# Tillage and Land Modification to Control Wind Erosion

N. P. Woodruff and Leon Lyles
MEMBER ASAE MEMBER ASAE

THE charge given those asked to prepare papers for this conference included that we (a) do more than present results of research with which we may have been involved (b) look to the future and present advanced concepts, and (c) attempt to determine the type of tillage and land modification and the kind of research needed in the future.

This paper presents a brief review of the wind-erosion problem, considers the principles of wind control, discusses tillage in relation to wind-erosion control now and in the future, and considers land modification in relation to wind-erosion control now and in the future.

## Wind Erosion Problem

Wind erosion occurs whenever a bare, smooth, loose, dry, and pulverized soil of sufficient area is exposed to strong winds. Wind erosion is serious in areas with low and variable precipitation, high frequency of drouth, high temperatures and evaporation rates, and variable high wind velocities (42)*. The general world areas most susceptible to wind erosion are much of North Africa and the Near East, parts of southern and eastern Asia, Australia and Southern South America, the semiarid and arid portions of North America, and the steppes and Siberian plains of the USSR (28). In North America most of the wind erosion occurs in the Great Plains, the Columbia River basin, the muck and sandy soil areas around the Great Lakes, and the Gulf and Atlantic Seaboards (36). The wind erosion problem is largely encountered in dryland areas with fine-textured soils where wheat and sorghum are grown, but special problems often develop on sandy irrigated lands, in rangelands where dunes form, and in intensively tilled subhumid sandy and sandy loam soils.

## Principles of Wind Erosion Control

Most simply stated, movement of soil by wind is initiated when the pressure of the wind against the surface soil grains overcomes the force of gravity on the grains (11). However, the whole process of wind erosion and its control is much more complicated than that. The subject includes not only the physical force of the wind, the three phases of the wind erosion process, i.e., soil-particle initiation, transportation, and deposition, but also the intricate processes and conditions that suppress erosion. The severity of wind erosion depends on equilibrium condition among soil, vegetation, and climate. Wind erosion is accelerated by processes that cause surface soil to disintegrate and vegetative cover to be depleted. Conversely, it is hindered by processes that cause soil consolidation and aggregation and by vegetative cover accretion. The speed or intensity of all the processes fluctuate considerably with the vagaries of the weather and with various land uses.

Five principles of wind-erosion control can be establishd from analyses of wind-erosion phenomena, namely: (a) Produce or bring to the soil surface aggregates or clods large enough to resist the wind force, (b) roughen the land surface to reduce wind velocity and trap drifting soils, (c) reduce field widths along the prevailing wind direction by establishing wind barriers or trap strips at intervals to reduce wind velocity and soil avalanching, (d) establish and maintain vegetation or vegetative residues to protect the soil, and (e) level or bench land where economically feasible to reduce effective field widths and erosion rates on slopes and hilltops where converging streamlines of windflow cause increased velocity and shear stress.

To follow those principles and to design tillage and land-modification systems for wind-erosion control, engineers and soil conservationists must know the variables that influence wind erosion and how to evaluate the relative significance of each variable. Research has provided some criteria and equations that may be useful in designing tillage machines and practices and modifying the slope of the land to provide better wind-erosion control.

One equation that has several possibilities in design of control measures is the wind erosion equation (37):

$$E = f\ (I', C', K', L', V) \qquad [1]$$

where $E$ is average annual soil loss in tons per acre, $I'$ is the soil erodibility index measured in terms of soil aggregates greater than 0.84 mm in diam and percent slope of land, $C'$ is the climatic factor measured in terms of wind velocity and surface soil moisture, $K'$ is soil surface roughness, $L'$ is unsheltered field width measured along the direction of the prevailing wind, and $V$ is vegetative cover.

Another is the critical surface barrier ratio equation (11)

$$\frac{D_s}{H} = \frac{a}{V_* - V_{*t}} \qquad [2]$$

in which $D_s$ is the distance between nonerodible surface barriers, $H$ is the height of barriers, $V_*$ 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 coefficient that describes the shape, porosity, and other characteristics of the barrier.

A third equation with possibilities for use in designating wind-erosion control practices, particularly those requiring land modification, is the one for wind erodibility of knolly terrain (12)

$$I_s = as^b + (cd^s)^{-1} \qquad [3]$$

where $I_s$ is soil loss expressed as a percent of that from level land under equal soil and wind conditions, $s$ is percentage knoll slope, and $a$, $b$, $c$, and $d$ are constants related to position, i.e., slope or hilltop.

Applications of those equations in analyses of wind erosion problems and design of control measures are illustrated later in this paper.

### TILLAGE IN RELATION TO WIND-EROSION CONTROL

## Present Methods of Tillage

Two kinds of tillage are carried out in areas subject to wind erosion: (a) regular and (b) special or emergency.

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The authors—N. P. WOODRUFF and LEON LYLES—are research investigations leader and agricultural engineer, SWC, ARS, USDA, Manhattan, Kans.

* Numbers in parentheses refer to the appended references.

† Fryrear, D. W. A Method of Reducing the Number of Terraces in a Parallel Terracing System. ASAE Paper No. 64-220 presented at the 1964 Annual Meeting of the American Society of Agricultural Engineers at Fort Collins, Colo., 1964.

‡Jacobson, Paul. Improvements in Bench Terracing. ASAE Paper No. 67-233 presented at the 1967 Annual Meeting of the American Society of Agricultural Engineers at Saskatoon, Sask., Canada, 1967.

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*Regular Tillage*

Regular tillage primarily prepares a suitable seedbed and controls weeds for crop production. Machinery developed for regular tillage can be broadly classed into three types: (a) those that cut beneath the surface without stirring or turning the tilled layer, e.g., subsurface sweep, (b) those that stir and mix the soil, e.g., one-way disk, and (c) those that turn or invert the tilled layer, e.g., moldboard plow.

In wind erosion areas, stubble-mulch farming is extensively practiced because it manages plant residues for year-round protection of the soil surface. The first and second types of tillage machines are used in the stubble system because they conserve more residue on the surface than does the moldboard plow. Numerous publications are available, e.g. (3, 4, 5, 11, 18, 24, 38, 41), describing the stubble-mulch system and evaluating the performance of various kinds of stubble-mulch tillage implements. Problems are associated with the system such as weed control, implement clogging, planting difficulties, etc., but it is one of the most effective conservation practices available today to control erosion and conserve soil moisture in the semiarid climate.

Recently considerable research has been devoted to developing minimum tillage and chemical - weed - control methods. The minimum tillage method is used mostly for row crops like grain sorghums. Generally they have produced yields equal to other conventional methods and have provided effective erosion control (14). Effectiveness of herbicides as a substitute for tillage has varied. Anderson (2) has reported that they can replace one or more summer-fallow tillage treatments in Canada. Fenster et al. (15) reported good chemical weed control in an alternate wheat-fallow rotation in western Nebraska, and Fairbanks et al. (14) reported good weed control with chemicals applied immediately behind the till-planter but found sorghum seedling emergence reduced somewhat.

*Special or Emergency Tillage*

Special or emergency tillage is accomplished to bring clay to the surface for possible increased cloddiness and to roughen the land to prevent wind erosion. The practice includes shallow roughening with such implements as chisels, field cultivators, listers, and one-way disks with every other disk removed to create ridges, and deep plowing with huge disk or moldboard plows to bring clay to the surface. Here, also, numerous publications are available describing and evaluating the practice (6, 9, 11, 17, 28, 34, 39). Emergency tillage is generally referred to as the "last resort"; however, it can be effective in controlling wind erosion if it is accomplished when the soil is moist and compact and if there is sufficient clay to produce stable clods and effective roughness. It has little value in extremely sandy soils where clods cannot be formed and where ridges may be blown smooth under mildly erosive conditions. Deep plowing has been shown to be temporarily effective in reducing wind erodibility of sandy soil if layers having a clay content of at least 27 percent can be found within tillage depth and brought to the surface (10).

## Tillage Needs for the Future

Agriculture/2000 (16) states: "The experts envision all the field work on this farm (farm of the year 2000) carried out by automated machinery, directed by tape-controlled programs, and supervised by television scanners." The publication also predicts that weather will no longer be the incalculable threat it remains today, because satellites will provide long-range forecasting "providing time to prepare for, divert, or dissipate damaging storms." Tweedy (1) envisions need for a 4-wheel drive, 225-hp 10-ton tractor by 1970. The tractor would have two PTO's, one at the side and one at the rear, as well as new design for hitch and drawbar attachments, and would permit duel use of implements. *Kansas Farmer* (19) reports from intensive interviews with representatives of eight of the large farm machinery companies that tractors will have more horsepower; optimum till-planters will be available to plow, spread fertilizer, inject pesticides and herbicides, drop seeds, and then re-cover the seedbed with residue in one pass over the field; PTO power will be developed for ground-working tools; plow cutting edges will be vibrated; compressed air films will be used to reduce sliding friction between plowshare and soil, and high-frequency sound waves may be used to loosen soil.

If it becomes possible to divert or dissipate damaging storms, then wind erosion will not be a problem and the methods used to till the soil will be of little consequence. Also, if new designs of tractors and methods of tillage become a reality, tillage for wind-erosion control might be accomplished in an entirely different manner. However, the time when we are able to dissipate storms may be in the distant future and certainly development of new tillage methods, whether they be ultrasonic or revisions of present methods, will require a basic understanding of the principles of wind-erosion control, wind-erosion mechanics, and the major factors that influence wind erosion.

## Residue Conservation

The "cardinal" or "golden" rule of wind erosion control, i.e., that the land be covered with vegetation, will still likely be applicable in the future. Therefore, one of the chief needs for future tillage will be to conserve and orient residues for more effective protection. The importance of even very small amounts of residue in reducing erosion is evidenced by the steepness of the curves in Fig. 1. The amount of flattened residue required to reduce erosion to 5 tons per acre, a value often taken as the tolerable amount, is twice as large as that required for standing residue. Methods of tillage that conserve more residue and leave residue more erect are needed. Relationships between orientations other than standing and flattened are lacking, indicating need for more research.

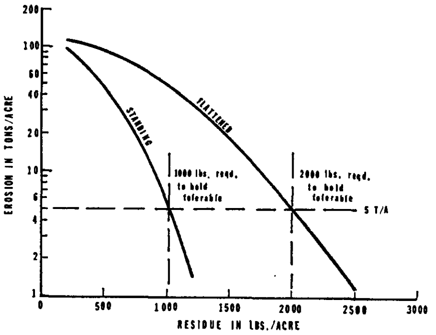


**FIG. 1 Effect of amount and orientation of residue on erosion of soil by wind. Computed from wind erosion equation (37) for a loamy fine sand with an I′of 134, a K′ of 1.0, a C′ of 100, and a field length L′ of 400 ft**

The kind of machine needed appears to be one similar in design to the subsurface sweep used today. Perhaps continued use of the present implement combined with herbicides can provide more effective cover where it is needed to control wind erosion. However, research needs to be conducted to explore possibilities of (a) placing stationary or rotating fingers or rods on the rear of subsurface blades to maintain more residue on the soil surface, (b) vibrating the blades or tillage points to fragment the soil so that nonerodible stable aggregates are placed on the soil surface and fine particles are sifted to lower depths in the tillage layer, (c) using a conveyor system that lifts a thin layer of topsoil with residue while a blade, chisel, or rotovator stirs the soil, then replaces the top layer on the surface, (d) using a system that collects and conveys residues to the rear of the tillage point and redistributes it in an anchored windrow, and (e) developing a suitable preservative and method of application to prevent rapid deterioration of residues.

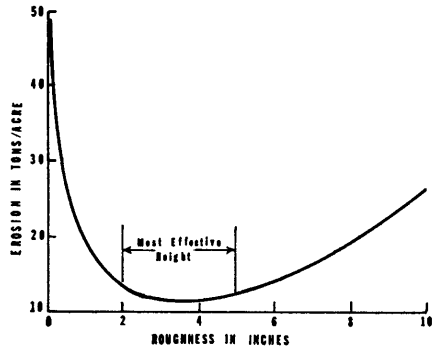


FIG. 2 Effect of surface roughness on erosion of soil by wind. Computed from the wind-erosion equation (37) for a loamy fine sand with an I' of 134, a C' of 100, a V of 3,300 (1,000 lbs per acre of flattened small grain residue), and a field length L' of 400 ft

## Surface Roughness

Perhaps another tillage requirement for future wind-erosion control will be that it leave a rough or ridged surface. Some information on the most desirable degree of roughness for maximum efficiency in controlling erosion can be obtained from equation [1]. Fig. 2 shows the effect of roughness on wind erodibility of a loamy fine sand. The most effective height is 2 to 5 in. The deep-furrow drills used to plant small grains generally produce roughness within that range and, consequently, provide an erosion-resistant surface. The concept of working only a very narrow width in the bottom of the furrow for seed placement and leaving the ridge between rows untilled with chemical weed control probably would provide good protection from wind erosion and should be evaluated for that potential. Another system worthy of additional research is the graded furrow concept developed primarily for water erosion control†. The 10-in. ridges used would not produce the most effective surface for wind-erosion control but research should be conducted to evaluate the effectiveness of lower ridges.

## Soil Cloddiness

Production of stable clods is a third area in future tillage needs. More research is also needed to obtain a better understanding of the soil cloddiness role in controlling wind erosion.

In discussions with farmers and in farmers' bulletins, general statements regarding cloddiness requirements are made, such as "50 percent of the surface soil ought to have clods greater than 0.4 in. in diameter" (40), or "half the surface clods ought to be greater than 1/25-in. in diameter" (6), or "two-thirds of the surface soil by weight ought to be of nonerodible (greater than 0.84 mm. in diameter) size fractions" (8). While that kind of information may give some idea of cloddiness requirements, it is not very useful in designing practices and machines for future wind-erosion control. Equation [1] provides some information on cloddiness requirements. For example, Fig. 3 shows data plotted from the equation, assuming different degrees of cloddiness and using values of the other variables as indicated in the legend. This graph shows that a cloddiness of 46 percent greater than 0.84 mm. in diameter would be required to hold erosion to a tolerable 5 tons per acre. While this information has some value, it still does not provide the detailed information on numbers of different clod sizes and shapes needed to design tillage equipment to meet future demands for wind-erosion control. However, the concept of a

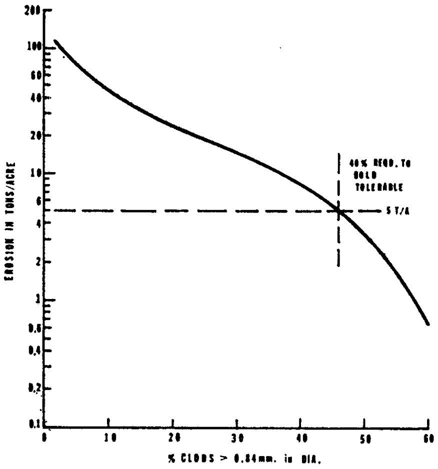


FIG. 3 Effect of soil cloddiness on erosion of soil by wind. Computed from the wind erosion equation (37) for a soil located in a zone where the climatic factor C' is 100, the field length L' is 400 ft, the roughness K' is 1.0, and the residue V is 3,300

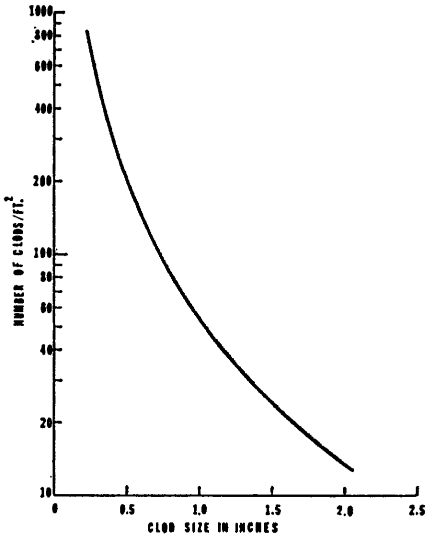


FIG. 4 Number of clods of different sizes required on the soil surface to control wind erosion. Computed from the critical surface barrier ratio equation (11) for angular clods having a coefficient "a" of 138 on soils with a minimal drag velocity $V_{*t}$ of 40 cm per sec and a wind proximate drag velocity associated with wind of 50 mph measured 50 ft above a smooth fallow field)

critical surface barrier ratio conceived by Chepil (7, 11) and presented here as an equation [2] can be used to provide more detail on the kind of cloddiness needed to be produced by tillage. Fig. 4 is a plot of equation [2] using values of variables indicated in the legend. It shows numbers of clods required to bring erosion to zero. The number varies with clod size and the larger the clod size the fewer the number required. Further research to evaluate "a" values could provide information useful in developing design criteria for future tillage machines.

Once we know the cloddiness requirements for wind-erosion control, then further research is necessary to find how best to produce that cloddiness. Such research must examine effects of soil moisture, texture, and density in addition to possible machine designs. Lyles and Woodruff (20, 21, 22) investigated the influence of soil density, moisture, and texture on soil cloddiness and determined that there was an optimum moisture level which produced more cloddiness of increased stability, that increasing density by compaction greatly increased clod yield and strength, but the amount and rate of increase was related to texture. Other investigators (10, 31, 34, 39) have examined clod-production characteristics of stubble-mulch tillage implements, deep plows, and emergency tillage implements. Results depend somewhat on moisture conditions at time of tillage, soil density, and previous tillage, but, in general, chisels produce more clods than subsurface sweeps, deep plows increase soil cloddiness at least for a few years, and all machines in all kinds of operations could do a better job than they now do of producing cloddiness for wind-erosion control.

Some research effort has been expended in testing a few commercial agricultural soil packers to obtain design criteria for impact tools to increase cloddiness and in building a prototype implement. The tests of commercial agricultural packers (22) have shown that common rolling-type soil packers do not appreciably increase soil bulk density even at optimum moisture conditions and that weight requirements and costs for large rolling static packers as used in road construction are prohibitive and impractical for farm operations. Lyles and Dickerson (23) presented these design criteria for impact-type tools to increase the cloddiness potential of sandy loam soils:

(a) Packing pressure of at least 22 psi per packing component
(b) Packing component size of at least 17 sq in. per component
(c) Not more than 8 in. of spacing between packing component centers

(d) Frequency of component application—from 350 to 700 impacts per min.

(e) A packing component stroke of at least 6 in.

They presently are developing and testing a prototype impact tool to increase the cloddiness potential of soils. The machine has impactors driven by a tractor PTO through a right-angle drive unit with sprockets and roller chains to a cam and follower arrangement. The compacting apparatus is being assembled with components of a chisel-plow into an integral tillage machine. It is believed that such a packing apparatus either attached to a chisel as in the present design where it might be used as an emergency tillage tool or to a wheat drill or other last-operation-before-planting tillage implement could effectively increase soil cloddiness without affecting seed germination or plant growth and thereby reduce wind erodibility of many winter-wheat area soils.

Other possible areas concerned with soil cloddiness where improvements in tillage for wind-erosion control could be made appear to be in: (a) applying chemicals such as calcium acrylate before tillage to increase stability of individual aggregates and thereby improve aggregation, or calcium chloride to increase rate of absorption of water thereby increasing soil strength (27, 36), (b) combining compaction before tillage with use of chemicals, (c) combining compaction before tillage with spraying of organic and inorganic soil stabilants such as asphalts, resins, and latex emulsions on soil clods and aggregates after tillage to prevent their disintegration under natural weathering, (d) developing machines that collect and lift soil clods over tillage points and place them back on the surface after the soil has been stirred, (e) applying ultrasonics (19) where high-frequency sound waves may loosen the soil only sufficiently to permit seed germination and not pulverize areas between rows, and (f) developing vibrating tillage blades or points capable of forming many small or medium-size aggregates rather than a few large ones.

## Land Modification in Relation To Wind-Erosion Control

Land modification is taken here to mean leveling, grading, benching, or any form of massive earth movement that appreciably changes land topography. It does not include strip cropping, shelterbelts, crop rotations, or microchanges in surface roughness.

## Present Land Modification Systems

Except for some very limited leveling of major hummocks and dune crests as an initial step in dune stabilization (26, 28, 30, 32) and some limited use of earthen banks for wind barriers in England (29), very little land modification is done today strictly to control wind erosion. Land generally is modified for irrigation, water-erosion control, and moisture conservation. Leveling for irrigation, coupled with crop selections and intensive agricultural operations, leaves the soil pulverized with little or no vegetative residue and may contribute to wind erosion (25). Land modification for water erosion control and moisture conservation has consisted principally of constructing graded and level terraces and some benches. The influence of such modifications on wind erosion is difficult to evaluate. Any modification that alters the terrain or places abrupt barriers in the path of wind would have some influence on wind erosion control. However, barrier influence in impeding windflow, especially in the level, flat expanses of the Great Plains where wind erosion is a particular hazard and where the principal water-conservation structure is a low, broad-based level terrace, now seems to be negligible. Probably the indirect benefits gained from additional water retained in the soil, which produces more substantial vegetative cover, are much more important (26).

## Land Modification Needs For the Future

The experts quoted in Agriculture/2000 (16) see the land carefully graded and contoured to control erosion and to reduce use of precious water. When they look at the farmland of the new century, they see a land that "presents a striped pattern, for crop rows are separated by impervious strips that catch rainfall and drain it to nourish plants. Whole hillsides of unproductive land are treated to shed previously wasted water rainfall. . . ." Jacobson† in discussing bench terracing observes that we presently have the knowledge and the tools available to economically produce an easily farmed topography free from erosion. Those statements and the knowledge that our national interstate highway program of the past 10 years has developed machinery and technology capable of mass modification of natural topography prompts speculation that we will have extensive land modification in the future. The modification probably will be done primarily for water-erosion control, irrigation, or moisture conservation. However, it is generally known that (a) wind erosion starts on exposed knolls, (b) soil loss rate is greater from tops and slopes of knolls and hills than from level land, and (c) field length over which the wind travels influences the erosion rate and amount, so any land modification that changes any of those factors, whether for wind erosion control or for some other purpose, will influence erosion of soil by wind.

Research data on windflow and wind erosion up slopes and over undulating terrain are meager and there are no data available to evaluate the influence of land modification on wind erosion. However, the wind erosion equation (equation [1]), a paper by Chepil (12) dealing with wind erodibility of knolly terrain, which produced equation [3], and a review of foreign literature on land-modification systems permit some speculation on the possible effects of changing topography.

Reducing field length $L'$ (Fig. 5) is plotted from equation [1], assuming the field and climatic conditions indicated in the legend. It demonstrates the influence of field length $L'$ on wind erosion. Since a maximum suspended load of soil material that a given wind can carry is approached and reached after the wind has moved substantial distances (in this case 1,000 to 2,000 ft), reducing field length from 6,000 to 2,000 ft or even from 2,000 to 1,000 ft would not result in substantial reductions in soil loss. However, a reduction

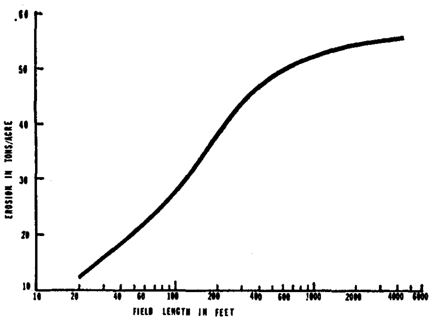


FIG. 5 Effect of field length L′ on erosion of soil by wind. Computed from the wind-erosion equation (37) for a loamy fine sand with an I′ of 134, a C′ of 100, a V of 3,300 (1,000 lbs per acre of flattened small grain residue), and a K′ of 1.0

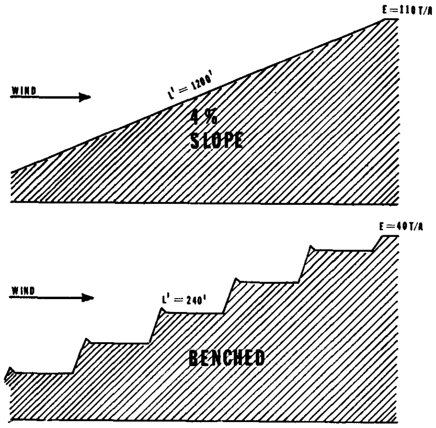


FIG. 6 Potential effects of benching and leveling land on wind erosion. Computed from the wind erosion equation (37) for a loamy fine sand with an I′ of 134 on the benches and leveled land and 214 on sloping land, a C′ of 100, a K′ of 1.0, a V of 3,300, and a field length L′ of 1,200 ft on sloping and leveled land and 240 ft on benched land

from 1,000 to 100 ft, which might be within the range resulting from benching of slopes, could reduce soil losses 50 percent.

Fig. 6 indicates potential effects of benching land. The top diagram illustrates a field with a 4 percent slope oriented so the prevailing wind direction is directly up the slope. Doughty and staff (13) and Chepil (12) have found that the streamlines of flow representing equal wind velocities over knolls and slopes are compressed, indicating steeper velocity gradients and, therefore, greater shear stress than occurs over level terrain. Chepil showed the relation between soil loss and slope to be formulated by equation [3] and indicated that for a 4 percent slope the soil loss would be 160 percent of that for the same soil and field conditions on level land. Under those conditions the resulting soil loss is shown to be 110 tons per acre. The bottom diagram illustrates the same field benched with widths recommended by Jacobson‡ for 4 percent land. Assuming no cumulative barrier effect from berms, cuts, and fills, and that wind energy remains constant for each bench, the erosion is shown to be only 40 tons per acre.

## Earthen Bank Barriers And Clay Additions

While it seems that the kind of land modification discussed in the preceding paragraph would be most practical and likely to be used in the future, there are two other possibilities that have been tried on a limited scale in other countries and that seem to have sufficient merit to justify further investigation and research. One is earthen banks placed at intervals across eroding fields in England and described by Sneesby (29). He reported banks 2 ft high provided protection for 20 yd. That extent of protection seems optimistic in view of investigations of other types of barriers (33, 35) which have shown protected distances equal to only 9 to 12 times the height of the barrier for winds reaching 40 mph at the 50-ft elevation. While erosion-control systems requiring such close spacing might not be practical for large-scale farming in the Great Plains, they might be practical for sandy lands where vegetable or other high economic value crops are grown.

Another control measure, also mentioned by Sneesby, which could be classed as a form of land modification is clay or marl additions to surface soil. In England, clay and marl are obtained and applied to the land by digging pits and trenches at one location and hauling and spreading the material. Sneesby reports that the method provides wind erosion control, but it is expensive and temporary because the material slakes and disintegrates and, therefore, must be replaced. Again, it is a measure that appears to be applicable only to sandy lands or high economic value crops. A determination of the feasibility of using the method would require evaluation of sources of supply and cost comparisons between clay additions and application of petroleum or latex surface films.

## Summary

This paper briefly reviews the wind-erosion problem, discusses requirements and principles of wind-erosion control, reviews present tillage and land modification practices in relation to wind-erosion control, proposes and speculates on some future tillage and land modification needs, and indicates some research needs.

Wind erosion occurs in many areas of the world where the climate is characterized by low and variable precipitation, high frequency of drouth, high temperatures and evaporation rates, and variable high wind velocities.

The five principles of wind-erosion control involve producing cloddy surfaces, roughening land, reducing field width, covering the land with vegetation or vegetative residue, leveling and benching land. Equations useful in designing wind erosion control practices are mentioned.

The stubble-mulch method of farming is the most effective tillage practice for wind-erosion control used in present-day agriculture. Special tillage designed to roughen the soil surface and increase soil cloddiness, such as chiseling, listing, and deep plowing, is an effective present-day emergency or "last resort" wind-erosion control measure.

Except for some very limited leveling of major hummocks on dune crests as an initial step in dune stabilization, there is very little land modification done today strictly for wind-erosion control.

The discussion of tillage needs for the future includes analyses to determine residue, surface roughness, and soil cloddiness requirements to control wind erosion and some ideas for development of different kinds of machines and tillage practices to meet the requirements, including impact packers, vibrating tillage points, use of ultrasonics, and cloddiness and residue collection and conveyor systems.

The discussion of land modification needs for the future includes analyses of the effects on erosion of windflow over long lengths of field, windflow up slopes and over hills, and speculates on the effects on wind erosion of shortening field length and leveling and benching. Use of earthen barriers and additions of clay and marl are also considered as other land-modification possibilities to attain wind-erosion control.

## References

1 AE in Action. Power projections produce new design concepts. *Agricultural Engineering* 48:(6) 346-347, 349, June 1967.

2 Anderson, C. H. Soil conservation in the semiarid region of Western Canada. Presented at First Pan-American Congress of Soil Conservation, Sao Paulo, Brazil, and scheduled for publication in Proceedings of Congress, 14 pp., 1966.

3 Anderson, D. T. Handling straw and trash cover. Agr. Inst. Rev. 8:13-15, 1953.

4 Anderson, D. T. Surface trash conservation with tillage machines. Canad. Jour. Soil Sci. 41:99-114, 1961.

5 Anderson, D. T. Some factors affecting trash conservation with the heavy-duty cultivator. Canad. Agr. Engin. 7:45-46. 49, 56, 1965.

6 Anderson, D. T., and Committee. Soil erosion by wind, cause, damage, control. Canada Dept. Agr. Pub. 1266, 26 pp., 1966.

7 Chepil, W. S. Properties of soil which influence wind erosion: I. The governing principle of surface roughness. Soil Sci. 69:149-162, 1950.

8 Chepil, W. S. Erosion of soil by wind. 1957 Yearbook of Agr., USDA, pp. 308-314, 1957.

9 Chepil, W. S., Woodruff, N. P., and Siddoway, F. H. How to control soil blowing. USDA Farmers' Bul. No. 2169, 16 pp., 1961.

10 Chepil, W. S., Moldenhauer, W. C., Hobbs, J. A., Nossaman, N. L., and Taylor, H. M. Deep plowing of sandy soil. USDA, ARS Prod. Res. Rpt. No. 64, 14 pp., 1962.

11 Chepil, W. S., and Woodruff, N. P. The physics of wind erosion and its control. Advances in Agron. 15:211-302, 1963.

12 Chepil, W. S., Siddoway, F. H., and Armbrust, D. V. Wind erodibility of knolly terrain. Jour. Soil and Water Conserv. 19: (5) 179-181, 1964.

13 Doughty, J. L., and Staff. Report of investigations. Soil Research Laboratory, Canada Dept. of Agr., Swift Current, Sask., Canada, pp. 37-38, 1943.

14 Fairbanks, G. E., Sloan, R. F., Manges, H. L., and Morin, R. E. Minimum tillage for corn and sorghum crops in Kansas. Kans. Agr. Exp. Sta. Bul. 465, 20 pp., 1963.

15 Fenster, C. R., Burnside, O. C., and Wicks, G. A. Chemical fallow studies in winter wheat fallow rotations in Western Nebraska. Agron. Jour. 57:469-470, 1965.

16 Freeman, O. A. Agriculture/2000. U. S. Government Printing Office Brochure, 72 pp., 1967.

17 Harper, H. J., and Brensing, O. H. Deep plowing to improve sandy land. Okla. Agr. Exp. Sta. Bul. No. B-362, 28 pp., 1950.

18 Horning, T. R., and Oveson, M. M. Stubble mulching in the Northwest, ARS, USDA, Agr. Information Bul. No. 253, 28 pp., 1962.

19 Kansas Farmer Staff Report. What's coming next? Kansas Farmer, pp. 28, 32-33, March 4, 1967.

20 Lyles, Leon, and Woodruff, N. P. Surface soil cloddiness in relation to soil density at time of tillage. Soil Sci. 91:178-182, 1961.

21 Lyles, Leon, and Woodruff, N. P. How moisture and tillage affect soil cloddiness for wind erosion control. *Agricultural Engineering* 43: (3) 150-153, 159, March 1962.

22 Lyles, Leon, and Woodruff, N. P. Effects of moisture and soil packers on consolidation and cloddiness of soil. *Transactions of the ASAE* 6:(4)273-275, 1963.

23 Lyles, Leon, and Dickerson, J. D. General design criteria for impact tools to increase cloddiness potential and reduce wind erodibility of sandy loam soils. *Transactions of the ASAE* 10: (2) 220-222, 1967.

24 McCalla, T. M., and Army, T. J. Stubble mulch farming. Advances in Agron. 13:125-196, 1961.

25 Mech, Stephen J., and Woodruff, Neil P. Wind erosion on irrigated lands. Agronomy Monograph No. 11. Irrigation of Agricultural Lands. Amer. Soc. Agron., pp. 964-973, 1967.

26 Nichols, M. L., and Chambers, T. B. Mechanical measures of erosion control. 1938 Yearbook of Agr., USDA, pp. 646-665, 1938.

27 Raney, W. A., and Edminster, T. W. Approaches to soil compaction research. *Transactions of the ASAE* 4: (2) 246-248, 1961.

28 Robins, J. S., and Staff of Agricultural Engineering Branch, Land and Water Development Division of the Food and Agriculture Organization of the United Nations. Soil erosion by wind and measures for its control on agricultural lands. FAO Agricultural Development Paper No. 71, 88 pp., 1960, Rome.

29 Sneesby, N. J. Wind erosion and the value of shelterbelts. Jour. Min. Agr. 60:263-271, 1953.

30 U. S. Army Corps of Engineers. Report on wind erosion control for G/M training facility. U. S. Army Engineer District, Los Angeles, California, 75-1, 40 pp., 1960.

31 Wenhardt, A. Surface clod production characteristics of some tillage machines on a clay loam soil. Canad. Jour. Agr. Engin. 4:33-35, 1962.

32 Weymouth, Norman. The Unisol 91 stabilization technique. Presented at First Pan American Congress of Soil Conservation, Sao Paulo, Brazil. Scheduled for publication in Proceedings of Congress, 1966.

33 Woodruff, N. P., and Zingg., A. W. Wind-tunnel studies of fundamental problems related to windbreaks. USDA, SCS-TP-112, 25 pp., 1952.

34 Woodruff, N. P., Chepil, W. S., and Lynch, R. D. Emergency chiseling to control wind erosion. Kans. Agr. Exp. Sta. Tech. Bul. 90, 24 pp., 1957.

35 Woodruff, N. P., Fryrear, D. W., and Lyles, Leon. Reducing wind velocity with field shelterbelts. Kans. Agr. Exp. Sta. Tech. Bul. 131, 26 pp., 1963.

36 Woodruff, N. P. Wind erosion laboratory finds answers. Soil Conserv. 29(7):152-154, 1964.

37 Woodruff, N. P., and Siddoway, F. H. A wind erosion equation. Soil Sci. Soc. Amer. Proc. 29(5): 602-608, 1965.

38 Woodruff, N. P., Fenster, C. R., Chepil, W. S., and Siddoway, F. H. Performance of tillage implements in a stubble mulch system: I. Residue conservation. Agron. Jour. 57:45-49. 1965.

39 Woodruff, N. P., Fenster, C. R., Chepil, W. S., and Siddoway, F. H. Performance of tillage implements in a stubble mulch system: II Effects on soil cloddiness. Agron. Jour. 57:49-51, 1965.

40 Woodruff, N. P. Wind erosion mechanics and control. Presented at First Pan American Congress of Soil Conservation, Sao Paulo, Brazil, and scheduled for publication in Proceedings of Congress, 1966.

41 Woodruff, N. P.. Fenster, C. R., Harris, W. W., and Lundquist, Marvin. Stubble-mulch tillage and planting in crop residue in the Great Plains. *Transactions of the ASAE* 9(6):849-853, 1966.

42 Zingg, A. W. Speculation of climate as a factor in wind erosion problems of the Great Plains. Kans. Acad. Sci. Trans. 56:371-377, 1953.