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Review article

Wind erosion from cropland in the USA: a review of problems, solutions and prospects

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Abstract

Agricultural practices dominate over climatic variability in determining temporal variability in dust blowing on cropland in the USA. Farming operations that increase wind erosion and dust emissions include plowing, leveling beds, planting, weeding, seeding, fertilizing, mowing, cutting, baling, spreading compost or herbicides and burning fields. Methods of controlling sediment loss include planting windbreaks and special crops to alter wind flow; retaining plant residue after harvesting; tilling soil to bury erodible particles, create aggregates that resist entrainment, and increase surface roughness; improving farm equipment; and stabilizing soil surfaces using water or commercial products. Government programs prescribe air quality standards, provide education programs, and cost-share and incentive payments to assist farmers in controlling erosion and dust production. Problems continue because farmers do not consider wind erosion a significant problem. Dust events have nevertheless decreased in some areas, indicating that improved management practices may be effective where accepted by farmers.
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1. Introduction

Wind erosion, transport, and deposition occur over more than one third of the land surface of the Earth (Chen and Fryrear, 1996). Soil dust affects atmospheric composition and climate change (Prospero et al., 1983), transport of herbicides on sediments (Larney et al., 1998), soil texture, nutrient content, vegetation growth and productivity (Grantz et al., 1998), characteristics of deep-sea sediments (Prospero et al., 1983), and human health (Norton and Gunter, 1999). The frequency of blowing dust may be caused by natural processes and is common in desert environments, but agricultural activities that disturb the soil can greatly increase the frequency and amount of airborne dust (Prospero et al., 1983; Tegen and Fung, 1995; Zhibao et al., 2000). Aeolian transport of cultivated and grazed soils is a global problem that has generated studies in Europe (Goossens et al., 2001), Africa (Bielders et al., 2000), Asia (Zhibao et al., 2000), Australia (Gillieson et al., 1996), and South America (Buschiazzo et al., 1999).

Erosion and transport of soil has negative effects both within and outside the source area, and the capability of dust to be transported great distances

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makes the problem of both national and international scope (Prospero et al., 1983; Argabright, 1991; Zhibao et al., 2000). In the USA, the negative off-site impacts of erosion from farms are potentially greater than onsite losses in soil productivity, so society may have greater incentive for reducing erosion than farmers have (Uri, 1999). For example, by the mid 1980s, off-site costs associated with wind erosion in the State of New Mexico were estimated at $466 million per year, dwarfing the $10 million per year on-site costs (Huszar and Piper, 1986).

Wind erosion and transport from croplands contributes only a fraction of the total amount of atmospheric dust, but it is a contribution that can be reduced by careful management. Review of human actions and government programs in locations where problems of aeolian dust have been severe and have been addressed in comprehensive research and education programs provides insight that can be applied to locations where wind erosion is now becoming critical as local climates change to more arid conditions, as marginal land is cultivated, and as increasing mechanization changes the amount and rate of soil reworking. This paper provides a review of problems of wind erosion on cropland in the USA, where wind erosion has been a chronic problem and where many actions already have been taken to control it. The review is intended to identify the magnitude of the problem, the great variety of potential solutions, and the progress that has been made in implementing these solutions.

2. Spatial and temporal aspects of wind erosion and transport

2.1. Locations susceptible to dust production

About 90% of wind erosion in the USA occurs west of the Mississippi River, and about 60% occurs in the Great Plains (Ervin and Lee, 1994). This semi-arid and sub-humid region (Fig. 1) is the largest problem area for dust emissions from agricultural operations in the USA (Tegen and Fung, 1995). Other major problem areas include parts of California and Washington, where dry conditions prevail and agriculture is important. Wind erosion of agricultural lands is a problem in other arid states, such as Arizona and New Mexico, in less arid lands, such as Wisconsin (David and Rhyner, 1999) and Illinois (Chagnon, 1983), and in the humid east, although it occurs at smaller scale.

The worst area in the Great Plains is the southern high plains of Texas near Lubbock (Fig. 1) that has the national maximum of 47.5 dust days per year (Hagen and Woodruff, 1973). Here, the land is flat and

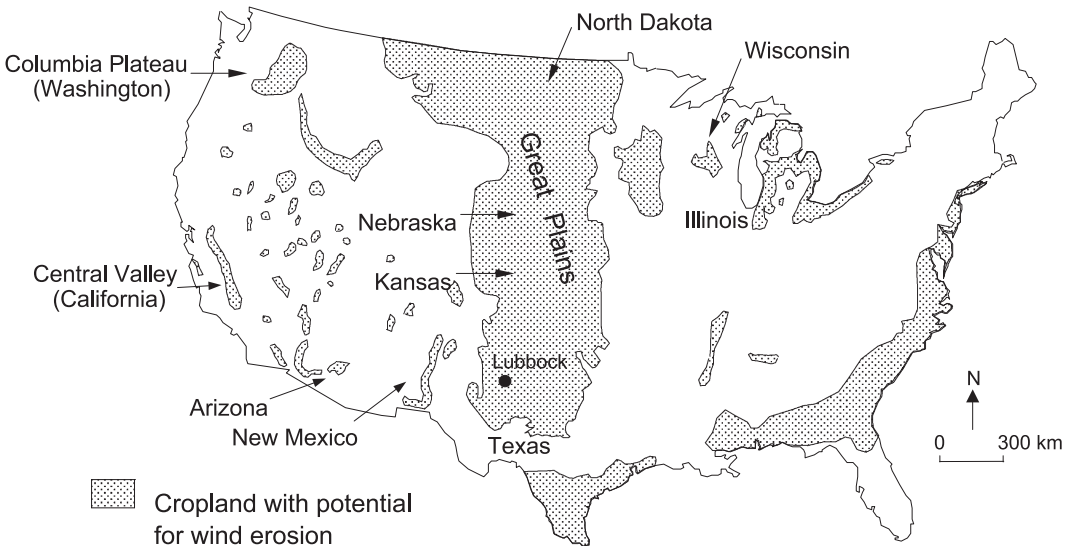

Fig. 1. Locations of cropland areas of the USA that have the greatest potential for wind erosion and locations of sites mentioned in text. Modified from base map in USDA, SCS National Cartographic Center, Fort Worth, TX, 1988.

composed mostly of Quaternary aeolian sand and loess. Land use is predominately agricultural, with some cattle ranching. Most cropland is devoted to cotton farming, and planting is in May and harvesting is in November, leaving the soil bare for the remainder of the year (Lee et al., 1994). In the colder, northern Great Plains, seasonal freeze–thaw action helps break the soil down into small aggregates, and strong winds from Canada increase the potential for deflation (Todhunter and Cihacek, 1999).

Much of the dust produced from soil erosion in California (Fig. 1) is from desert environments, but cropland is also prone to dust generation, such as in the Central Valley, where agriculture is industrialized and the climate is a semi-arid Mediterranean type with long dry summer and fall (Clausnitzer and Singer, 1996). Problems occur on the Columbia Plateau in Washington (Fig. 1), where dryland farming of large fields of winter wheat occurs in the east and irrigated farming occurs in the west. Each fall after harvest, half the dryland soils are bare due to the 2-year crop rotation system; all irrigated soils are bare and dry; and the surrounding rangelands are dry and covered by sparse grasses and shrubs (Claiborn et al., 1998).

2.2. Temporal perspective

The greatest amount of data on wind erosion frequency and adverse impacts of wind erosion in the United States is on the Great Plains. Massive conversion of much of the vast, nearly treeless, landscape of the Great Plains into cropland began in the late 1800s, resulting in reduction in soil fertility and moisture and an increase in susceptibility to wind erosion (Eckholm, 1976; Todhunter and Cihacek, 1999). Gasoline-operated machines became commonplace in the early 20th century. The number of powered tractors in the state of Kansas (Fig. 1) alone increased from 3000 in 1915 to 66,000 by 1930, and the land devoted to wheat farming increased by 50% between 1925 and 1930 in places (Opie, 1993). At least 80 million ha in the USA were already suffering from accelerated erosion in the 1920s, with 20 million ha of formerly productive cropland already abandoned (Eckholm, 1976). Erosion problems were greatly accelerated in the period of drought in the 1930s that became known as the "Dust Bowl." This prolonged drought coincided with a national economic depression and falling grain prices that caused many farmers to abandon their fields, leaving soils exposed to erosion (Opie, 1993). Locations outside the Great Plains (Fig. 1) also were affected during the Dust Bowl (Chagnon, 1983). Huge dust clouds moved over the eastern US and the Atlantic Ocean in the upper westerly winds, and dust fell over the country (Eckholm, 1976; Trimble and Crosson, 2000).

Problems with wind erosion had been addressed in the literature prior to the Dust Bowl (Bates, 1911), but that event provided greater stimulus for research. Soil surveys were initiated; wind erosion control programs were established and administered by state and federal agencies; special wind tunnels were developed; and numerous papers were published and synthesized by Chepil and Woodruff (1963). Another by-product of the Dust Bowl and subsequent activities was the creation of the Soil Conservation Service (now the Natural Resources Conservation Service) and the Agricultural Research Service of the US Department of Agriculture (USDA) that provide assistance to farmers in implementing soil conservation practices and test new methods of controlling erosion.

Drought affects moisture in the soil, crop growth, and the amount of crop residue remaining after harvesting (Merrill et al., 1999) and can greatly increase the potential for erosion losses. Merrill et al. (1999) estimated losses in drought years to be 11 to 6100 times greater than in wetter years. However, climatic variability is not necessarily the primary determinant of dust production in agricultural land. The drought of the mid-1950s in Lubbock, Texas lasted from 1951 to 1957 and had 28 months of extreme drought, whereas the Dust Bowl lasted from 1933 to 1936 and had 10 months of extreme drought, and the driest month was not as dry as the driest month in the 1950s (Lee et al., 1993). Although the drought in the 1950s was longer and more intense than in the Dust Bowl years, problems of dust storms were less severe, leading Lee et al. (1993) to conclude that agricultural practices play the dominant role in determining temporal variability in blowing dust.

3. Sources and causes of aeolian transport from croplands

Factors affecting susceptibility of the surface of agricultural lands to aeolian transport (Table 1) in-

Table 1
Factors affecting susceptibility of agricultural lands to aeolian transport

Factor	Impact on erosion potential	Common action to improve/control
Climate/weather		
Climate	sets natural controls; constrains crop options	avoid marginal land; plant compatible crop
Wind speed/ direction	determines amount of surface erosion	employ wind breaks; change surface of field
Temperature/ humidity	affects air density; surface erodibility	select optimum time for farm operations
Soil properties		
Aggregate size	affects erodibility for given wind condition	use tillage to create clods
Dry aggregate stability	affects rate of breakdown to small sizes	control subsequent saltation
Clay content	produces clods that resist erosion	use tillage to bring clay to surface
Bulk density	moisture potential; particle erodibility	tillage
Surface characteristics		
Roughness (ridges, clods)	reduces surface shear; traps saltating grains	tillage; control subsequent saltation
Surface crust	stabilizes surface; resists erosion	initial tillage (continued tillage breaks surface)
Surface moisture	affects surface erodibility	select appropriate crop and residue
Field width	affects sediment source width, saltation	employ wind breaks; reduce field size
Ground cover		
Crop type	affects wind, soil properties, seasonality	optimize crop silhouette, time harvested
Crop residue	reduces wind erosion	make an important aspect of crop selection
Windbreaks	decrease wind speed and surface exposed	optimize their location; maintain through time
Active farm operations		
Land preparation, cultivation, harvest	direct suspension by tools and machines	reduce operating speed and personal exposure; plant crop requiring fewer operations
Use of access routes	direct suspension by vehicles	use surface stabilizers

clude climate, wind, and atmospheric characteristics; sediment supply (controlled by soil properties and surface characteristics); effectiveness of ground cover (controlled by vegetation characteristics); and active farming operations. Sediments transported by aeolian processes move by suspension, saltation or surface creep (Fig. 2B). The coarser soil particles that move by saltation and surface creep may be removed from an individual field but are often deposited nearby, whereas fine soil that moves in suspension as dust may be carried great distances and lost from an entire agricultural region (Gillette, 1986).

Active farming operations that have the potential for increasing the likelihood of dust emissions include plowing, leveling beds, planting, weeding, seeding, fertilizing, mowing, cutting, baling, spreading compost, spreading herbicides, and burning fields to control weeds and predators. Clausnitzer and Singer (1997) found that land preparation accounted for 67% of all operations but 82% of the respirable dust, whereas cultivation and harvest accounted for 33% of the operations but only 18% of the respirable dust. Land preparation creates more dust because it requires more contact with the soil and is usually conducted when soil moisture is low. Differences in dust production among cropping systems are due to inherent plant growth characteristics (differences in biomass and dryness of plant, season when harvested that affects dryness of soil) and the number of farming operations required for a given crop (Clausnitzer and Singer, 1997). Clausnitzer and Singer (1996) found a 20% increase in the amount of emissions associated with organically grown crops relative to traditionally grown counterparts because the time required for the winter cover crop to decompose and provide an organic fertilizer source delayed harvesting until the dry season.

Soil properties affecting susceptibility to wind erosion include intrinsic properties (e.g. clay or organic content) that change slowly through time and dynamic properties (e.g. surface bulk density and aggregate size distribution) that change more rapidly to management or climatic influences and control daily soil erodibility (Zobeck, 1991). Soil elevation differences produced by tillage, create roughness elements (Fig. 2) that are oriented (when produced by tillage tools and tractor wheels) or non-oriented, e.g. the random distribution of clods (large soil

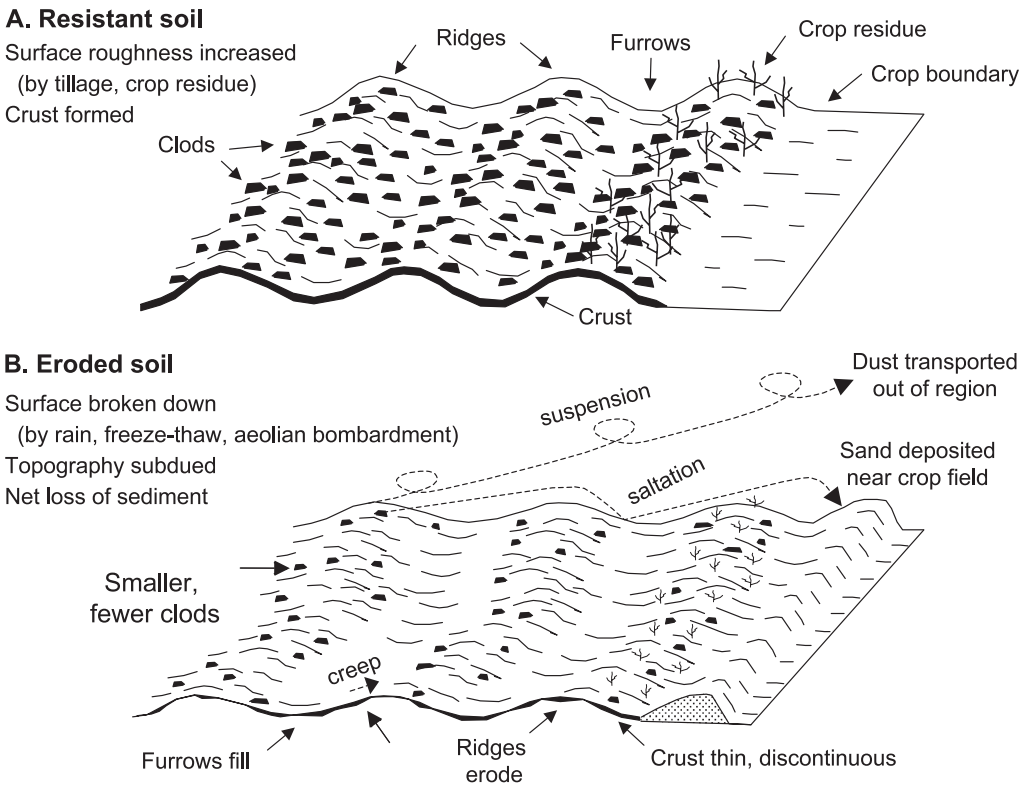

Fig. 2. Characteristics of farm fields affecting susceptibility to wind erosion.

aggregates) (Zobeck, 1991). Cloddiness is influenced by soil moisture, type of tillage implement, speed and depth that the implement is operated (Fryrear, 1984). The size distribution of aggregates on the surface is an indicator of their susceptibility to aeolian transport. Mineral aggregates greater than 0.84-mm diameter are generally considered nonerodible by wind in predicting large-scale transport volumes, although aggregates as large as 2 mm can be moved by wind, and erodible organic aggregates can be much larger than mineral aggregates because of their lower density (Zobeck, 1991).

Rainfall can create a relatively thin consolidated crust (Fig. 2A) that is more compact and more mechanically stable than the soil below it (Zobeck, 1991), although clods and surface crusts tend to break down to a more erodible size as a result of subsequent raindrop impact or freeze–thaw processes. Clods and surface crusts may also break down under the impact of saltating sand grains (Shao et al., 1993), and much of the erosion during strong-wind events is caused when blowing soil particles strike and dislodge other particles from the soil surface. Ridges trap mobile sediments between them and reduce the rates of erosion and the potential for intergranular impacts, but ridges may break down, and furrows may fill with aeolian deposition, leaving the surface more susceptible to deflation (Fig. 2).

Details on spatial and temporal variations in mass sediment flux associated with a single wind erosion event are provided by Stout and Zobeck (1996). They found that substantial temporal variations occurred due to changes in wind strength and erodibility of the field surface, with greater transport rates occurring through time (even at lower wind speeds) as the surface became more erodible. The pattern of mass flux variation was dependent on height. Grains saltating near the surface were controlled primarily by surface roughness, and the sediments consisted of a broad range of particle sizes from 50 to 300 μm. The size mode shifted to smaller particles farther from the surface, with few particles larger than 90 μm above

0.7-m elevation. The flow of dust at higher elevations was less affected by surface conditions directly below than flow in the saltation layer, and the quantity of dust in transport increased steadily with distance across the field. In contrast, most of the saltating grains were trapped near field boundaries (Stout and Zobeck, 1996).

The methods used to sample aeolian transport across farm fields are similar to methods used to sample sand-dune systems, except that greater attention is devoted to suspended particles because of their greater significance on and off site. Mass flux and grain size characteristics are determined from samples obtained from vertical arrays of sediment traps. Estimates of transport potential are determined from vertical arrays of anemometers and temperature sensors. At least three anemometers (preferably more) should be used to define the vertical velocity profile and estimate critical shear velocity near the surface at a given point. Wind strength will vary across a field, so vertical arrays should be placed at several locations. Only a single wind vane (for wind direction) and relative humidity sensor (for air density) may be required for each vertical array on flat, open fields, but more wind vanes would be needed where local topography or windbreaks cause pronounced changes in wind direction. The large number of variables and lack of uniformity in atmospheric processes and surface conditions across a field may result in mass flux values that depart greatly from estimates obtained from the physically based equations derived from theory and wind-tunnel studies. These differences simply underscore the need to conduct more field studies to provide the data to improve prediction.

4. Predicting aeolian transport and sediment loss

Wind erosion prediction equations were developed in the 1950s and refined to produce the Wind Erosion Equation (WEQ), published in the early 1960s (Chepil and Woodruff, 1963; Woodruff and Siddoway, 1965). The equation uses input on soil erodibility, local wind climate, soil surface roughness, distance across the field, and vegetative cover. The equation was based on wind tunnel data and laboratory relationships but designed so details could be added using accessory charts and tables as more data became available (Chepil and Woodruff, 1963). The WEQ was designed for large fields with unchanging surface conditions and long time scales to produce average annual estimates of soil loss (Hagen, 1991), and it was most appropriately applied to conditions on the Great Plains and farming practices that are now dated. Subsequent empirical adaptations of the WEQ are identified by Argabright (1991).

A Revised Wind Erosion Equation (RWEQ) (Fryrear et al., 2000a) was developed to make use of management inputs, including size, shape, orientation of the field; soil properties; crop canopy; crop yield; harvest height and number of standing stalks; tillage operations; amount and rate of irrigation; height, density, spacing and orientation of wind barriers; and gradient of hills. The RWEQ can decay residue vegetation due to weather conditions or evaluate burial or flattening from tillage; it also can modify soil roughness due to tillage and decay soil roughness due to rainfall or irrigation (Fryrear et al., 2000a). The model has been tested on a range of soil, climate and crop conditions (Fryrear et al., 2000a), and used with field data to evaluate alternatives to control wind (Merrill et al., 1999).

Another computational system, the Wind Erosion Prediction System (WEPS) (US Department of Agriculture, 2001) was designed to make use of personal computers and existing natural resource databases. WEPS is a continuous, daily-time step model designed to simulate actual erosion processes and allow extrapolation to conditions that have not been field tested; predict erosion from single storms; predict the probability of dust storm events; estimate qualitative changes caused by reworking of the field surface; and improve assessment of spatial and temporal variability (Argabright, 1991). The system has an option to identify soil loss from suspension, saltation and surface creep to estimate off-site impacts.

5. Impacts caused by wind erosion and dust

Previous reviews indicate that (1) wind erosion reduces soil productivity because of the loss of plant nutrients, degradation of soil structure, loss of storage capacity for water for plants, and reduced uniformity

of soil conditions within a field; (2) dust abrades and buries plants and blocks sunlight; and (3) aeolian deposition reduces reservoir storage capacity, clogs streams and drainage channels, deteriorates aquatic habitats, muddies recreational waters, damages water distribution systems and pollutes water systems with agricultural chemicals (Davis and Condra, 1989; Ervin and Lee, 1994; Grantz et al., 1998; Larney et al., 1998).

Health risks associated with elevated levels of dust include skin irritations and diseases, eye irritations, shortness of breath, respiratory disorders such as chronic obstructive airways disease, occupational asthma, interstitial lung disease, lung fibrosis, lung emphysema, hyper-responsiveness, hypersensitivity, and increased risk of lung and skin cancer (Clausnitzer and Singer, 1996). The human respiratory tract is an effective barrier to most aerosol particles greater than about 10 μm because of its convolutions, sticky mucous lining and high relative humidity, but the efficiency of particle capture in the respiratory tract decreases with decreasing particle size (Prospero et al., 1983).

The U.S. Environmental Protection Agency established regulations for quantity of airborne particulates in 1982 and updated the standards in 1987 and 1996. A PM_{10} size (median diameter of 10 μm) is the critical standard, based on hospital emergency room visits for respiratory diseases (Norton and Gunter, 1999). EPA guidelines require communities to monitor PM_{10} levels and develop plans to reduce emissions. PM_{10} levels cannot exceed 150 μg m^{-3} of air in 24 h or an annual mean of 50 μg m^{-3}. A $PM_{2.5}$ was added as a standard by the EPA in 1997, using a 24-h level of 65 μg m^{-3} and an annual standard of 15 μg m^{-3}. Stricter regulatory standards may be imposed by states (Clausnitzer and Singer, 1997).

Concentrations of dust on the Columbia Plateau in the fall vary from 10 to 34 μg m^{-3} during non-windy periods, but can exceed 500 μg m^{-3} on an hourly basis during strong-wind events (Claiborn et al., 1998). Most counties in California exceed their PM_{10} standard, but the annual averages of both PM_{10} and $PM_{2.5}$ have declined at most sites (Dolislager and Motallebi, 1999). Concentrations of dust associated with farming may far exceed regulatory standards (Clausnitzer and Singer, 1996, 1997), although soil dust is usually more benign than aerosols in urban air (Prospero et al., 1983), and the concentrations decrease markedly downwind from actively farmed areas (Clausnitzer and Singer, 1997). Despite high local concentrations of dust on croplands, farm workers often do not regard exposure to dust as hazardous (Nieuwenhuisen and Schenker, 1998).

6. Methods of controlling sediment loss from fields

6.1. Windbreaks and shelterbelts

The large literature on windbreaks, wind barriers, and shelterbelts (collectively termed windbreaks), includes monographs, edited compendia and special issues of scientific journals (Bates, 1911; Tinus, 1976; Sturrock, 1988; Burke, 1998), simulation studies (e.g. Wang and Takle, 1995), and field studies (Grant and Nickling, 1998). Vegetative windbreaks may be planted, left as remnants of formerly forested areas, or allowed to grow naturally in fencerows after tractors have cleared fields (David and Rhyner, 1999). They decrease wind speed, the width of field exposed to strong winds, and thus the rate of erosion and the damage to aggregates from saltating particles. Windbreaks also trap snow, protect farmsteads, provide wildlife habitat and modify microclimate, which may reduce risk of drought (Black and Siddoway, 1971; Brandle et al., 1992; Fryrear et al., 2000b). Large-scale establishment of windbreaks occurred during and after the Dust Bowl (Bates, 1934), and they are now an important element of the Great Plains landscape.

The height, spacing and porosity (plant spacing, stalk and leaf width) of windbreaks are important in reducing wind speeds and deflation. A windbreak of moderate effectiveness will at least partially reduce the velocity of a wind normal to it for a distance of about 30 times the windbreak height (Borrelli et al., 1989). Velocity reductions for average tree windbreaks can range from 60% to 80% near the barrier and downwind to a distance of about 10 × barrier height and about 20% at a distance of about 20 × barrier height (Tibke, 1988). Bilbro and Stout (1999) identify wind velocity patterns and derive equations for evaluating reductions in wind speed from alternative windbreak types. Fryrear et al. (2000b) developed

an equation for computing wind reduction patterns for the RWEQ model to aid decisions on the wind barriers for specific farms.

Not all windbreaks are favorably placed, exist in sufficient quantity, or are able to retain their effectiveness through time, and many aspects of plants (stage of growth, leafiness, flexibility) are difficult to control (Bilbro and Stout, 1999; David and Rhyner, 1999). Windbreaks take up critical space, and many old established windbreaks may be removed to accommodate new irrigation systems or larger machinery or to create larger fields (Black and Siddoway, 1971; Chagnon, 1983; David and Rhyner, 1999; Todhunter and Cihacek, 1999). Most windbreaks on the Great Plains are in the more humid portions, where wind erosion control is less critical than in the semi-arid portions, where trees and shrubs are difficult to establish (Black and Siddoway, 1971). Artificial barriers, such as wood or fabric fences can provide protection where conditions do not favor long-term re-vegetation (Grantz et al., 1998), but the high cost of material and labor to construct them generally restricts their use to high-value crops (Tibke, 1988).

6.2. Crop selection and harvesting

The type of crop grown influences soil aggregate size and erodibility. After harvesting, the amount of plant residue and its height, orientation, diameter and density of stalks, and survivability determine effectiveness against wind erosion (Bilbro et al., 1991). Nielsen and Aiken (1998) measure and quantify effects of a silhouette area index on wind speed and compare results with bare soil surfaces. Bilbro and Fryrear (1994) discuss equations showing relationships between soil cover and plant residue silhouette and the ratio of protected soil to bare soil.

Decisions are required on which type of residue crop is desirable. Residue can be standing or flat. Standing residue provides a greater initial effect on controlling wind erosion because it absorbs more wind energy and raises the zero-velocity point above the soil (Hagen, 1996). Conservation rotation, using a cash crop (e.g. cotton), followed by a non-commercial crop that reduces wind erosion during the winter season (e.g. wheat), is a way of controlling erosion that is suitable where there is insufficient soil moisture to harvest two commercial dryland crops per year (Bunn, 1997). Strip cropping, leaving the maximum residue height and all of the leaves in a few strips to function as windbreaks is another option (Bunn, 1997).

6.3. Tillage

Actively tilling fields can temporarily enhance the likelihood of entrainment of dust, but the field subsequently may be more resistant to wind erosion because tillage buries erodible particles, creates large aggregates that resist entrainment, and produces ridges and runnels that increase surface roughness and provide traps for saltating grains (Fig. 2). Subsoil in dry regions can remain moist for long periods and have a higher clay content than the surface soil, so bringing subsoil to the surface can both enhance yields and produce clods that reduce erosion (Bunn, 1997). However, when the new soil dries and clods break up, the fine particles become susceptible to wind erosion, and repeated tillage can create an increasingly sandy and less adhesive soil (Bunn, 1997). Using tillage to control erosion is less desirable than using crop residue, but it is often less costly (Bunn, 1998), and it may be the best method in semi-arid regions where the cultivated crops preferred by farmers for economic reasons do not produce enough residue (Fryrear, 1984).

Methods of tilling to reduce entrainment of fine particles are evaluated by Grantz et al. (1998), who found that furrows reduced aeolian dust 93% near the surface and from 24% to 33% above 1-m height, while increasing the threshold friction velocity for dust emission from about 45 to 65 cm s^{-1}. High ridges may erode at their crests, and weathering of tracks and filling with deposition from subsequent events (Fig. 2B) can reduce their effectiveness through time (Stout and Zobeck, 1996).

Conservation tillage is a method that does not invert the topsoil and leaves enough crop residue in the field after harvest to protect the soil throughout the non-growing season. The advantages and limitations of conservation tillage (reviewed by Uri, 1999) include: (1) retaining more soil and organic matter in the field; (2) providing better wildlife habitat by retaining more cover and food (including waste grain and insects), and (3) reducing consumption of fuel for farm machinery and carbon emissions to the atmo-

sphere. Conservation tillage was used on nearly 36% of planted land in 1996 in the USA (Uri, 1999).

6.4. Other methods to reduce dust emissions

Improvements in farm equipment can reduce dust production during preparation of soil, planting or harvesting (Southard et al., 1997) or reduce the exposure of farm operators by using enclosed air-conditioned cabs (Norton and Gunter, 1999). Reducing the speed of farm vehicles or carrying out activities early in the morning or late in the day, when relative humidity is high or solar radiation is low, can also reduce dust emissions (Clausnitzer and Singer, 1996). Watering can be used to control dust for winds up to 18 m s^{-1} and can suppress emissions associated with operation of equipment (Fitz and Bumiller, 2000), but its stabilizing effect is temporary. Commercial materials, including powders, polymers, and plant and animal products, can stabilize soil longer, but their costs may be too great for general farm use. Petroleum products may be unsuitable for productive cropland, but they can be used on the many unpaved roads and other bare surfaces required for farming operations. Stabilizing materials should be low in cost, have no adverse effect on plant emergence and growth, prevent initial erosion, reduce erosion for several months, and be easy to apply (Armbrust and Dickerson, 1971).

7. Government incentives for improving management practices

The diverse climatic regimes in the USA appear to preclude a single national approach to conservation addressing wind erosion (Bunn, 1998), but EPA guidelines for PM_{10} and $PM_{2.5}$ emissions provide a national standard that can be addressed at the municipal level. Federal and state governments provide money and education/extension services to assist farmers in adopting environmentally friendly methods. Economic incentives increase the likelihood that farmers will adopt better cropping systems (Bunn, 1997). Expenses incurred in windbreak construction are an allowable tax deduction, and further government compensation may be provided for the habitat value of windbreaks (Brandle et al., 1992). The US Department of Agriculture administers a variety of programs that provide cost-share and incentive payments to farmers that address soil erosion, help them comply with Federal and state environmental laws, and help them make beneficial, cost-effective changes. The Soil Bank Program of the 1956 Agricultural Act, the Conservation Reserve Program of the 1985 Food Security Act, and the 1990 Farm Act provide economic incentives to remove designated cropland from production, improve soils on land not needed for crop production, and utilize reduced tillage and crop residue management to reduce water and wind erosion. Government regulations and incentives can give priority to water quality and wildlife and not wind erosion or they can support a crop or land use that does not reduce erosion susceptibility, so they are not all favorable in reducing soil loss by wind (Bunn, 1998).

8. Prospect

There is an ongoing need for refinement and calibration of models of aeolian erosion and transport, including subroutines that evaluate management actions, but Trimble and Crosson (2000) also note the need for more field data and less reliance on models to get a truer picture of soil losses. Field studies that measure meteorological variables, surface soil properties, and soil flux simultaneously are rare (Fryrear et al., 1991; Stout and Zobeck, 1996), and much more fieldwork is still required to understand the many intricate relationships between the surface, soil and wind (Stout and Zobeck, 1996). The lack of site-specific field data does not preclude implementation of many of the options available to reduce aeolian erosion and transport. Problems of implementation appear to be more a function of economic and social factors.

Barriers to adoption of conservation measures include start up or transition costs associated with new methods or equipment, inadequate education, reliance on past traditions, or a history of failed field experiments (Bunn, 1997; Uri, 1999). Farmers tend to make changes in practice slowly, and the benefits to the rest of society are typically not included in a farmer's decision to adopt a new practice (Uri, 1999). Wind erosion has little perceived effect on land productivity, and operations to control erosion damage are a relatively minor portion of the entire list of operations needed to produce a crop (Sturrock, 1988;

Davis and Condra, 1989). A more fundamental problem is that there may be greater off-site costs resulting from wind erosion and transport that are not factored into the decisions by individual farmers (Huszar and Piper, 1986). Reluctance to implement soil-conservation policies and practices is not unique to the USA (Zhibao et al., 2000). This reluctance can be overcome when severe erosion events associated with periods of drought remind farmers and the rest of society of the advantages of compatible methods of farming (Bunn, 1998; Todhunter and Cihacek, 1999).

Despite the sizeable literature on wind erosion and appropriate solutions, problems continue to occur as many farmers continue to plant crops where it is difficult to protect soil from erosion. Many management techniques do not require sophisticated technology or great costs to implement, but they may require a willingness of farmers to change practices. There is still a need for detailed information about the economics of conservation practices with emphasis on stories of successes of farmers to gain broader acceptance of practices that will reduce wind erosion and dust production (Brandle et al., 1992). Although problems continue, dust events have decreased in some areas, indicating that improved management practices may be effective in reducing wind erosion of soil where they are accepted by farm managers (Godon and Todhunter, 1998).

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