taiwan. Sneesby (1953), reporting results of studies in England, indicated that solid barriers 20 feet high provided wind erosion protection for 340 feet, and earthen banks 2 feet high provided 50- to 60-foot protected lengths.

In the United States, research on and application of artificial barriers to wind erosion control has been limited. Whitfield (1938) used sign board type artificial barriers constructed from sheet metal roofing and timber frames for wind intensifiers to reduce the height of sand dunes prior to stabilization by planting grass. Snowfences constructed from lath held together with wire providing a density of approximately 40 per cent have been used for protecting vegetable crops (Schultz and Carlton, 1958). These fences have not proved very effective as control measures because they provide only a relatively short zone equal to 10 H, or about 40 feet of velocity reduction of sufficient magnitude to reduce wind velocities below the threshold for initiation of soil movement (Woodruff and Zingg, 1955). The close spacing thus required makes them infeasible.

D. Crop Strips and Crop Rows

Crop strips function not so much as protective barriers but as soil traps designed to reduce soil avalanching. Crop strips or strip cropping are terms used to describe a method of farming, usually involving two or more crops, whereby strips of erosion-resistant crops are planted between strips of erosion-susceptible crops. The strips are usually all the same width.

Crop rows involve only one crop and will be discussed here from the standpoint of the effects of different row spacings on wind erosion.

1. Strip Cropping

Strip cropping as usually practiced does not require any change in cropping practices, nor does it remove any land from cultivation. The field is subdivided into alternate strips of erosion-resistant crops and erosion-susceptible crops or fallow (Fig. 18). Erosion-resistant crops are

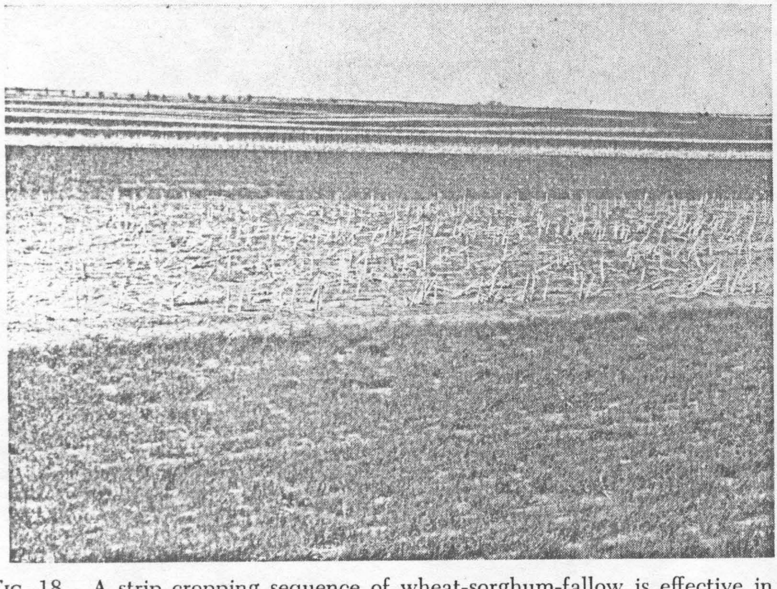

Fig. 18. A strip cropping sequence of wheat-sorghum-fallow is effective in controlling wind erosion.

small grains and other closely seeded crops that cover the ground rapidly. Erosion-susceptible crops are cotton, tobacco, sugar beets, peas, beans, potatoes, peanuts, asparagus, and most truck crops. Corn and sorghum are intermediate in their resistance to wind erosion.

Chepil (1957c) and Chepil *et al.* (1961) have indicated that strip cropping controls soil blowing by reducing soil avalanching, which increases with width of eroding field. Since the rate of avalanching varies directly with field erodibility, the actual width of strip required varies greatly with factors that influence field erodibility such as soil texture, wind velocity and direction, quantity of crop residue, degree of soil cloddiness and surface roughness.

Chepil (1960a) has made detailed studies of the effectiveness of crop strips in relation to soil texture and direction of erosive winds. He has reported that directional deviation of erosive winds from the perpendicular requires correspondingly narrower strips, and that required width of strip increases as soil texture becomes finer, except for clays and silty clays subject to granulation (Table XX). Mathews (1954) has recommended that strips should not be wider than 16 rods in order to be sufficiently effective, or narrower than 5 rods in order to make economical use of farm machinery. In the southern Great Plains where

TABLE XX
Average Width of Strips Required to Control Wind Erosion Equally on Different Soil Classes and for Different Wind Directions[a]

	Width of strips[b]		
Soil class	Wind at right angles to strips (feet)	Wind deviating 20° from right angles (feet)	Wind deviating 45° from right angles (feet)
Sand	20	18	14
Loamy sand	25	22	18
Granulated clay	80	75	54
Sandy loam	100	92	70
Silty clay	150	140	110
Loam	250	235	170
Silt loam	280	260	190
Clay loam	350	325	250

[a] Data from Chepil (1960a).

[b] For negligible surface roughness, average soil cloddiness, no crop residue, 1-foot high erosion-resistant stubble on windward, 40-mile-per-hour-wind velocity at 50-foot height, and a tolerable maximum rate of soil flow of 0.2 ton per rod width per hour.

cotton is grown, some special forms of wind strip cropping are employed wherein cotton in two to four rows is alternated with various numbers and sequences of rows of sorghum or of other high-residue yielding crops (Burnett *al at.*, unpublished data, 1962).

In conclusion, the chief benefit from strip cropping for wind erosion control is realized because the strips control soil avalanching and the serious damage which can result from it. Strip cropping alone will not fully control wind erosion; it must be supplemented with other practices, such as stubble mulching, to be fully effective. In combination with strip cropping, the supplementary practices need not be as intensive as they would have to be for large fields.

2. *Crop Rows*

The relative effectiveness of different row spacings for wind erosion control has not been fully evaluated. Generally speaking, the closer the row spacing, the more effective will be the crop. Most close-spaced crops, i.e., those planted with drills with spacing ranging from 7 to 14 inches, are erosion resistant once they are established. Sorghum, corn, cotton, and other crops normally planted in 40- to 42-inch rows are not so resistant. Recent experiments have shown that some of these crops can be grown in closer-spaced rows without detrimental effects on yields.

The direction of crop rows with reference to prevailing erosive winds has some effect on erosion. Siddoway (unpublished data, 1962) has shown that the relative amount of erosion from soil planted to wheat in 10-inch rows is about six times greater when the wind is blowing parallel to the rows than when the wind is perpendicular to the rows. Zingg *et al.* (1952) working with a portable wind tunnel with 9-inch high sorghum stubble in 40-inch rows showed soil losses three times greater with rows parallel to the wind than with rows perpendicular to the wind.

VII. The Wind Erosion Equation

A. General Framework

A wind erosion equation, with all its accompanying charts and tables, has been developed to indicate the relationships between the amount of wind erosion and the various field and climatic factors that influence erosion (Agricultural Research Service, 1961; Chepil, 1962a). The equation is being modified continually as new data become available. It is designed to serve a twofold purpose:

(1) As a tool for determining the potential amount of wind erosion on any field under existing local climatic conditions.

(2) As a guide for determining the conditions of surface roughness, soil cloddiness, vegetative cover, sheltering, or width and orientation of field necessary to reduce the potential wind erosion to an insignificant amount.

The equation embodies the major primary factors that govern wind erodibility of land surfaces. These primary factors influence wind erosion directly. They have been recognized during the course of many years of accumulation of experimental data on the problem. Some of them may be grouped or converted for convenience into equivalent factors, or may be disregarded, as follows:

Individual Primary Factors	*Equivalent Factors*
Per cent soil fractions > 0.84 mm. as determined by standard dry sieving, A	Soil erodibility, I
Mechanical stability of the surface crust, F_s	Transient, and therefore generally disregarded
Average wind velocity, v Average moisture of soil surface, M	Local climatic factor, C
Soil surface roughness, K	Same
Distance (along prevailing wind erosion direction across field, D_f) Distance (along prevailing wind erosion direction protected by barrier, D_b)	Equivalent width of field, L
Quantity of vegetative cover, R Kind of vegetative cover, S Orientation of vegetative cover, K_o	Equivalent quantity of vegetative cover, V

The percentage of nonerodible dry soil fractions > 0.84 mm., A, as determined by standard dry sieving is an equivalent of their true percentage and of their stability against breakdown by tillage and abrasion from wind erosion. Sieving breaks a portion of the nonerodible clods to smaller, erodible ones. The problem is to sieve the soil with such vigor or for such period of time to neither overemphasize nor underemphasize the influence of one of these factors in relation to the other. Therefore, the method of dry sieving is standardized (Chepil, 1962a). The percentage of nonerodible dry soil fractions > 0.84 mm. in diameter as determined by standard method of dry sieving is directly related to *soil erodibility I*. This relation was derived from three major studies:

(1) Wind tunnel experiments on the relation between soil cloddiness and wind erodibility (Chepil, 1950b; Chepil and Woodruff, 1954, 1959).

(2) Field measurements in the vicinity of Garden City, Kansas, during 1954-1956 on the relation between wind tunnel erodibility and natural field erodibility (Chepil, 1960b).

(3) Analysis of intensity-frequency of occurrence of climatic conditions in the vicinity of Garden City, Kansas, during 1954-1956 (Chepil *et al.*, 1962).

The mechanical stability of the surface crust, F_s, if the crust is present, is of little consequence in the long run. It is disintegrated readily under the action of abrasion after wind erosion has started. It is a transitory condition and has some significance only if we desire to determine erodibility of the field at the moment the estimation is made. If we are interested in average erodibility for the entire soil-drifting season or year, as we ordinarily are, this condition should be disregarded.

The rate of soil movement by wind varies directly as the cube of wind velocity, v, and inversely as the cube of average soil surface moisture M. It is convenient to consider these two factors together as a *local wind erosion climatic factor, C*. A map has been prepared indicating the approximate value of this factor for any location in the United States and the agricultural areas of Canada (Chepil *et al.*, 1962).

The *soil surface roughness, K*, is expressed in terms of height of standard soil ridges (the same as ridge roughness equivalent of Zingg and Woodruff, 1951) and means that the surface, other factors being equal, will resist the wind as much as the standard soil ridges in which nonerodible clods do not exceed ¼ inch in diameter and which have a height-spacing ratio of 1:4. For example, a ridge roughness equivalent of 2 inches for a given soil surface means that the wind drag against the surface will be as great as against the surface composed of standard ridges 2 inches high and 8 inches apart running at right angles to wind direction, composed of the same proportion of erodible and nonerodible fractions as the soil, and exposed to the same drag velocity of the wind as the soil.

Width of field or field strip alone does not determine how erodible it is unless the prevailing wind direction and the presence or absence of adjoining wind barriers are taken into account too. No matter how narrow the field strip might be, if wind direction is parallel to its length, the strip would be almost as erodible as a large field of a width equal to the length of the strip. Furthermore, if any barrier is present on the windward side of the field, the distance D_b (along the prevailing wind erosion direction) which it fully shelters from the wind must be subtracted from the total distance D_f (along the prevailing wind erosion direction) across the field to determine the unsheltered distance across the field along the prevailing wind erosion direction. This is the distance L that directly determines the quantity of erosion. It may be termed the *equivalent width of field.*

The quantity R, kind S, and orientation K_o of vegetation or vegetative cover can be expressed together in terms of equivalent pounds per acre. The equivalent vegetative material is small grain stubble to which S has been assigned the value of 1. The equivalent orientation is the absolutely flat, small-grain stubble with straw aligned parallel with wind direction, for which K_o has been assigned the value of 1. The *kind of vegetative cover factor,* S, denotes the total cross-sectional surface area of the vegetative material. The finer the material, the greater its surface area, the more it slows down the wind velocity, and the more it reduces wind erosion. The *orientation of vegetative cover factor,* K_o, is in effect the vegetative surface roughness factor and the two terms mean the same thing. The more erect the vegetative matter, the higher it stands above the ground, the more it slows down the wind velocity near the ground, and the lower the rate of erosion. The factors R, S, and K_o are multiplied together to give what is termed the *equivalent quantity of vegetative cover,* V (Chepil, 1962a). The wind erosion equation then may be expressed as

$$E = f\,(I,C,K,L,V) \tag{27}$$

which says that the potential average annual quantity of erosion, or soil loss, E, expressed in tons per acre is a function of the following factors:

I = soil erodibility,
C = local wind erosion climatic factor,
K = soil surface roughness,
L = equivalent width of field (the maximum unsheltered distance across the field along the prevailing wind erosion direction),
V = equivalent quantity of vegetative cover.

The mathematical relationships among the factors in the wind erosion equation are complicated, but charts and tables have been prepared from which the quantity of erosion (soil loss), as influenced by each of these factors, can be read at a glance (Chepil, 1962a). Moreover, the charts and tables can be used in reverse to determine what conditions are necessary to reduce wind erosion to any degree. Space is too limited here to include these charts and tables and to indicate how they can be used to estimate the potential soil loss of a field or the conditions needed to reduce the soil loss to an insignificant amount.

B. Data Needed to Estimate Potential Soil Loss

Each of the individual primary factors that influence wind erosion must be determined before the potential soil loss can be estimated. They are as follows:

Datum 1. *Soil erodibility I* in tons per acre per annum, determined from percentage of nonerodible soil fractions > 0.84 mm. in diameter. The percentage of nonerodible fractions is determined by standard dry sieving (Chepil, 1962b) or from reference tables of known average cloddiness of different soils during the wind erosion season.

Datum 2. *Local wind erosion climatic factor C*, in per cent, estimated for a particular geographic location from the wind erosion climatic map (Chepil *et al.*, 1962).

Datum 3. *Soil surface ridge roughness equivalent, K*, in inches. Usually *K* is equal to the average height of clods or ridges of which the soil surface is composed (Zingg and Woodruff, 1951; Chepil, 1962a). Several measurements can be made with a ruler and averaged. Widely spaced ridges, such as those used in emergency tillage for wind erosion control, have a ridge roughness equivalent less than their height. Usually, if the distance between them is increased beyond the 1:4 ratio, their ridge roughness equivalent is decreased proportionately. Thus, if the ridges are 6 inches high and the distance between them, measured along the prevailing wind erosion direction, is 48 inches, their height spacing ratio is 1:8, as compared to 1:4 for standard ridges, so that their ridge roughness equivalent is 4/8 of 6 inches, or 3 inches, if soil cloddiness remains the same as for standard ridges.

Datum 4. *Distance* D_f, in feet across the field (along prevailing wind erosion direction). This distance can be measured or computed from the width of field if the prevailing wind erosion direction is known (Chepil, 1959a). No adequate published data on the prevailing wind erosion direction at various geographic locations are available at present (1962).

Datum 5. *Distance* D_b, in feet (along prevailing wind erosion direction) of full protection from wind erosion afforded by a barrier, if any, adjoining the field. This distance for standard pervious continuous barrier is about 10 times the height of the barrier (Woodruff and Zingg, 1952). Data on the effectiveness of different kinds of barriers in shielding the soil surface from erosion are meager. If height of barrier is no greater than normal height of stubble, the influence is negligible and no evaluation is made.

Datum 6. *Quantity of vegetative cover, R,* above the ground in pounds per acre. This is estimated by sampling, cleaning, drying, weighing, and computing on a pounds per acre basis in accordance with standard procedure (Chepil and Woodruff, 1959). For some types of standing stubble, such as sorghum or corn, the quantity can be estimated roughly from height of stubble and number of stalks per unit area. Unpublished supplementary charts and tables are available to facilitate this type of estimation. All quantities of R presented in this review are based on washed, oven-dry material multiplied by 1.20. This represents approximately the average thoroughly cleaned, air-dry weights.

Datum 7. *Kind of vegetative cover factor,* S (dimensionless), obtainable from supplementary tables (Chepil, 1962a).

Datum 8. *Orientation of vegetative cover factor,* K_o (dimensionless), obtainable from supplementary charts (Chepil, 1962a).

VIII. Needed Research

Field and supplemental wind tunnel studies on the basic causes, effects, and remedies of wind erosion began in the severe dust storm period of the 1930's. Data have been collected and recorded continuously till the present time. The first attempt to apply some of this information as part of the wind erosion equation was published by Chepil and Woodruff in 1954. From then, general wind erosion research and research as applied to the wind erosion equation have been continued simultaneously. One is not and could not be separated from the other.

Considerable information still is required on air flow, temperature, evaporation, and crop yields in the vicinity of windbreaks and other types of surface barriers such as snowfences, hedges, crop strips, crop rows, ridges, and soil clods. Part of this study is expected to be applied to classification standards for shelterbelts presently in existence in the Great Plains. Ultimately it is hoped that greater clarification may be made of the principles governing air flow patterns and soil erodibility in the vicinity of barriers ranging from the size of clods to field shelterbelts. Experiments on models in a wind tunnel are being initiated to speed up attainment of basic information on this subject.

Much damage to soils and crops could be avoided if severe wind erosion conditions could be predicted a few months to a year ahead of their occurrence. Such predictions might be possible in view of the fact that severe wind erosion conditions tend to occur in cycles. A prediction of severe conditions one growth season ahead of their occurrence should give farmers ample opportunity to establish special tillage and cropping practices that would be effective.

Although it is known at present what soil structure approaches an ideal condition for resisting wind, little information is available on how best to create such a condition and at the same time permit the soil to absorb water freely and serve as a good medium for crop growth. None of the present cropping systems, including grasses, are entirely suitable, and some are detrimental. Studies are needed on new techniques of developing a suitable soil structure. More information is needed on the influence of moisture on soil structure as influenced by different types of tillage action. Possibilities of finding new methods and materials to develop desirable sizes of stable soil aggregates should be explored further.

It is recognized that vegetative covers, alive or dead, offer one of the most effective conditions for controlling wind and water erosion. However, better implements and probably more extensive education on how best to use the present implements are needed to maintain protective crop residues on the surface, to control wind and water erosion, runoff, and evaporation, and to maintain high level of crop yields.

One of the problems associated with present methods of maintaining vegetative covers is that they tend to leave the surface soil loose, fine, and highly erodible by wind. When drought occurs and vegetative covers become depleted, serious erosion sometimes occurs. Implements that improve structure of the surface soil and at the same time maintain vegetative residues on the surface need to be improved. Information on how to preserve vegetative matter above the ground or how to develop vegetative matter resistant to decomposition also is needed. Recognition, selection, and development of plant species suited for reclaiming eroding sand dune land is needed urgently.

The general framework of the wind erosion equation has been developed, but many details are still lacking. These details may be filled with accessory charts and tables as more research information becomes available.

Information is needed on the average soil surface roughness K for soil surfaces tilled with different implements on different soil classes, with different soil moisture contents. This information is important to determine the nature of the implements and methods of tillage that might be more suited than the present ones for permanent and emergency tillage programs for wind erosion control.

Information is needed on the average distance D_b of full protection from wind erosion afforded by barriers of various degrees of air penetrability in various geographic regions and for various soils. This type of information for windbreaks and other barriers is presently almost completely lacking.

Information is needed on the prevailing wind erosion direction for various locations. Available data needed to determine the prevailing wind erosion direction include: (a) average hourly wind velocity from each of the 16 points of the compass, and (b) per cent duration of wind from each of the 16 points of the compass. The prevailing wind erosion direction needs to be computed from the above data. A map then can be prepared for estimating the prevailing wind erosion direction on individual farms. This type of information would be valuable in determining factors D_f and D_b and, inversely, in determining how wide crop strips running in a certain direction should be to control wind erosion in various regions.

Soil erodibility I, based on standard dry sieving procedure, needs to be determined for various soil types wherever wind erosion is a problem.

Information on the values of kind of vegetative cover factor S and orientation of vegetative cover factor K_o is needed for cultivated and grass crops other than those already investigated.

It is expected that the wind erosion equation will become more useful as more specific information on the influence of the major primary factors I, C, K, D_f, D_b, R, S, and K_o becomes available.

IX. Conclusion

This review has been devoted to discussion of progress made in obtaining new information on wind erosion and its control. However, the solution of the problem is dependent on the overall progress made in research, testing, and extension.

It is beyond the scope of this review to discuss the overall progress made in the solution of the wind erosion problem. Substantial progress apparently has been made. Probably the best evidence of this is the fact that the severity of dust storms in the Great Plains during the 1950's was considerably less than during a period of similar climatic conditions in the 1930's (Chepil and Woodruff, 1957; Chepil *et al.*, 1962; unpublished data by Chepil *et al.*) This difference is believed to be due to better techniques, more favorable financial resources, and more earnest desire on the part of everyone to conserve the soil.

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