Influence of Mechanical Disturbance on Erodibility of Sandy Loam Soils by Wind

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INTRODUCTION

The erodibility of soils, which is an expression of their ability to resist wind erosion, is a result of soil evolution in an environment. For a given soil in a favorable environment, weathering such as wetting and drying and freezing and thawing, disturbs the original soil structure and makes the soil more erodible (Chepil, 1954). Disturbing surface soils, by over-grazing that reduces surface coverage, over-cultivation, destruction of soil aggregates by mining, construction, off-road traffic, and military activities, stimulates and accelerates soil wind erosion in dryland regions, leading to desertification (Fryrear and Lyles, 1977; Gillette *et al.*, 1980; 1982; Dregne, 1988; 1990; Saxton *et al.*, 1996). Anthropogenic activities in wind erosion susceptible regions has made the problem more complex.

An understanding of the mechanisms and the relationships between erosion and erodible variables is essential for the prediction of soil erosion. In the 1940's Chepil (1942) recognized that the size-distribution of dry aggregates was more important than discrete particles in resisting wind erosion. Chepil and Bisal (1943) developed a dry sieving method to determine the structure and the relative resistibility of soils to wind erosion. Dry aggregate structure was employed as an index for evaluating the erodibility of freshly cultivated soils. Factors effecting the soil mechanical stability such as clay content as well as the units of soil structure were analyzed. Mechanical stability of soils was defined as the resistibility of soil aggregates to the agents of tillage, abrasion by sand-laden wind, and weathering. An exponential function was suggested by Chepil (1951; 1952) to describe the dependence of the breakdown rate of soil aggregates to the soil mechanical stability.

Soil properties such as silt, clay, organic matter etc., and disturbing agents such as wetting and drying, freezing and thawing were investigated (Chepil, 1953; 1954; 1955a; 1955b). The concept of abrasion-susceptibility of soils was developed and expressed by a coefficient of abrasion (Chepil, 1955a; 1955b). Cohesive strength was thought inversely proportional to the sizes of soil particles and expressed in modules of rupture. These investigations were summarized by Chepil and Woodruff (1963) who established a theoretical basis for understanding the mechanisms of soil structure that resists wind erosion. Chepil noted that tillage tends to loosen the bond between individual soil particles and aggregates and to increase the erodibility by wind. Some aspects of Chepil's theory, however, are not adequate. For instance, the inverse relationship between cohesive strength and sizes of soil particles is only applicable to loose soils. Shear strength of a dry soil block mass would display more complex mechanical behavior. Therefore, Woodruff and Siddoway (1965) emphasized the needs for further study of soil erodibility for various soil conditions.

Other factors influencing soil erodibility such as soil moisture, soluble salt and % $CaCO_3$ were also studied (Chepil, 1954; 1956; Belley, 1964; Gillette *et al.*, 1980; Nickling and Ecclestone, 1981; Zobeck and Popham, 1990; Chen *et al.*, 1996). Chepil (1954) pointed out that $CaCO_3$ tends to destroy soil organic matter, reducing mechanical stability of soils. Gillette *et al.* (1982) suggested that $CaCO_3$ is favorable to the crust-formation on desert soils, and thus may strengthen soil resistibility to wind erosion.

Following Chepil's theory of abrasive resistance and the related factors of the crushing energy, size, speed, impact angle, and stability of abraders were investigated extensively (e.g., Hagen, 1984; Lyles, 1988; Hagen *et al.*, 1992). An energy-based index to express, and a technique to measure, the dry aggregate stability was also developed (Skidmore and Layton, 1992).

Few investigations have been done to study the erodibility of other geological targets. Suzuki and Takahashi (1981) suggested, by laboratory experiments, that the abrasion rate is a negative power function of the compressive strength of the experiment rock specimen. The stability of Earth materials and corresponding resistance of materials on other planets were theoretically evaluated by Greeley and Iverson (1985).

The fact that "blocks of fine silt remain as a compact mass that resisted the direct force of wind" (Chepil, 1955b, p. 158) is true. There is evidence that a packed dry soil has a high bulk density and an improved mechanical stability. Chen (1991) showed that the wind erosion rate of a disturbed loessal soil was 3.8 fold of the original soil. Lyles and Woodruff (1963) suggested soil compaction as a wind erosion prevention method. Smalley (1970) theorized the relationship between packing density and inter-particle binding strength, though his idea was not verified by experiments or field measurements. Smalley's theory only explained the primary resistibility of soils in the stable state. Once a soil is disturbed, the loosened sand particles would stimulate erosion and fine particles would be emitted into the air. Fryrear (1984) found that different tillage operations affect the soil aggregation and soil resistance to wind erosion. Schilinger *et al.* (1996) recommended a minimum tillage method for increasing soil stability.

Gillette *et al.* (1980; 1982) related the erodibility of desert soil crusts and availability of fine particles emitting into the atmosphere to anthropogenic disturbances. They analyzed the relationships between rupture module, clay content, water-stable salt, $CaCO_3$, thickness of crusts, etc. by comparing threshold velocities for disturbed and undisturbed desert soils.

The resistibility of soils to wind erosion is partially controlled by soil texture, structure units, and composition and by packing state and packing density, which are influenced by ex-ternal factors. Regardless of the types of material, cohesiveness of a soil also relates to the ex-ternal agents such as the disturbance extent and time. To our knowledge the intrinsic property of the cohesive force is not defined. We do not describe the concept of disturbance extent, nor wind erodibility at different disturbances. Without this knowledge it would be inadequate to predict the wind erosion rate.

Loessal sandy loam is a main soil family in the drylands soil-category of the Northern Loess Plateau of China. Due to the dry climate, loose soil structure, and long history of unsuit-able land use, severe wind erosion hinders the economic development and the social prosperity.

Objectives of this research were: (1) to determine how disturbing the surface soils stim-ulates wind erosion; (2) to search for factors influencing mechanical stability; (3) to develop equations to express the causality of the erosion rate and the disturbance extent; and (4) to pro-vide principles for designing prevention systems to control desertification caused by wind erosion.

RESEARCH SETTINGS, MATERIALS, METHODS, AND PROCEDURES

The Northern Loess Plateau of China, adjacent to the Ordos Desert on its north, lies in the temperate steppe zone where the annual precipitation is 300-500 mm and the annual mean temperature is 9.2 °C. Soil categories in the transition belt from Loess Plateau to Ordos Desert are mainly loessal sandy loam (grey calcium earth), black sandy loam, and loamy sand. Dry farming and extensive animal husbandry are the major land uses. Seventy-five percent of the cultivated land is rain-fed (Chen *et al.*, 1996). The loose, bare, and dry soils are prone to wind erosion during the long, dry, windy winter and spring seasons. A surveyed field showed that 73% of pasture and farmland were medium and severely wind eroded (Chen, 1989). Unsuitable cultivation, over grazing, and large scale open-mining bring the fragile ecosystem to a high potential for severe wind erosion. If suitable measures are not taken, disturbance of surface soils could accelerate wind erosion and the desertified area would expand.

The penetrability, or hardness (a measure of soil strength and a primary soil property that influence soil resistance to mechanical disturbance) was measured in the field by employing a TE-3 static type penetrometer. Values of soil hardness depend on the texture, structural property, and water content of the soil.

Soil hardness values at different depths of a soil profile, as a function of penetration depth of the probe, were obtained by

$$S_h = \frac{\alpha \eta h g}{S} \tag{1}$$

where

- S_h = soil hardness, N cm^{-2}
- h = penetration depth, cm
- η = calibration coefficient of the force measuring springs. The three levels of spring were selected depending on soil hardness (25, 50, and 75 kg cm^{-1}, respectively).
- S = cross section area of the probe, cm^2
- g = acceleration due to gravity, cm s^{-2}
- α = dimensionless conversion constant.

Three replications were made at each site. The mean value was taken to represent the hardness of a soil at that condition. Undisturbed soil samples were taken from the field with sample boxes 0.95 × 0.27 × 0.15 m.

Indoor experiments were conducted in a push type laboratory wind tunnel, with a test section 16 m long, 1 m wide and 0.6 m high at the Desert Research Institute of the Chinese Academy of Sciences. The undisturbed soil sample was mounted on an electronic balance, 12 m from the entry of the working section (Fig. 1). The surface of the experimental sample was set flush with the floor of the wind-tunnel. The effective eroding area of the specimen was 0.2565 m^2.

Grain size distributions of the samples used in the wind-tunnel tests are shown in Table 1. All of them displayed coarse soil textures and were prone to wind erosion.

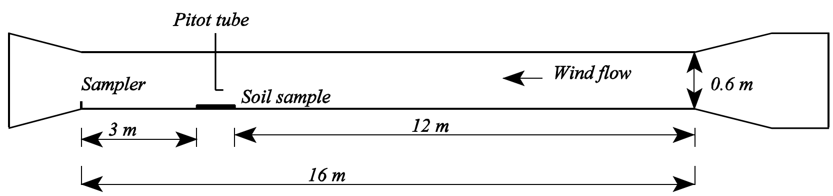

Figure 1. A sketch diagram of the working section of the push-type wind tunnel used in this experiment. The air regulator and diffusor are not to scale.

Table 1. Weight percentages by size distribution of three soils used in wind tunnel tests.

	-------------- Grain size distribution, *mm*			------------------
Soil	>0.05	0.05-0.005	<0.005	Mean diameter
Loessal sandy loam	72.45	23.89	3.66	0.114
Black sandy loam	71.11	28.89	0.00	0.130
Loamy sand	82.84	16.33	0.83	0.198

Wind velocity was measured, as described in Chen *et al.* (1996), with Pitot tubes connected to barometers. The pitot tubes were parallel to the central axis of the wind tunnel and mounted at 0.1 and 0.3 m above the sample surface. Wind velocities were increased from 5 to 25 m s^{-1}. Duration for each wind condition varied from 2 to 30 minutes depending on wind speeds and surface conditions of the samples.

Wind-velocity profiles in the wind-tunnel boundary layer were considered as a logarithmic function of height. Friction velocity was then calculated by the following equation (Bagnold, 1941).

$$U_* = \frac{\kappa U_{0.3}}{\ln\left(\frac{Z_{0.3}}{Z_0}\right)} \qquad \textbf{(2)}$$

where

U_*	=	friction wind velocity, m s^{-1}
κ	=	Von Karman constant taken as 0.4
$U_{0.3}$	=	free steam speed (m s^{-1}) measured at 0.3 m
$Z_{0.3}$	=	height 0.3 m above the surface
Z_0	=	aerodynamic roughness height was then estimated by the following equation

$$\log Z_0 = \frac{\left(\log Z_{0.3} - \frac{U_{0.3}}{U_{0.1}} \log Z_{0.1}\right)}{\left(1 - \frac{U_{0.3}}{U_{0.1}}\right)} \qquad \textbf{(3)}$$

where

$U_{0.3}$	=	wind velocity at the height 0.3 m ($Z_{0.3}$)
$U_{0.1}$	=	wind velocity at the height 0.1 m ($Z_{0.1}$).

$U_{0.3}$ was considered as the free stream velocity. The relationship between the friction and free stream velocities was developed by the least square regression method as shown in Equation (4) and Fig. 2.

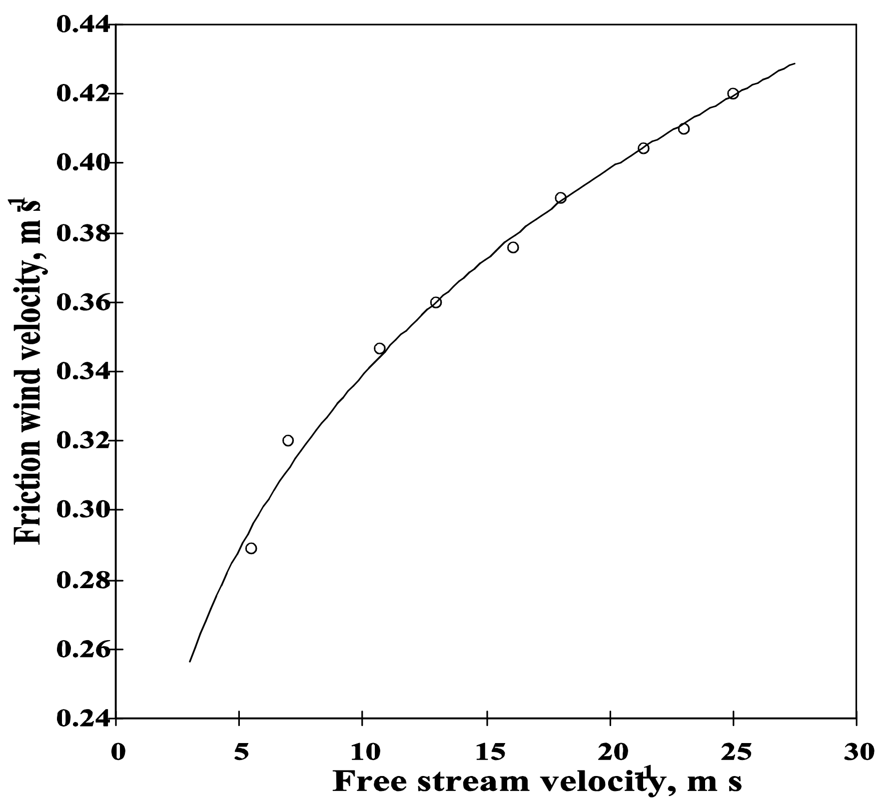

Figure 2. Relationship between the friction and free wind velocities established in the wind tunnel tests. It is significant at the 0.01 levels.

$$U_* = 0.15 + 0.082\ln(U_{0.3}) \qquad R^2 = 0.9596 \tag{4}$$

which was significant at the 0.01 level. The drag of the air flow was then calculated according to Bagnold (1941) in equation (5),

$$\tau = \rho U_*^2 \tag{5}$$

where

τ	=	shear stress, N m^{-2}
ρ	=	air density, 1.23 kg m^{-3} at 15 °C.

Quantities of eroded soil from the sample tray were weighed with an electronic balance which was connected to a computer; the erosion rate (mass weight loss) was recorded automatically. A step-like passive slit sampler (Chen and Fryrear, 1996), set flush with the floor, was installed at the outlet of the working section of the duct, 3 m downwind of the sample tray. The slit sampler was used for calculating mass flux in the flow layer 0-0.2 m above the surface. These samples were analyzed to determine grain-size distribution. The erosion rate was calculated by:

$$R_e = \frac{Q}{AT} \tag{6}$$

where

R_e	=	erosion rate, kg m^{-2} min^{-1}
Q	=	quantity of eroded material, kg
A	=	surface area of the sample tray (0.2565 m^2)
T	=	duration of experiment, min.

By multiplying the particle speed U_p and the erosion rate R_e, momentum fluxes of the eroded soils could be calculated by

$$F_t = R_e U_p \tag{7}$$

where

F_t	=	momentum flux of the transporting material, N m^{-2}
U_p	=	particle velocity, m s^{-1} .

Greeley and Iverson (1985) suggested that particle speeds be 50-60 % of the free stream velocity. A high-speed video camera photographing particles in wind-tunnel tests showed a range of particle speeds of 53-89 % of the free stream wind velocity. The relationship can be expressed by the following exponential function.

$$U_p = a + b\, e^{\left(\frac{-U_{free}}{c}\right)} \qquad \textbf{(8)}$$

where

U_p	=	particle velocity, m s^{-1}
U_{free}	=	free stream velocity measured at the height 0.3 m above the surface
a	=	regression constant (4.249 in this research)
b	=	regression constant (0.403 in this research)
c	=	regression constant (6.786 in this research).

All of the eight tested size fractions from 0.125 to 0.5 mm in diameter showed the R^2 >0.98 at the 0.01 significance levels. A force index was then proposed to express the relativity of the excess erosivity of wind force to the force that is transporting the eroded soil material.

$$F_{surp.} = \tau - F_t \qquad \textbf{(9)}$$

where

$F_{surp.}$ = surplus erosive force of the air flow that may be used for further erosion while transporting the eroded loose soils.

By this definition, $F_{surp} = 0$ means a steady state of equilibrium transport without further erosion or deposition. $F_{surp} < 0$ indicates a deficient erosive wind force and deposition. $F_{surp} > 0$ denotes a surplus of erosive wind force and further erosion may occur.

The disturbance ratio, which is a measure of the extent of the disturbance of surface soils by mechanical forces, including anthropogenic forces such as tillage and natural forces such as weathering by drying and wetting, freezing and thawing, is defined as equation (10) and Figure 3.

$$R_d = \frac{A_{disturbed}}{A_{total}} = \frac{\sum_{i=1}^{n}\left(\pi R_i^2\right)}{A_{total}} \qquad \textbf{(10)}$$

where

R_d	=	disturbance ratio (values taken as 0~1 or percentages),
$A_{disturbed}$	=	disturbed surface area (m^{-2} for this work),
A_{total}	=	total surface area in consideration (0.2565 m^{-2} for these experiments), and
R_i	=	radius of the disturbed area (cm), i = 1, 2, 3, . . . n.

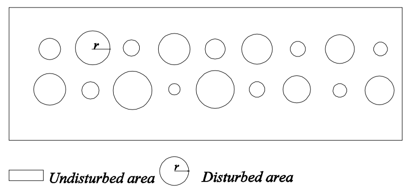

Figure 3. A sketch diagram shows the treatment on the soil sample surface and the definition disturbance ratio. The disturbed area shown in the diagram is not drawn to scale.

Based on this definition the relationships among soil erosion rate, soil hardness, wind force, and soil surface disturbance ratio were analyzed and reported below.

RESULTS AND DISCUSSIONS

Mechanical stability of surface soils depends on soil texture, water content, and soil structure. It can be expressed with intrinsic soil forces of adhesion, cohesion, inter-particle binding, and packing conditions. Soil-aggregates are more important than the discrete particles in resisting mechanical disturbance (Chepil, 1942). Smalley (1970) suggested a parameter of packing density. Soils would display different mechanical stabilities if the packing density was different, providing the other properties were the same. Investigations on the stability of aggregates are important for understanding the processes of soil resistibility to wind erosion. Adhesion force and other inter-particle forces relating to tensile force vary with soil texture and water content when the soil is loose. However, adhesive forces might be neglected if the soil is packed. Cohesion forces are caused by inter-particle physical-chemical mechanisms, including Van der Waals forces, static electronic charge, organic matter, carbonate content, etc. These basic properties, including soil texture, chemical composition, even the distribution of water-stable aggregates of a soil, would not change when the soil is mechanically disturbed. The packing density varies significantly with mechanical disturbance and will affect soil erodibility.

Soil erodibility may be significantly reduced depending on soil hardness and packing density. Soil hardness is related to soil texture and water content as functions,

$$S_h = f\left(F_b, P_d, F_w\right) \qquad \textbf{(11)}$$

where

S_h = soil hardness, Newtons cm^{-2}
F_b = inter-particle binding force
P_d = packing density, kg m^{-3}
F_w = weight of soil particles, including discrete and aggregate particles.

F_b is a function of several parameters.

$$F_b = f(F_a,\ F_c,\ S_w) \qquad \textbf{(12)}$$

where

F_a = adhesion force
F_c = cohesive force
S_w = soil water content, g kg^{-1}.

P_d is expressed by:

$$P_d = f\left(D_p,\ C_{org},\ F_p\right) \qquad \textbf{(13)}$$

where

F_p = compacting force exerted externally and the weight of soil particles themselves
C_{org} = organic matter
D_p = particle diameter .

For a surface with uniform sized particles F_w may be found by:

$$F_w = \frac{\pi}{6} D_p^3 \left(\rho_p - \rho_a\right) g\, n \qquad \textbf{(14)}$$

where

D_p = particle diameter, cm
ρ_p = particle density, gm cm^{-3}
ρ_a = air density, gm cm^{-3}
g = acceleration due to gravity, cm s^{-2}
n = number of particles on the surface.

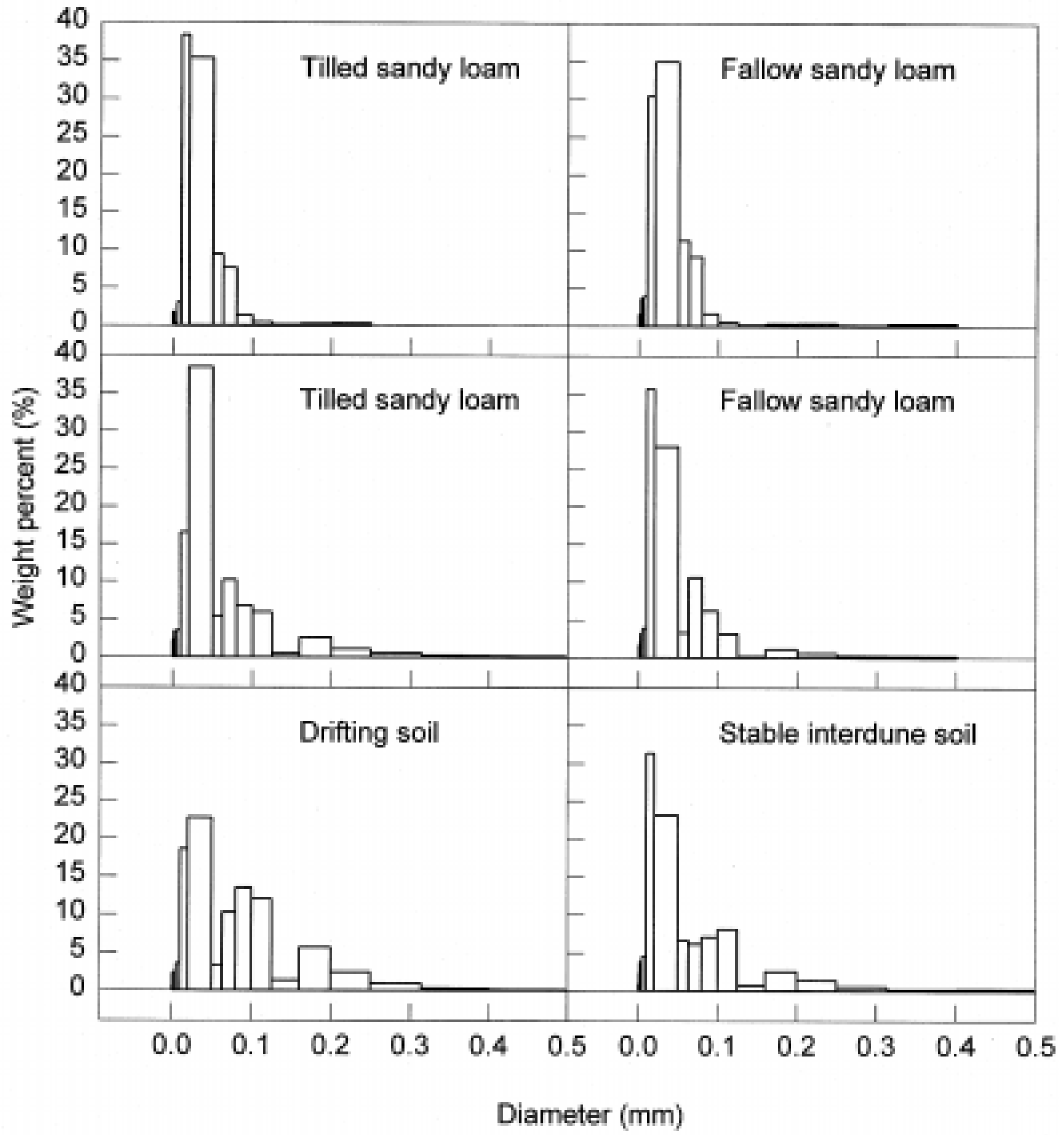

Fig. 4 Histograms of grain-size distrobution of the field investigation loessal sandy loam and loamy sand soils. As shown in the upper two-pair diagrams that the soil textures of the tilled and fallow soils were actually the same. The drifting soil, however, was coarser than the stable interdune soil.

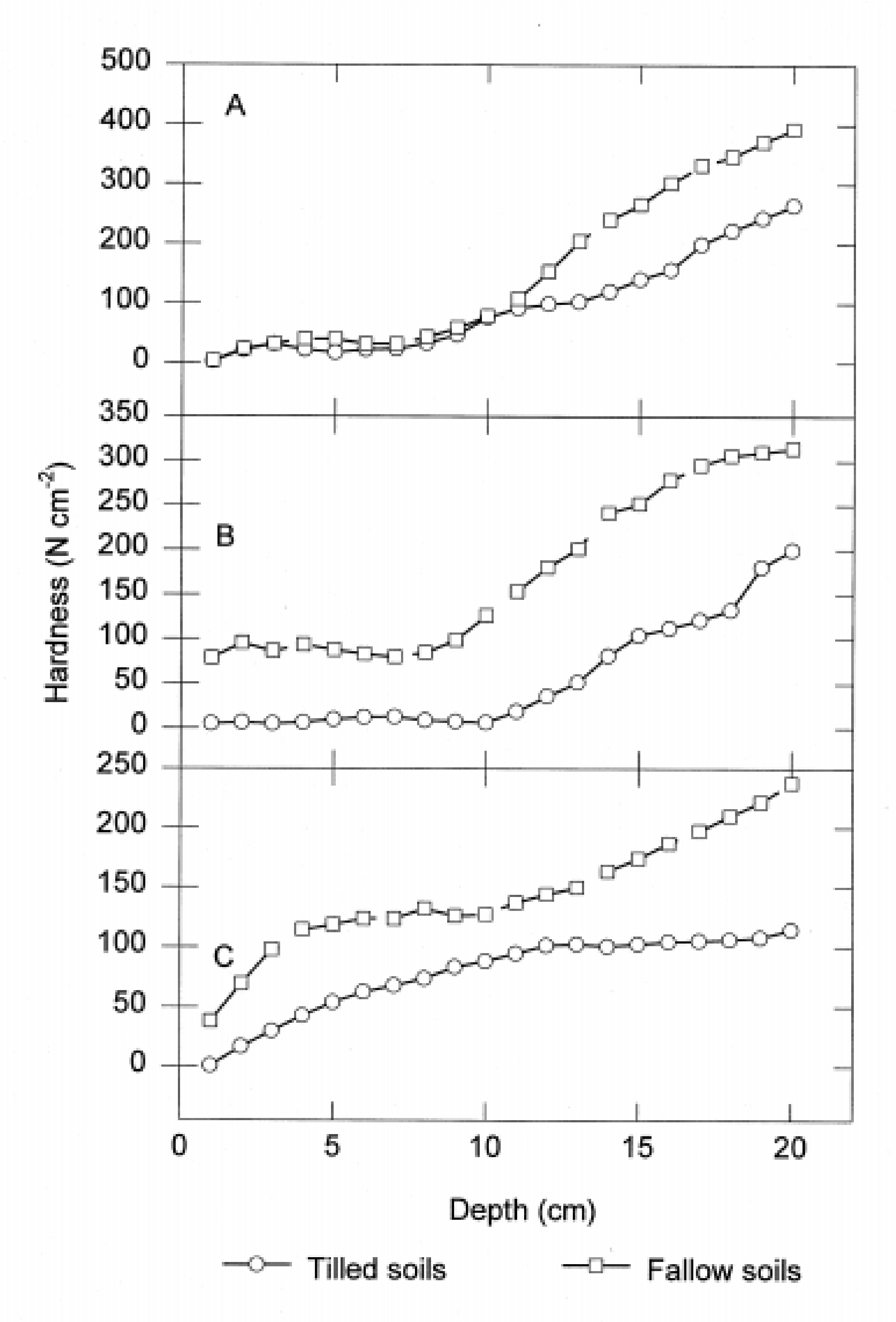

Fig. 5 Depth distribution of the soil hardness in different structural conditions.

For a given soil, size distribution of discrete particles may be considered unchangeable. Aggregate sizes change because they are basically controlled by the size distribution of the discrete particles. Natural weathering and anthropogenic agents might effect the binding force within a soil by changing soil moisture. These effects, however, are more important for loose soils rather than well-structured soils. For a compacted massive soil, packing density and mechanical stability would be more affected by mechanical disturbance. Anthropogenic agents such as tillage, mining, and off-road traffic can modify soil packing density. Loose fine soil is readily eroded by wind. A massive structured soil is hard to erode. These considerations were certified by the experimental results.

There is no doubt that surface disturbance can destroy soil structure, loosen soil density, and possibly stimulate wind erosion. Textures of tilled and fallow loessal sandy loam soils are the same (Fig.4 and Table 2), but the mechanical stabilities are different (Fig. 5A and 5B). First, the soil hardness in the plow layer, the upper 0.1 m in depth, was much lower than that below the plow layer. Second, undisturbed soils displayed more hardness than the disturbed ones. Third, the fallow soil showed a hardness value closer to tilled soil (Fig. 5A) than the 2-year-fallow soil (Fig. 5B). Fourth, the drifting soil was coarser with a lower mechanical stability because of frequent aeolian processes.

Surface disturbance affects the penetrability of soils (Fig. 5). Mechanical disturbance destroys soil structure and separates soil particles from aggregates, which increases erosion.

Table 2. Weight percentages by size distribution of the investigated soils in different structural conditions[a]

	--------------------------		Grain-size distribution, *mm*		--------------------------		
Sample ID	>0.5	~0.25	~0.125	~0.063	~0.02	~0.01	Mean diameter
TSL1	-	0.30	0.76	18.33	78.84	1.77	0.044
FSL1	-	0.73	0.90	22.13	74.54	1.63	0.045
TSL2	0.20	1.84	9.09	22.40	64.39	2.07	0.053
FSL2	-	1.07	4.44	20.10	72.80	1.60	0.047
SLPA	0.23	2.13	11.37	20.00	65.37	0.93	0.052
DS	3.33	25.47	24.57	21.7	23.69	1.23	122.376
SIS	0.23	3.66	19.07	27.04	49.51	0.50	63.009

a. TSL = Tilled sandy loam soil. FSL = Fallow sandy loam soil. SLPA = Sandy loam soil covered with perennial alfalfa. DS = Drifting soil. SIS = Stable interdune soil.

Wind-tunnel tests of influence of disturbance ratios on erosion rate of a sandy loam soil by wind are shown in Fig. 6. To analyze the influence of the disturbance ratio, an erosion coefficient was defined as

$$C_e = \frac{SER}{\rho U_{0.3}} \quad \textbf{(15)}$$

where

C_e	=	a dimensionless erosion coefficient
SER	=	soil erosion rate, kg m^{-2} min^{-1}
ρ	=	density of the air, 1.23 kg m^{-3} at 15 °C.

The term $\rho U_{0.3}$ denotes the air flow rate, which has the same units as SER ($M L^{-2} T^{-1}$). The C_e, then, may be regarded as a measure of the erosion rate per unit air flux. It displays a power relationship with the disturbance ratio R_d at the 0.01 significance levels (Fig. 6).

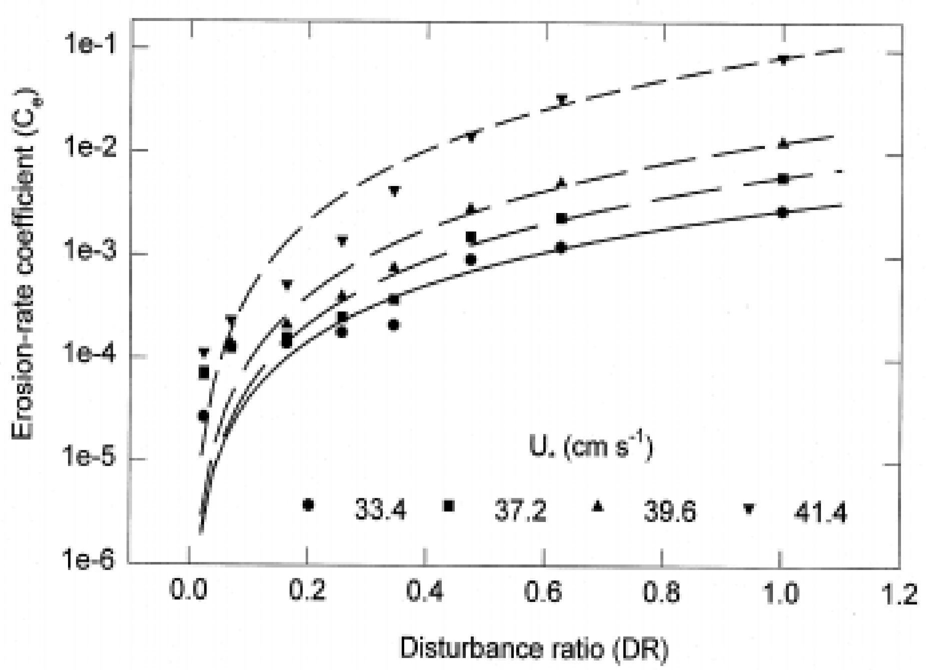

Fig. 6 Distributions of the soil erosion coefficient against the surface disturbance ratio. The ordinate is in logarithmic scale that was intentionally to show the differnce of the erosion coefficients more distictly under different friction wind velocities at lower surface disturbance ratios.

$$C_e = aR_d^{\,b} \qquad \textbf{(16)}$$

where

a and b = regression constants (Table 3).

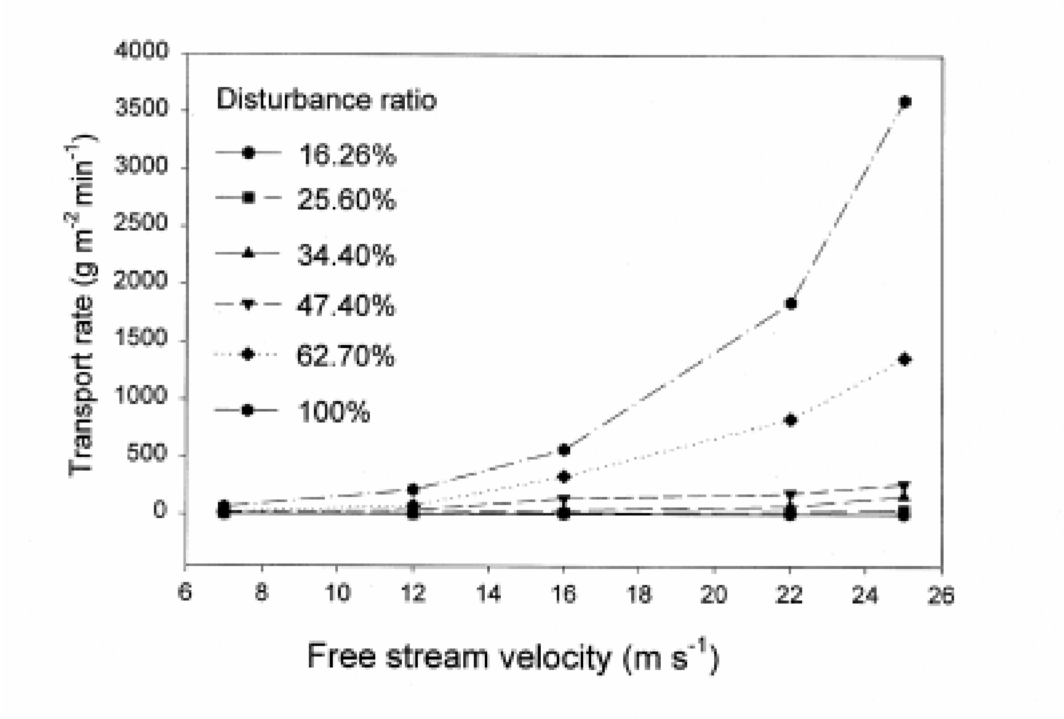

Fig. 7 An example of the relationship between the transport rate versus wind velocities obtained on a loessal sandy loam soil-sample. Evidently the most severe influence of wind velocities is at the conditions of the disturbance ratio over 50% ratios.

The soil erosion rate increased with the increasing surface disturbance ratio (DR) under all wind forces. The slopes of the curves of the erosion rate coefficient versus the disturbance ratio became larger with the increasing R_d. This revealed an increasing rate of the erosion coefficient, especially when the surface disturbance became larger than 50%. In other words, a slight disturbance may be tolerable, whereas further disturbance destroys the soil structure and the erosion rate increases rapidly.

Table 3. Parameters of the relationship between the disturbance ratio of surface soils and the erosion coefficient of soils by wind[a]

	$C_e=aR_d^b$			
U_* (cm s^{-1})	a	b	R^2	F_{stat}
33.9	0.0028	1.8297	0.997	1713.25
37.2	0.0059	2.0488	0.997	1980.86
39.6	0.0129	2.1410	0.996	1506.88
41.4	0.0864	2.2897	0.993	880.53

a. C_e = SER/$\rho U_{0.3}$, the erosion coefficient. R_d = ratio of surface soil disturbance. a and b = dimensionless constants. R^2 and F_{stat} = correlation coefficient and the threshold value in F-test. All the relationship equations are significant at the 0.01 levels.

Figure 7 is another example of erodibilty of a sandy loam soil influenced by surface disturbance, in which the relationship between the erodibility of a soil and disturbance ratios is plotted directly by the transport rate and the wind velocity. At least two aspects should be mentioned here. First, the curves cluster into two groups. The lower cluster represents the relationship between the erosion rate and the disturbance ratios less than 50%. The higher cluster represents the dependence of erosion rate on the mechanical disturbance ratios larger than 50%. Secondly, the affect of wind velocities, combined with the influence of mechanical disturbance, consisted of the whole erodible and erosive processes. The erosion rate increased profoundly when the shear stress of the air flow exceeds 0.66 N m^{-2}.

These relationships were also certified by the experimental results of black sandy loam and loamy sand soils as shown in Fig. 8, in which an index of the air flow rate was shown on the abscissa. The air flow rate (AFR), being a product of the air density (ρ) times the free stream speed $U_{0.3}$, has the same units as the erosion rate, so both the SER and AFR have the unified units ($M L^{-2} T^{-1}$). It is clear from Fig. 8 that the erosion rates for all experimental soils of black sandy loam, loessal sandy loam, and loamy sand increased with the increase of the air flow rate by an exponential function. All the relationship equations were significant at the 0.01 levels (Table 4).

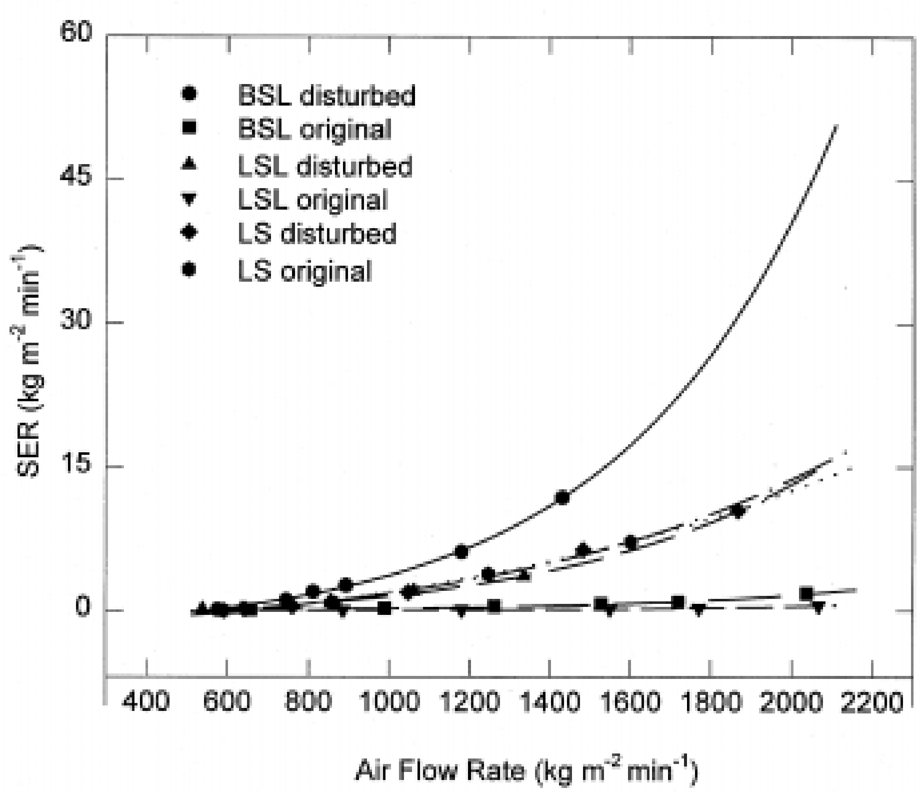

Fig. 8 Relationship of the soil erosion rate against the air flow rate manifested by several soils under disturbed and undisturbed conditions. BSL denotes black sand loam soils, LSL stands for the loessal sandy loam soils, and LS represents the loamy sand.

$$R_e = a + b\, e^{\left(\frac{-\rho\, U_{0.3}}{c}\right)} \tag{17}$$

where

R_e	=	soil erosion rate, M L^{-2} T^{-1}
$\rho U_{0.3}$	=	air flow rate (AFR, kg m^{-2} min^{-1})
ρ	=	density of the air (1.23 kg m^{-3} at 15 °C).
a, b, and c	=	demensionless regression coefficients.

Table 4. Parameters of the relationship equations between the disturbance ratio of surface soils and the erosion coefficient of soils by wind.

	---------- R_e** ----------				
Sample*	a	b	c	R^2 ***	F_{stat} ***
Disturbed LS.	-6.017	3.412	-1180.34	0.995	323.51
Original LS.	-3.297	1.537	-831.24	0.994	79.93
Disturbed BSL.	-2.601	0.906	-517.49	0.999	1318.98
Original BSL.	-0.004	0.037	-527.13	0.990	184.20
Disturbed LSL.	-1.439	0.605	-625.56	0.991	157.70
Original LSL.	0.005	0.009	-507.56	0.996	389.18

* LS = Loamy sand. BSL = Black sandy loam. LSL= Loessal sandy loam.
** R_e = soil erosion rate (SER, kg m^{-2} min^{-1}).
*** R^2 and F_{stat} = correlation coefficient and the threshold value in F-test, respectively.

All the disturbed soils manifested higher erodibility than the undisturbed soil condition, though the values of the difference were variable. The difference of erosion rates between the disturbed and undisturbed black sandy loam soils were larger than the loessal sandy loam soils. These were probably influenced by soil grain-size distribution and contents of organic matter and $CaCO_3$. Black sandy loam soils were developed on stabilized dunes. This soil does not contain particles finer than 0.005 mm in diameter, but it does have higher % organic matter (0.665) and % $CaCO_3$ (2.445) (Tables 1, 2 and 5). While it was stabilized, the black sandy loam soil possessed well-packed structure and much higher resistibility to wind erosion. Unfortunately, once it was disturbed, the structural force and the inter-particle binding force exerted mainly by organic matter and by $CaCO_3$ were lost.

Loessal sandy loam soils contained higher weight percentage of fine particles such as silt and clay (Tables 1 and 2), though the contents of organic matter and $CaCO_3$ were 0.284 % and 0.697 % (Table 5) lower than the black sandy loam. Silt and clay particles are more prone to form a massive structure to resist mechanical disturbance. The undisturbed dry loessal sandy loam soil resisted wind erosion at the highest level in the three experimental soils. Even the disturbed loessal sandy loam still possessed higher resistibility than the other soils to wind erosion.

Table 5. Organic matter and $CaCO_3$ in the experimental soils.

Soils	Sample No.	Organic matter, %	$CaCO_3$, %
Black sandy loam	1	0.922	1.75
	2	0.678	1.74
	3	0.354	3.62
	4	0.636	2.67
Loessal sandy loam	1	0.294	0.68
	2	0.277	0.71
	3	0.280	0.70
Loamy sand	1	0.154	0.044
	2	0.112	0.079
	3	0.074	0.075
	4	0.054	0.058

Loamy sand soils were the sandiest of the experimental soils. Its organic matter and $CaCO_3$ contents were 0.099 % and 0.064 % (Table 5). This soil was sampled at a drifting dune. The weak stabilized soil was not well structured, so the difference between the erodibility of disturbed and undisturbed soils was small (Fig. 8).

It might suggest that excluding the external compacting forces, soil properties such as silt and clay contents were more important in forming the mechanical stability than the percent organic matter and percent $CaCO_3$ for the soils in the Northern Loess Plateau. To describe erosion patterns it is essential to know how the erosion rate varies with surface disturbance ratios and wind velocities. For the experimental soils the surface disturbance ratio and the wind velocity were under control. Therefore, the effect of the surface disturbance ratio and the wind velocity on the erosion rate could be obtained by a multi-variable regression analysis,

$$R_e = 8.83 \times 10^{-5}\ R_d^{2.6}\ U_{0.3}^{2.4} \qquad R^2 = 0.90 \qquad \mathbf{(18)}$$

By using friction wind velocities,

$$R_e = 0.98\, R_d^{2.7}\ U_*^{1.2} \qquad R^2 = 0.89 \qquad \mathbf{(19)}$$

where

R^2 = the correlation coefficient.

Both Equations (18) and (19) were significant at the 0.01 levels. The surface disturbance ratio was more important than wind force in stimulating erosion rate.

For a given soil under a specific wind velocity, the erosion rate varied with its structural stability, which becomes the critical property in forming resistibility to wind erosion.

$$f\left(S_h\right) = \frac{dR_e}{dS_h} = -\lambda R_e \tag{20}$$

where

S_h = soil hardness or penetrability, N m^{-2}

λ = dimensionless coefficient of soil erodibility.

By integration Equation (20) becomes:

$$R_e = \alpha e^{-\lambda S_h} \tag{21}$$

where

α = a constant (s m^{-1}) equivalent to the bulk aerodynamic resistance of the transporting material to the air flow. It is analogous to the difference in the concentration of momentum between the atmosphere and the eroding surface divided by the momentum flux (Grace, 1977). Here it denotes the potential value of the maximum erosion rate for the case of thoroughly disturbed structureless state of a soil.

As shown in Table 6 and Fig 9, the distribution trends of the relationship of erosion rates against the surface disturbance ratios and the soil hardness values were the same, though the coefficients λ and α were changeable with soil types. For the experimental loessal sandy loams it was:

$$R_e = 0.115\, e^{-0.0098\, S_h} \tag{22}$$

and for the experimental black sandy loam:

$$R_e = 0.265 e^{-0.0078 S_h} \tag{23}$$

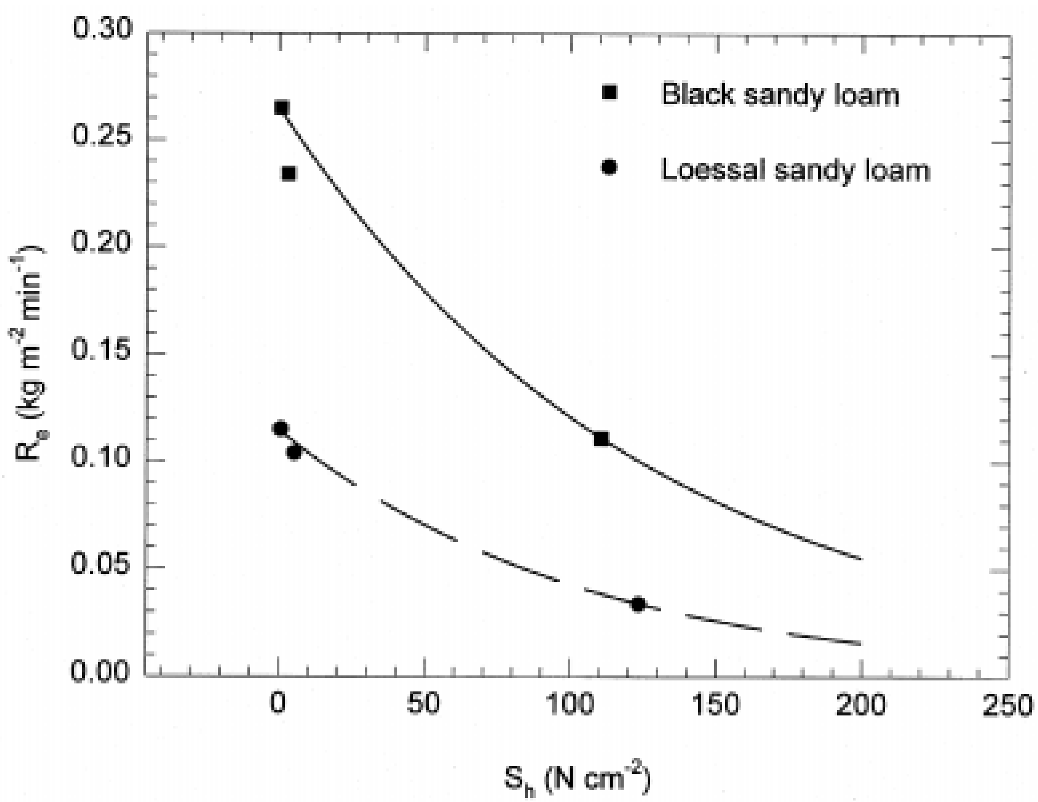

Fig. 9 Soil hardness is a comprehensive index to express soil penetrability, and thus shear strength, which mainly relates to soil texture. The experimental results on the black sandy loam soils revealed that the soil erosion rate decreased by an exponential function of the increasing soil hardness for a given textured soil.

Table 6. Soil erosion rate (SER) as influenced by surface disturbance ratios and soil hardness.

		----- Loessal sandy loam -----		----- Black sandy loam -----	
Structure state	Rd, *%*	S_h, *N cm^{-2}*	R_e, *kg m^{-2} min^{-1}*	S_h, *N cm^{-2}*	R_e, *kg m^{-2} min^{-1}*
Original	<10	123.5	0.034	110.6	0.111
Disturbed	70-80	5.3	0.104	3.2	0.234
Disturbed	90-100	0.7	0.115	0.6	0.265

The two equations revealed that the content of fine particles was significantly important not only in forming aggregates, but also in forming a total stable structure. As discussed earlier, the loessal sandy loam soil, due to its fineness in particle composition, possessed higher inter-particle cohesive force and massive bulk structure when it was dry. This was shown in the experiment where the loessal sandy loam displayed a higher hardness value and increased resistance to wind erosion

(Fig. 9). The mechanical stability of the black sandy loam was lower than the loessal sandy loam because of its coarser texture. Higher contents of organic matter and $CaCO_3$ should strengthen the mechanical stability of soils. The absolute values of organic matter and $CaCO_3$ were low, though the contents in the experimental black sandy loam were higher than in the loessal sandy loam (Table 5).

Wind erosion on a surface with loose erodible materials is a process that occurs when the air flow picks up particles and moves them by surface creep, saltation and suspension. In this case, the inter-particle force can be neglected, therefore, the air flow does not need to disintegrate particles from the surface. The total work done by the air flow, roughly, equals the work done by the air in transporting materials readily existing on the surface. If a surface consists of original structured soil such as soil crust or sediments (loess deposits) the total work done by the air flow consists of two parts. One is the work used for disintegrating particles from the unerodible soil aggregates, soil blocks or sedimentary strata. Second is the transportation of the eroded particles. The ratios of these two parts can reflect the stability of a surface. A smaller F_{surp} value refers to a state of unsaturated transport. The present work shown in Table 7 and Fig. 10 indicated that under a nonsaturated transport condition, the F_{surp} values increased with the increase in the shear stress for all experimental surface conditions. A stronger air stress would exert more force and an increase in erosion. Decreases in a and b values (Table 7) with the increase in the surface disturbance ratio manifested an increasing trend of transportation work rather than erosion work. This trend at low shear stress was not as distinct of the higher shear stress. The reason might be the air flow was more readily saturated by material at its low energy state than at high energy. The material availability for transport influenced by different surface disturbance conditions at low shear stress state were not so characterized; but in a higher shear stress state, the higher surface disturbance ratios prepared more available loose materials for transport, the surplus force of the air flow for further erosion, therefore, became relatively lower than that in the state of a lower disturbance ratio.

Table 7. Parameters in the relationship equations of F_{surp} versus τ.

	-----------------------	$F_{surp}=a\tau^b$	-----------------------
R_d %)	a	b	R^2
16.3	0.998	0.999	0.999
25.6	0.994	0.994	0.999
34.4	0.982	0.972	0.999
47.4	0.953	0.969	0.999
62.7	0.920	0.931	0.999
95.0	0.909	0.901	0.999

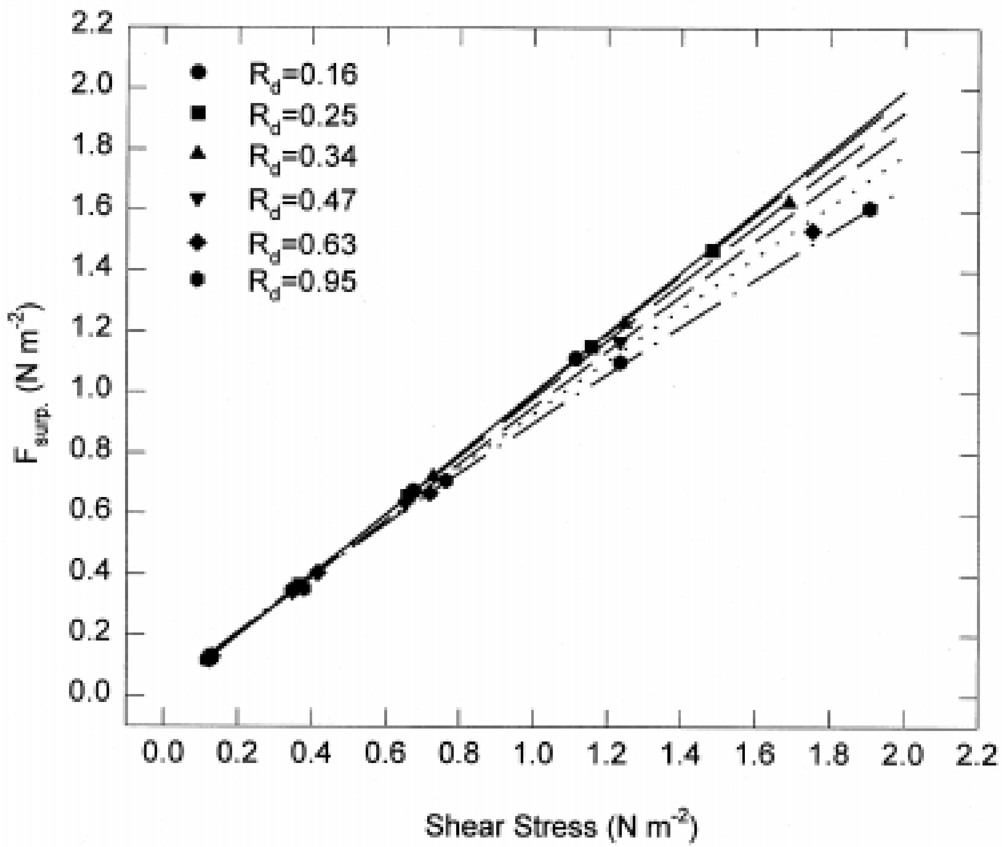

Fig. 10 The F_{surp} increased by a power function with the increasing shear stress of the air flow. The more the surface soil was disturbed unsuitable, the less portion of the air flow may be available for further erosion. That is to say most force of the air flow might be used in transporting the loose disturbed surface soils rather than in disintegrating by impacting or breaking down soil particles from the structured soil.

CONCLUSIONS

Mechanical stability of soils is an important property of soils resisting mechanical disturbance and a measure of erodibility of soils by wind. It consists of several primary factors, in which the packing density is probably the most critical. Therefore, the external compacting forces in forming a high resistibility of soils to wind erosion must be taken into consideration when analyzing soil stability and predicting the soil erosion rate. For the experimental sandy loam soils, contents of silt and clay particles were more influential than that the percent organic matter and percent $CaCO_3$ in forming their structural stability.

Disturbance of surface soils may provide temporary wind erosion control, but excessive soil disturbance may stimulate and accelerate wind erosion. The increase of erosion rate manifested an exponential function of the surface disturbance ratio. The influence of surface disturbance on erodibility of surface soils is more serious than that of wind velocity. It is recommended that lessening surface disturbance in the Loess Plateau would be the best way to protect the loessal soils from wind erosion and expansion of desertification.

Regardless of other indexes, soil hardness can be used, theoretically and practically, as a comprehensive index to predict soil erosion by wind. This paper only reports the primary results on the dependence of soil erodibility to its structural stability and disturbance ratio conducted on loessal sandy loam soils. Knowledge in understanding the mechanisms of influence of intrinsic structures of soils and surface geological sediments or rocks on their resistibility to mechanical disturbance and fluid shearing shear stress are still needed.

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