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"Wind Erosion Control"

E.L. Skidmore
United States Department of Agriculture
Agricultural Research Service - Central Plains Area
Wind Erosion Research Unit
Kansas State University
Manhattan, Kansas 66506
U.S.A.

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MAIN BUILDING STRADA COSTIERA, 11 TEL. 22401 TELEFAX 224163 TELEX 460392 ADRIATICO GUEST HOUSE VIA GRIGNANO, 9 TEL. 224241 TELEFAX 224531 TELEX 460449
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WIND EROSION CONTROL

E. L. SKIDMORE

ARS, USDA, Kansas State University, Manhattan, Kansas 66506, U.S.A.

Abstract. Wind erosion is a serious problem in many parts of the world. It physically removes from the field the most fertile portion of the soil, pollutes the air, fills road ditches, reduces seedling survival and growth, lowers the marketability of many vegetable crops, and creates new desert landforms and landscapes. It is generally worse in arid and semi-arid than in subhumid climates.

A wind erosion equation was developed as a result of many investigations on the factors influencing wind erosion. It is a useful guide to the principles of wind erosion control. The functional relationship is expressed as $E = f(I, K, C, L, V)$, where E is potential average annual soil loss per unit area, I is a soil erodibility index, K is a soil ridge roughness factor, C is a climatic factor, L is the unsheltered median travel distance of wind across a field, and V is an equivalent quantity of vegetative cover.

Principles suggested by the wind erosion equation for controlling wind include: stabilizing erodible surface with various materials; producing a rough, cloddy surface; reducing field width or the distance wind travels in crossing an unprotected field with barriers and strip crops; and establishing and maintaining sufficient vegetative cover. This last item is sometimes referred to as the "cardinal rule" for controlling wind erosion.

1. Introduction

Wind erosion is a serious problem in many parts of the world, and extensive aeolian deposits from past geologic eras give evidence that it is not a recent phenomenon.

Wind erosion is worst in arid and semi-arid areas where these conditions frequently occur: (1) loose, dry, finely divided soil; (2) smooth soil surface devoid of vegetative cover; (3) large fields; and (4) strong winds (FAO, 1960). Arid and semi-arid lands are extensive. Arid lands comprise about one-third of the world's total land area and are the home of one sixth of the world's population (Dregne, 1976; Gore, 1979). General areas most susceptible to wind erosion on agricultural land are: much of North Africa and the Near East, parts of southern and eastern Asia, Siberian Plain, Australia and southern South America, and the semi-arid and arid portions of North America. (FAO, 1960).

Lands undergoing desertification become vulnerable to wind erosion (Secretariat of UNCOD, 1977, p. 14). In pastoral rangelands, composition of pastures subject to excessive grazing in dry periods deteriorates, the proportion of edible perennial plants

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decreases, and the proportion of annuals increases. The grazers also trample vegetation and pulverize soil aggregates. The thinning and death of vegetation in dry seasons or droughts increase the extent of bare ground, and surface-soil conditions deteriorate, increasing the fraction of erodible aggregates on the soil surface. In rainfed farming, removal of the original vegetation and fallow expose the soil to accelerated wind and water erosion.

Extensive soil erosion in the Great Plains, USA, during the last half of the 19^{th} century and in the prairie region of western Canada during the 1920s warned of impending disaster, and during the 1930s a prolonged dry spell culminated in dust storms and soil destruction of disastrous proportions of the prairie regions in both werstern Canada and the Great Plains of the United States (Anderson 1975; Svobida, 1940; Malin, 1946abc; Johnson, 1947; Hurt, 1981).

Wind erosion physically removes from the field the most fertile portion of the soil and therefore lowers productivity of the land (Daniel and Langham, 1936; Lyles, 1975).

Some soil from damaged lands enters suspension and becomes part of the atmospheric dustload. Hagen and Woodruff (1973) estimated that eroding lands of the Great Plains contributed 244 and 77 million tons of dust per year to the atmosphere in the 1950s and 1960s, respectively. Jaenicke (1979) estimated the source strength of mineral dust from the Sahara at 260 million tons per year. Dust obscures visibility and pollutes the air, causes automobile accidents, fouls machinery, and imperils animal and human health.

Blowing soil fills road ditches; reduces seedling survival and growth; lowers the marketability of vegetable crops like asparagus, green beans, and lettuce; increases the susceptibility of plants to certain types of stress including diseases; and contributes to transmission of some plant pathogens (Hayes, 1965, 1966; Claflin *et al.*, 1973).

2. Control Principles

Principles for controlling wind erosion include: stabilizing with various materials; producing a rough, cloddy surface; reducing effective field width with barriers; and establishing and maintaining sufficient vegetative cover (Woodruff *et al.*, 1972).

Those principles for controlling wind erosion are summarized by the general functional relationship given by Woodruff and Siddoway (1965) as a wind erosion equation in the form $E = f(I, K, C, L, V)$, where E is potential average annual soil loss per unit area, I is a soil erodibility index based on fraction of nonerodible soil aggregates (particles > 0.84 mm) in the erodible size range, K is a soil ridge roughness factor, C is a climatic factor, L is the unsheltered median travel distance of wind across a field and V is equivalent quantity of vegetative cover.

The equation was developed as a result of many years of studying the factors influencing wind erosion. It has been used widely for its intended purposes to determine both the potential erosion from a particular field and the field conditions (soil cloddiness, roughness, vegetative cover, sheltering by barrier, or width and orientation of field) neccessary to reduce potential erosion to a tolerable amount.

2.1 Stabilizers

Various soil stabilizers have been evaluated to find suitable materials and methods to control wind erosion (Armbrust and Dickerson, 1971; Armbrust and Lyles, 1975; Chepil, 1955; Chepil and Woodruff, 1963; Chepil *et al.*, 1963; Lyles *et al.*, 1969; Lyles *et al.*, 1974). Several tested products successfully controlled wind erosion for a short time but many were more expensive than equally effective wheat straw anchored with a rolling disk packer (Chepil *et al.*, 1963). The following are criteria for surface-soil stabilizers; (1) 100 percent of the soil must be covered, (2) the stabilizer must not adversely affect plant growth or emergence, (3) erosion must be prevented initially and reduced for the duration of the severe erosion hazard, usually for at least two months each season, (4) the stabilizer should apply easily and without special equipment, and (5) cost must be low enough for profitable use (Armbrust and Lyles, 1975). Armbrust and Lyles (1975) found five polymers and one resin-in-water emulsion that met all those requirements. They added, however, that before soil stabilizers can be used on agricultural lands, methods must be developed to apply large volumes rapidly. Also, reliable preemergent weed-control chemicals to use on coarse-textured soils must be developed as well as films resistant to raindrop impact, yet still allow water and plant penetration without adversely affecting the environment.

Periodically, symposia (DeBoodt and Gabriels, 1975) are held on soil conditioning which include papers on some aspect of using soil conditioners for controlling wind erosion. DeBoodt (personal communication), Ghent, Belgium, believes that activating neutral sand surfaces with iron sulfate and stabilizing the surface with ureaformaldehyde has much promise as an inexpensive and effective method for controlling wind erosion on sandy soils.

2.2 Rough, cloddy surface

Chepil and Milne (1941a), investigating the influence of surface roughness on drifting dune materials and cultivated soils, found that the initial intensity of drifting was always much less over a ridged than a smooth surface. Ridging cultivated soils reduced the severity of drifting, but ridging highly erosive dune materials was less effective because the ridges disappeared rapidly. The rate of flow varied inversely with surface roughness.

Armbrust *et al.*, (1964) studied the effects of ridge roughness equivalent on total quantity of eroded material from three simulated, cultivated soils exposed to different friction velocities. From their data, a curve can be constructed showing the relationship between quantity of eroded material and ridge roughness equivalent. Presumably, that is the origin of the chart by Woodruff and Siddoway (1965, Fig. 4) showing a soil-ridge roughness factor as a function of soil-ridge roughness. The soil-ridge roughness factor estimates the fractional reduction of erosion caused by ridges of nonerodible aggregates, and is used in the wind erosion equation. It is influenced by ridge spacing and ridge height and it is defined relative to a 1:4 ridge height to ridge spacing ratio. Mathematically, soil-ridge roughness equals four times ridge height squared divided by ridge spacing. A soil-ridge roughness of 6 cm reduces wind erosion 50 percent. As roughness increases to about 11 cm, the soil-ridge roughness factor remains about constant; then, with additional roughness, the effectiveness of ridges gradually decreases. More recently, Fryrear (1984) found a greater reduction in erosion than previously reported and erosion remained relatively constant as ridge roughness increased beyond 11 cm.

When ridges are mostly gone, vegetative cover is depleted, and the threat of wind erosion continues, a rough, cloddy surface resistant to the force of wind can be created on many cohesive soils with appropriate "emergency tillage". Lyles and Tatarko (1982) found that chiseling of growing winter wheat on a silty clay soil increased greatly nonerodible surface aggregates without influencing grain yields. Listers, chisels, cultivators, one-way disks with two or three disks removed at intervals, and pitting machines can be used to bring compact clods to the surface. Emergency tillage is most effective when done at right angles to the prevailing wind direction. Because clods eventually disintegrate (sometimes rapidly), emergency tillage offers, at best, only temporary wind-erosion control (Woodruff *et al.*, 1957, 1972).

2.3 Residue

Living vegetation or residue from harvested crops protects the soil against wind erosion. Standing crop residues provide nonerodible elements that absorb much of the shear stress in the boundary layer. When vegetation and crop residues are sufficiently high and dense to prevent intervening soil-surface drag from exceeding threshold drag, soil will not erode. Rows perpendicular to wind direction control wind erosion more effectively than do rows parallel to wind direction (Engelhorn *et al.*, 1952; Skidmore *et al.*, 1966). Flattened stubble, though not so effective as standing also protects the soil from wind erosion (Chepil *et al.*, 1955).

Soon after the disastrous "dirty thirties" in the US Great Plains, use of stubble-mulch systems was demonstrated to be a feasible method of reducing wind erosion on cultivated land (Duley, 1959). "Stubble mulching" is a crop residue management system using tillage, generally without soil inversion and usually with blades or v-shaped sweeps (McCalla and Army, 1961; Mannering and Fenster, 1983). The goal is to leave a desirable quantity of plant residue on the surface of the soil at all times. Residue is needed for a period of time even after the crop is planted to protect the soil from erosion and to improve infiltration. The residue used is generally that remaining from a previous crop.

Studies (Chepil, 1944; Chepil *et al.*, 1955; Siddoway *et al.*, 1965) to quantify specific properties of vegetative covers influencing wind erosion led to the relationship presented by Woodruff and Siddoway (1965), showing the influence of an equivalent vegetative cover of small grain and sorghum stubble for various orientations (flat, standing, height).

Efforts have continued to evaluate the protective role of additional crops (Craig and Turelle, 1964; Lyles and Allison, 1981), range grasses (Lyles and Allison, 1980), feedlot manure (Woodruff *et al.*, 1974), and the protective requirements of equivalent residue needed to control wind erosion (Lyles *et al.*, 1973; Skidmore and Siddoway, 1978; Skidmore *et al.*, 1979).

2.4 Barrier

Reducing the field width or the distance that wind travels in crossing unprotected field strips reduces wind erosion. Chepil and Milne (1941b) reported zero soil movement on the windward side of fields or field strips and increased soil movement with distance downwind. Later, Chepil (1946) found that the cumulative rate of soil movement with distance away from the windward edge of eroding fields was the main cause of increasing abrasion and gradual decrease in surface roughness along the direction of wind. He called this increase in rate of flow with distance downwind "avalanching":

> "Rate of soil flow increased with distance downwind across an eroding field until, if the field was large enough, it reached a maximum that a wind of a given velocity can carry. Beyond that point the rate of flow remained essentially constant" (Chepil, 1957).

Use of wind barriers is an effective method of reducing field width. Barriers have long been recognized as valuable for controlling wind erosion (Bates, 1911). Hagen (1976), and Skidmore and Hagen (1977) developed a model that, when used with local wind data, shows wind barrier effectiveness in reducing wind erosion forces: barriers will reduce wind forces more than they will wind speed (surface wind shear stress is proportional to wind speed squared); a properly oriented barrier, when winds predominate from a single direction, will decrease wind erosion forces by more than 50 percent from the barrier leeward to 20 times its height; the decrease will be greater for shorter distances from the barrier.

Different combinations of trees, shrubs, tall-growing crops, and grasses can reduce wind erosion. Besides the more conventional tree windbreak (Ferber, 1969; Read, 1964; Woodruff *et al.*, 1976), many other barrier systems are used to control wind erosion. They include annual crops like small grains, corn, sorghum, sudangrass, sunflowers (Carreker, 1966; Fryrear, 1963, 1969; Hagen *et al.*, 1972; Hoag and Geiszler, 1971), tall wheatgrass (Aase *et al.*, 1976; Black and Siddoway, 1971), sugarcane and rye strips on sands in Florida (Griffin, SCS Agronomist, personal communication, 1975).

Most barrier systems for controlling wind erosion, however, occupy space that could otherwise be used to produce crops. Perennial barriers grow slowly and are often established with difficulty (Dickerson *et al.*, 1976; Woodruff *et al.*, 1976). Such barriers also compete with the crops for water and plant nutrients (Lyles *et al.*, 1983). Thus the net effect for many tree-barrier systems is that their use may not benefit crop production (Frank *et al.*, 1977; McMartin *et al.*, 1974; Skidmore *et al.*, 1975; Skidmore *et al.*, 1974; Staple and Lehane, 1955). Perhaps the tree-barrier systems could be designed so that they become a useful crop, furnishing nuts, fruits, or wood.

2.5 Strip cropping

The practice of farming land in narrow strips on which the crop alternates with fallow is an effective aid in controlling wind erosion (Chepil, 1957). Strips are most effective when they are at right angles to the prevailing wind erosion direction but also provide some protection from winds that are not perpendicular to the field strip.

Strip cropping reduces erosion damage in the following ways: it reduces the distance the wind travels across exposed soil, localizes drifting that starts at a focal point, and reduces wind velocity across the fallow-strip when adjacent fields are covered with tall stubble or crops.

Although each method to control wind erosion has merit and application, establishing and maintaining vegetative cover, when feasible, remains the best defense against wind erosion. However, that becomes a difficult challenge as pressure increases to use crop residues for livestock feed and fuel for cooking.

References

Aase, J. K., F. H. Siddoway, and A. L. Black: 1976, 'Perennial Grass Barriers for Wind Erosion Control, Snow Management, and Crop Production', in *Shelterbelts on the Great Plains – Proceedings of the Symposium*, Great Plains Agricultural Publication No. 78, p. 69–78.

Anderson, C. H.: 1975, *A History of Soil Erosion by Wind in the Pallister Triangle of Western Canada*, Historical Series No. 8, Research Branch, Canada Department of Agriculture, 25 pp.

Armbrust, D. V., W. S. Chepil, and F. H. Siddoway: 1964, 'Effects of Ridges on Erosion of Soil by Wind', *Soil Science Society of America Proceedings*, **28**, 557–560.

Armbrust, D. V. and J. D. Dickerson: 1971, 'Temporary Wind Erosion Control: Cost and Effectiveness of 34 Commercial Materials', *Journal of Soil and Water Conservation*, **26**, 154–157.

Armbrust, D. V. and L. Lyles: 1975, 'Soil Stabilizers to Control Wind Erosion', *Soil Science Society of America, Special Publication No. 7*, Soil Conditioners, 77–82.

Bates, Carlos G.: 1911, 'Windbreaks: Their Influence and Value', USDA *Forest Service Bulletin*, **86**, 100 pp.

Black, A. L. and F. H. Siddoway: 1971, 'Tall Wheatgrass Barriers for Soil Erosion Control and Water Conservation', *Journal of Soil and Water Conservation*, **26**, 107–110.

Carreker, J. R.: 1966, 'Wind Erosion in the Southeast', *Journal of Soil and Water Conservation*, **21**, 86–88.

Chepil, W. S.: 1944, 'Utilisation of Crop Residues for Wind Erosion Control', *Sci. Agr.*, **24**, 307–319.

Chepil, W. S.: 1946, 'Dynamics of Wind Erosion: V. Cumulative Intensity of Soil Drifting Across Eroding Fields', *Soil Science*, **61**, 257–263.

Chepil, W. S.: 1955, 'Effects of Asphalt on Some Phases of Soil Structure and Erodibility by Wind', *Soil Science Society of America Proceedings*, **19**, 125–128.

Chepil, W. S.: 1957, 'Width of Field Strip to Control Wind Erosion', *Kansas Agricultural Experimental Station Technical Bulletin*, **92**.

Chepil, W. S. and R. A. Milne: 1941a, 'Wind Erosion of Soil in Relation to Roughness of Surface', *Soil Science*, **52**, 417–433.

Chepil, W. S. and R. A. Milne: 1941b, 'Wind Erosion of Soils in Relation to Size and Nature of the Exposed Area', *Sci. Agr.*, **21**, 479–487.

Chepil, W. S. and N. P. Woodruff: 1963, 'The Physics of Wind Erosion and Its Control', *Advances in Agronomy*, **15**, 211–302.

Chepil, W. S., N. P. Woodruff, F. H. Siddoway, D. W. Fryrear, and D. V. Armbrust: 1963, 'Vegetative and Nonvegetative Materials to Control Wind and Water Erosion', *Soil Science Society of America Proceedings*, **27**, 86–89.

Chepil, W. S., N. P. Woodruff, and A. W. Zingg: 1955, *Field Study of Wind Erosion in Western Texas*, USDA SCS-TP-125, 60 pp.

Claflin, L. E., D. L. Stuteville, and D. V. Armbrust: 1973, 'Windblown Soil in the Epidemiology of Bacterial Leaf Spot of Alfalfa and Common Blight of Beans', *Phytopathology*, **63**, 1417–1419.

Craig, D. G. and J. W. Turelle: 1964, *Guide for Wind Erosion Control on Cropland in the Great Plains States*, USDA SCS, Washington D.C., 104 pp.

Daniel, H. A. and W. H. Langham: 1936, 'The Effect of Wind Erosion and Cultivation on the Total Nitrogen and Organic Matter Content of Soil in the Southern High Plains', *Journal of the American Society of Agronomy*, **28**, 587–596.

DeBoodt, M. and D. Gabriels (Editors): 1976, *Third International Symposium on Soil Conditioning*, State University of Ghent, Belgium.

Dickerson, J. D., N. P. Woodruff, and E. E. Banbury: 1976, 'Techniques for Improving Survival and Growth of Trees in Semiarid Areas', *Journal of Soil and Water Conservation*, **31**, 63–66.

Dregne, H. E.: 1976, *Soils of the Arid Regions*, Elsevier Scientific Publishing Company, 237 pp.

Duley, F. L.: 1959, 'Progress of Research on Stubble Mulching in the Great Plains', *Journal of Soil and Water Conservation*, **14**, 7–11.

Englehorn, C. L., Q. W. Zingg, and N. P. Woodruff: 1952, 'The Effects of Plant Residue Cover and Clod Structure on Soil Losses by Wind', *Soil Science Society of America Proceedings*, **16**, 29–33.

Ferber, A. E.: 1969, *Windbreaks for Conservation*, USDA SCS, Agricultural Information Bulletin, 339.

Food and Agriculture Organization of the United Nations (FAO): 1960, *Soil Erosion by Wind and Measures for its Control on Agricultural Lands*, FAO Agricultural Development Paper No. 71.

Frank, A. B., D. G. Harris, and W. O. Willis: 1977, 'Growth and Yields of Spring Wheat as Influenced by Shelter and Soil Water', *Agronomy Journal*, **69**, 903–906.

Fryrear, D. W.: 1963, 'Annual Crops as Wind Barriers', *Transactions of the ASAE*, **6**, 340–342, 352.

Fryrear, D. W.: 1969, *Reducing Wind Erosion in the Southern Great Plains*, Texas A&M University, MP-929, September.

Fryrear, D. W.: 1984, 'Soil Ridges-Clods and Wind Erosion', *Transactions of the ASAE*, **27**, 445–448.

Gore, R.: 1979, 'The Desert: An Age-old Challenge Grows', *National Geographic*, **156**, 586–639.

Hagen, L. J.: 1976, 'Windbreak Design for Optimum Wind Erosion Control', in *Shelterbelts on the Great Plains–Proceedings of the Symposium*, Great Plains Agricultural Publication No. 78, 31–36.

Hagen, J. L. and N. P. Woodruff: 1973, 'Air Pollution from Duststorms in the Great Plains', *Atmospheric Environment*, **7**, 323–332.

Hagen, L. J., E. L. Skidmore, and J. D. Dickerson: 1972, 'Designing Narrow Strip Barrier Systems to Control Wind Erosion', *Journal of Soil and Water Conservation*, **27**, 269–270.

Hayes, W. A.: 1965, 'Wind Erosion Equation Useful in Designing Northeastern Crop Protection', *Journal of Soil and Water Conservation*, **20**, 153–155.

Hayes, W. A.: 1966, *Guide for Wind Erosion Control in the Northeastern States*, USDA SCS.

Hoag, B. K. and G. N. Geiszler: 1971, 'Sunflower Rows to Protect Fallow From Wind Erosion', *North Dakota Farm Research*, **28**, 7–12.

Hurt, R. D.: 1981, *The Dust Bowl: An Agricultural and Social History*, Nelson-Hall, Chicago, 214 pp.

Jaenicke, R.: 1979, 'Monitoring and Critical Review of the Estimated Source Strength of Mineral Dust from the Sahara', in Christer Morales (Ed.) *Saharan Dust: Mobilization, Transport, Deposition*, SCOPE 14, Wiley, 233–242.

Johnson, V.: 1947, *Heaven's Tableland—The Dust Bowl Story*, Farrar-Strauss, New York, 155–157.

Lyles, L.: 1975, 'Possible Effects of Wind Erosion on Soil Productivity', *Journal of Soil and Water Conservation*, **30**, 279–283.

Lyles, L. and B. E. Allison: 1980, 'Range Grasses and Their Small Grain Equivalents for Wind Erosion Control', *Journal of Range Management*, **33**, 143–146.

Lyles, L. and B. E. Allison: 1981, 'Equivalent Wind-Erosion Protection from Selected Crop Residues', *Transactions of the ASAE*, **24**, 405–408.

Lyles, L., D. V. Armbrust, J. D. Dickerson, and N. P. Woodruff: 1969, 'Spray-on Adhesives for Temporary Wind Erosion Control', *Journal of Soil and Water Conservation*, **24**, 190–193.

Lyles, L., N. F. Schmeidler, and N. P. Woodruff: 1973, 'Stubble Requirements in Field Strips to Trap Windblown Soil', *Kansas Agriculture Experimental Station Research Publication*, **164**, 22 pp.

Lyles, L., R. L. Schrandt, and N. F. Schmeidler: 1974, 'Commercial Soil Stabilizers for Temporary Wind Erosion Control', *Transactions of the ASAE*, **17**, 1015–1019.

Lyles, L. and J. Tatarko: 1982, 'Emergency Tillage to Control Wind Erosion: Influences on Winter Wheat Yields', *Journal of Soil and Water Conservation*, **37**, 344–347.

Lyles, L., J. Tatarko, and J. D. Dickerson: 1983, 'Windbreak Effects on Soil Water and Wheat Yield', *American Society of Agricultural Engineers*, Paper No. 83–2074.

Malin, J. C.: 1946a, 'Dust Storms—Part 1, 1850–1860', *The Kansas Historical Quarterly*, **14**, 129–144.

Malin, J. C.: 1946b, 'Dust Storms—Part 2, 1861–1880', *The Kansas Historical Quarterly*, **14**, 265–296.

Malin, J. C.: 1946c, 'Dust Storms—Part 3, 1881–1900', *The Kansas Historical Quarterly*, **14**, 391–413.

Mannering, J. V. and C. R. Fenster: 1983, 'What Is Conservation Tillage?', *Journal of Soil and Water Conservation*, **38**, 141–143.

McCalla, T. M. and T. J. Army: 1961, 'Stubble Mulch Farming', *Advances in Agronomy*, **13**, 125–196.

McMartin, W., A. B. Frank, and R. H. Heintz: 1974, 'Economics of Shelterbelt Influence on Wheat Yields in North Dakota', *Journal of Soil and Water Conservation*, **29**, 87–91.

Read, R. A.: 1964, *Tree Windbreaks for the Central Great Plains*, USDA Agronomy Handbook No. 250.

Secretariat of UNCOD: 1977, *Desertification: Its Causes and Consequences*, United Nations Conference on Desertification, Pergamon Press.

Siddoway, F. H., W. S. Chepil, and D. V. Armbrust: 1965, 'Effect of Kind. Amount, and Placement of Residue on Wind Erosion Control', *Transactions of the ASAE*, **8**, 327–331.

Skidmore, E. L. and L. J. Hagen: 1977, 'Reducing Wind Erosion with Barriers', *Transactions of the ASAE*, **20**, 911-915.

Skidmore, E. L., L. J. Hagen, D. G. Naylor, and I. D. Teare: 1974, 'Winter Wheat Response to Barrier-induced Microclimate', *Agronomy Journal*, **66**, 501–505.

Skidmore, E. L., L. J. Hagen, and I. D. Teare: 1975, 'Wind Barriers Most Beneficial at Intermediate Stress', *Crop Science*, **15**, 443-445.

Skidmore, E. L., M. Kumar, and W. E. Larson: 1979, 'Crop Residue Management for Wind Erosion Control in the Great Plains', *Journal of Soil and Water Conservation*, **34**, 90–96.

Skidmore, E. L., N. L. Nossaman, and N. P. Woodruff: 1966, 'Wind Erosion as Influenced by Row Spacing, Row Direction, and Grain Sorghum Population', *Soil Science Society of America Proceedings*, **30**, 505–509.

Skidmore, E. L. and F. H. Siddoway: 1978, 'Crop Residue Requirements to Control Wind Erosion', in W. R. Oschwald (Ed.) *Crop Residue Management Systems*, ASA Special Publication No. 31, 17–33.

Staple, W. J. and J. H. Lehane: 1955, 'The Influence of Field Shelterbelts on Wind Velocity, Evaporation, Soil Moisture, and Crop Yields', *Canadian Journal of Agricultural Science*, **35**, 440–453.

Svobida, L.: 1940, *An Empire of Dust*, Caxton Printers, Ltd., Caldwell, Idaho, 203 pp.

Woodruff, N. P., W. S. Chepil, and R. D. Lynch: 1957, 'Emergency Chiseling to Control wind Erosion', *Kansas Agriculture Experimental Station Technical Bulletin 90*.

Woodruff, N. P., J. D. Dickerson, E. E. Banbury, A. B. Erhart, and M. C. Lundquist: 1976, *Selected Trees and Shrubs Evaluated for single-row Windbreaks in the Central Great Plains*, USDA, ARS, NC-37.

Woodruff, N. P., L. Lyles, J. D. Dickerson, and D. V. Armbrust: 1974, 'Using Cattle Feedlot Manure to Control Wind Erosion', *Journal of Soil and Water Conservation*, **29**, 127–129.

Woodruff, N. P., L. Lyles, F. H. Siddoway, and D. W. Fryrear: 1972, 'How to Control Wind Erosion', *USDA ARS Agricultural Information Bulletin*, **354**, 22 pp.

Woodruff, N. P. and F. H. Siddoway: 1965, 'A Wind Erosion Equation', *Soil Science Society of America Proceedings*, **29**, 602–608.