EOLIAN DUST EROSION FROM AN AGRICULTURAL FIELD ON THE NORTH CAROLINA COASTAL PLAIN

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Abstract: Eolian erosion typically has not been considered a significant process on the humid southeastern coastal plain of the United States. A preliminary study of eolian erosion from an agricultural field was undertaken during the late winter of 2002 and early spring of 1999. During those times local agricultural practices leave fields bare while frontal systems produce frequent high wind events. Dust emissions were measured with two samplers; modified Wilson and Cooke passive dust traps and high-volume air samplers. Results of the study indicate that wind erosion is a significant process on agricultural fields of the North Carolina Coastal plain. Dust flux off of the field during the largest of five measured events was estimated as high as 126 kg/m with total losses of 3070 kg/ha. Atmospheric concentrations of suspended material were measured at 58,815 μgm^{-3}. Sediment erosion was not evenly distributed across the field. Erosion was focused over soils that are better drained. Low levels of soil moisture did not eliminate erosion but instead produced pulses of sediment emission as sustained wind continually dried then activated sequential layers of the field surface. Soil moisture and topography appear to be the primary controls on spatial erosion differences and soil characteristics likely play a secondary role. [Key words: wind erosion, aeolian erosion, agricultural erosion, dust.]

INTRODUCTION

Wind erosion is one of the most serious environmental issues in agricultural regions worldwide (Lopez, 1998). Despite this recognition, almost all research on wind-eroded sediment from agricultural fields has been focused on arid and semiarid regions of the Great Plains of North America (Fryrear, 1990; Stout, 1990; Nanney et al., 1993; Larney and Bullock, 1994; Stout and Zobeck, 1996), and other semiarid environments around the world (Leys, 1991; Leys and Raupach, 1991; Michels et al., 1995; Horning et al., 1998; Lopez, 1998). The narrow focus on arid and semiarid environments has left a gap in our knowledge about the importance of wind erosion in more humid climates. Fryrear (1990) hypothesized that although wind erosion from agricultural sites was most prevalent in semiarid environments, humid environments were not immune from the problem. Nanney et al. (1993) specifically mentioned the Atlantic coastal plain as a potential wind-erosion problem area because of the sandy soils, but provided no research findings for the region. They did, however, provide detailed data for a study in northwest Indiana. The Indiana site has an average annual rainfall of 90 cm, where Nanney et al. (1993) found annual erosion rates as high as 193 mt/ha. Another, even more dramatic example of the importance of wind erosion in a humid climate was conducted by Robinson

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(1968). He reported erosion results for a 5-day long windy period in Lincolnshire, England, that led to 50 mm of topsoil loss.

These studies suggest that wind erosion should be examined more closely in humid environments, especially in areas with extensive sandy soil such as the North Carolina coastal plain. This is a preliminary study designed to evaluate the importance of wind erosion from agricultural fields on the humid southeast coastal plain and evaluate the need for future studies. This paper focuses on suspended dust, although significant bedload transport is also known to occur. The main data set that is discussed in this paper was collected in February 2002 with the presentation of additional, supporting data collected in the spring of 1999.

Soil loss by wind erosion is important for a number of reasons, including loss of topsoil, loss of crop productivity and crop damage, and reduction of local air quality. Although little work has been done on eolian erosion on humid coastal plains, studies elsewhere demonstrate the significant impact of wind erosion on agricultural productivity. Hagen and Woodruff (1975) estimated that the Great Plains of the United States lose 31 million to 551 million tons of topsoil annually from dust erosion. A loss of 25 mm of topsoil in those regions is estimated to result in a 2% to 10% reduction in wheat yield (Lyles, 1975). Loss of topsoil is a concern because it is the most fertile portion of the soil. Wind erosion is particularly insidious because the process selectively winnows the silt and clay fraction of the soil, leaving behind sand-enriched soil with low fertility. Sterk et al. (1996) found that nutrient concentrations in wind-borne dust in southwest Niger increased with decreasing grain size (and thus height above the bed). At 0.5 m the nutrient concentration was three times higher than the parent soil from which the dust was eroded and at 2.0 m the nutrient concentration was 17 times higher than the parent soil. In a similar study in the Sinai region, Wassif et al. (1999) found nutrient enrichments in airborne dust of as much as 6.5 times the parent soil. The winnowing process is particularly problematic in eastern North Carolina because the soils are already sand rich and any loss of the clay fraction is significant.

Another environmental concern of eolian erosion is the off-site impact. Nanney et al. (1993) pointed to agricultural erosion as a major source of diffuse pollution that leads to respiratory ailments, visibility reductions, and damage to buildings. As with erosion research, those studies that have examined the impact of dust from agricultural regions (Hefflin and Jalaludin, 1994; Stetler and Saxton, 1996; Schenker, 2000), and more recently the impact of contaminants such as pesticides carried with the dust (O'Hara et al., 2000), have exclusively focused on semiarid environments.

STUDY AREA

Four general conditions have been identified that must be met for eolian erosion to occur (Wilson and Cooke, 1980; Fryrear, 1990; Kertesz et al., 1990) and all can be identified in the North Carolina coastal plain. These four conditions are sufficient wind velocities, dry conditions, sandy soils, and sparse vegetation cover. Regional wind velocities in eastern North Carolina peak in late winter and spring as frequent frontal systems associated with midlatitude cyclones pass through the

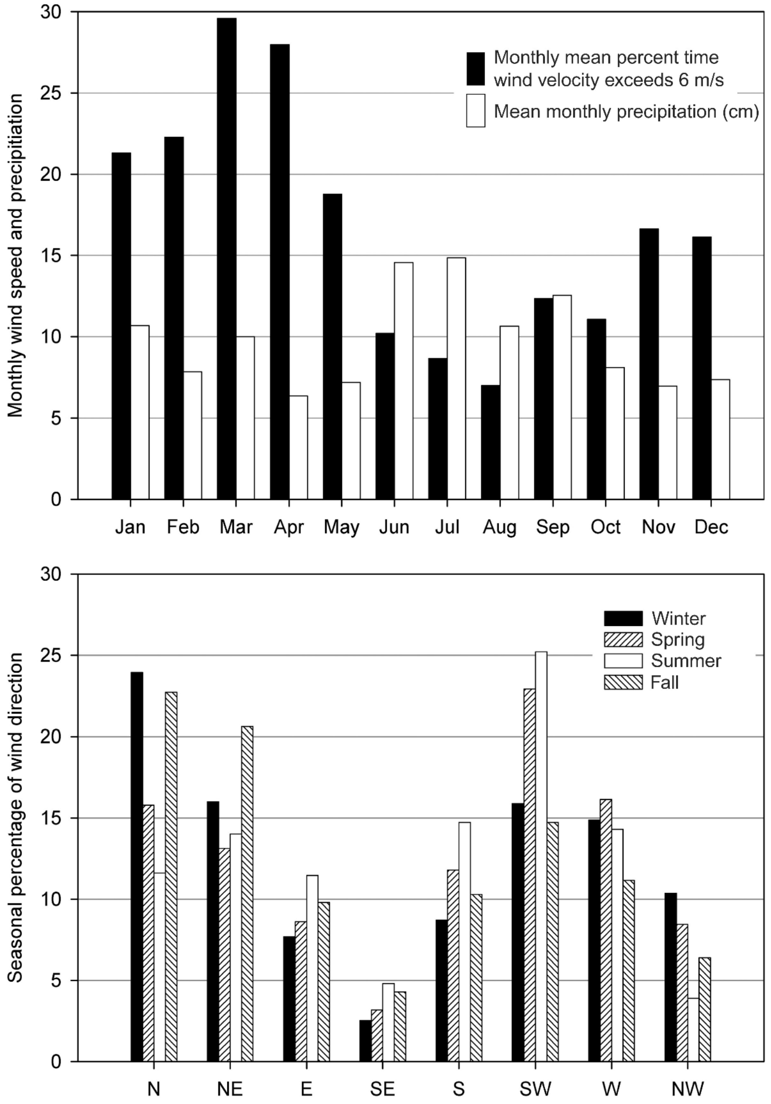

Fig. 1. Mean climatic conditions compiled from a climate station in Kinston, North Carolina, 12.9 km from the field site. Wind velocity and direction data are compiled from 1993 to 2001 data. Wind data were not recorded prior to 1993. Precipitation data include 1948 to 2001 data.

region. These fronts generally produce strong southwesterly winds ahead of the front, and strong northwesterly winds after the front passes (Fig. 1). Many of the fronts produce high winds with no rain. Although eastern North Carolina has a humid climate with an annual rainfall of about 127 cm, the winter and spring usually have drier conditions than the summer and fall. The North Carolina coastal

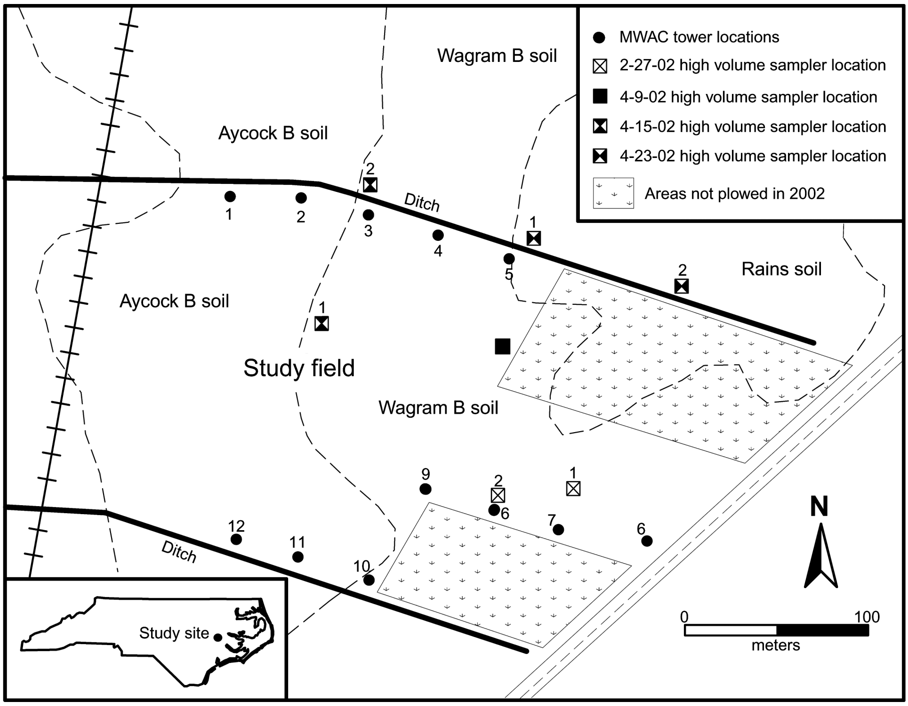

Fig. 2. The study field. The dashed lines represent soil boundaries. The unplowed areas represent the conditions during 2002, but change from year to year. During 1999, the entire field was plowed.

plain is dominated by soils of sandy loam and loamy sand (USDA, 1974), making them vulnerable to wind erosion when exposed (Nanney et al., 1993). General agricultural practices in eastern North Carolina often leave fields fallow during the winter and spring months. Farmers often plow and smooth fields in January and February in preparation for spring planting. The sandy soil, plus the concurrent seasonal occurrence of frequent wind events, drier conditions, and minimal vegetation cover lead to a strong potential for seasonal wind erosion on the North Carolina coastal plain.

The site for this study is an 11-ha field near Littlefield, North Carolina (Fig. 2). It is approximately 18 m above sea level and the topography of the field gently rolls with slopes less than 2%. The area is extensively ditched to drain the fields and lower the shallow water table. Ditches bound the north and south edges of the field (Fig. 2). Field soils include the Aycock, Wagram, and Rains series (USDA, 1974). The Aycock and Wagram soils are well-drained upland soils with sandy loam (Aycock) and loamy sand (Wagram) surface horizons. The Rains series is a poorly drained, fine sandy loam. Although wind erosion is commonly seen on the Wagram and Aycock soils, we have not observed it on the Rains series because those areas maintain higher soil moistures. The site is generally planted with tobacco, although cotton, corn, and soybeans are also rotated.

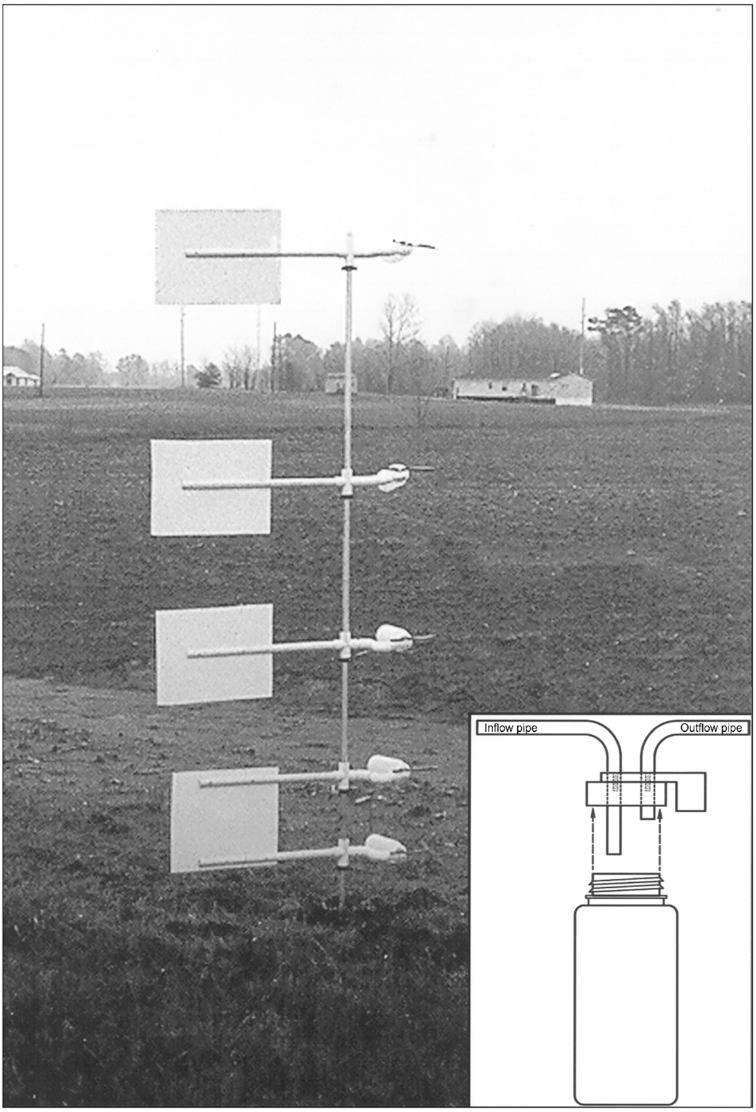

Fig. 3. Modified Wilson and Cooke trap tower and diagram.

DATA COLLECTION

The primary method of data collection on February 26 and 27, 2002, was a form of the Modified Wilson and Cooke (MWAC) towers (Fig. 3; Wilson and Cooke, 1980; Sterk et al., 1996; Sterk and Raats, 1996; Pease et al., 2002). The towers were built similarly to the style discussed by Sterk and Raats (1996). Our inlet and outlet tubes were copper pipe with an inside diameter of 7.9 mm and an input area of

48.7 mm^2. We mounted five traps on each tower at heights at 0.1, 0.3, 0.6, 1.2, and 2.2 m above the surface (Fig. 3). Each trap was attached to an independent vane so that variations in wind direction with height would not influence trap efficiency. Several researchers have examined the efficiency of the MWAC traps, but results vary. Goossens and Offer (2000) and Goossens et al. (2000) concluded that the MWAC trap is one of the most efficient traps that are commonly used. They found in wind tunnel and field experiments that the trap efficiency was generally greater than 90%, but they did find some variation in efficiency with wind speed when, at lower wind velocities, efficiency dipped to 75%. Sterk and Raats (1996) report only 49% efficiency for traps they built. Their wind tunnel tests indicated that the trap was not sensitive to wind speed, although they thought that the efficiency might change with grain size (Sterk and Raats, 1996). We were unable to test our traps under controlled conditions, and so no calibration corrections are used in this paper. Generally speaking, trap efficiencies are less than 100%, so our values should be considered as minimum estimates of the actual transport.

Twelve towers of five MWAC traps were placed along the north and south edges of the field to capture sediment as it left the field boundaries (Fig. 2). The placement of the towers was based on the usual southwest and northeast wind flow patterns. Traps were placed approximately 40 m apart. Sediment transport was determined using a model fit to each tower data set. During the 2002 events, an anemometer and wind vane were installed in the middle of the field, but a failure in the data logger prevented collection of the data. To compensate for the lost data, regional wind data were obtained from the Kinston, North Carolina, climate station and used as an approximation of wind conditions at the field site. The Kinston station is located 12.9 km southwest of the study field where wind direction and speed are monitored at an elevation of 10 m.

The second data collection method, and the only methods used to collect the 1999 data, involved the use of Graesby high-volume aspirated traps. The Graesby traps are almost identical to the SIERRA sampler described by Goossens and Offer (2000). The sampler is an aluminum box with a horizontal opening 38 × 38 cm. The opening is 1 m above the ground surface and shielded by a hood. Within the sampler is a filter mount with a surface area of 18 × 23 cm. Air is drawn through Whatman glass microfiber filters forcing dust to be impacted on the filter. Internal vacuum pressure is monitored to determine the airflow rate.

During 1999, samplers were deployed during three events during the spring. Wind speed data for the 1999 events were obtained from a single-height anemometer located at the research site. The anemometer was located along the southern edge of the field 1.4 m above the ground surface. Wind directions were not recorded at the site and are established from Kinston meteorological records. Although the MWAC tower data are more useful because the sampling occurred over a larger area and over a vertical distance, the inclusion of complementary atmospheric concentration data from 1999 helps to demonstrate that the 2002 events were not anomalous. In addition, we used the 1999 events to explore how different placements of the samplers affected the results.

Model for MWAC Data

Variations in mass transport with height above the bed have been examined in both wind tunnel and field settings (Zingg, 1953; Nalpanis, 1985; Zobeck and Fryrear, 1986; Vories and Fryrear, 1988; Sterk and Raats, 1996; Butterfield, 1999). Sediment moving in suspension can be described with the general power expression,

$$q(z) = az^b , \tag{1}$$

where q = quantity of sediment in suspension at height z, a and b = regression coefficients (Zingg, 1953; Nickling, 1978; Fryrear et al., 1991; Vories and Fryrear, 1991; Fryrear and Saleh, 1993; Sterk and Raats, 1996). The power equation is only accurate for grains moving in suspension because the quantity q tends toward infinity when z approaches zero, at the bed surface (Sterk and Raats, 1996). As a result, the function predicts unrealistic values of q in the saltation layer near the bed. Fryrear et al. (1991) showed that the lower limit of the power equation is about 30 cm, although Zobeck and Fryrear (1986) have used it as low as 15 cm and Vories and Fryrear (1991) suggested 50 cm as the lower limit.

Many studies have examined the vertical distribution of saltation layers (Williams, 1964; Fryrear et al., 1991; Vories and Fryrear, 1991; Fryrear and Saleh, 1993; Scott et al., 1995; Sterk and Raats, 1996; Butterfield, 1999) and have found that a function different from the suspension layer must be used to fit those data. The general exponential equation,

$$q(z) = ce^{dz} , \tag{2}$$

where q = quantity of sediment in saltation at height z, c and d = regression coefficients, describes the vertical distribution of sediment in the saltation layer (Nalpanis, 1985; Fryrear and Saleh, 1993). Using detailed wind tunnel data, Butterfield (1999) identified three regions of saltation with distinct profiles. He confirmed an exponential decay for sediment in saltation above 1.9 cm, but found that below 1.9 cm a power function more accurately described the mass flux. For field studies using traps with less vertical detail, it is probably reasonable to ignore the mass flux profile transition below 1.9 cm and use the standard exponential form.

Several authors have created combined equations to describe the entire mass flux profile (Vories and Fryrear, 1991; Fryrear and Saleh, 1993; Scott et al., 1995; Butterfield, 1999). Vories and Fryrear (1991) presented the combined equation:

$$q(z) = az^{-b} + c\exp(dz) . \tag{3}$$

The first term on the right hand side is the power expression for suspended load from equation 1 and the second term is the exponential equation for the saltation load (equation 2).

Sterk and Raats (1996) presented a slightly modified version of the combined equation in the form:

$$q(z) = a\left(\frac{z}{\alpha} + 1\right)^{-b} + c\exp\left(-\frac{z}{\beta}\right), \tag{4}$$

where α and β = length scales. The length scales were added to counter the problem of *q* approaching infinity as *z* approaches zero (Sterk and Raats, 1996). In order to reduce the total number of regression coefficients, Sterk and Raats (1996) fixed the coefficient α at 1 m.

Our lowest trap was 10 cm above the bed and, therefore, we found it difficult to fit the exponential function given by Sterk and Raats (1996) in equation 4. To eliminate that problem, we used the basic model described by Vories and Fryrear (1991) (equation 3) but retained the length parameters from the Sterk and Raats (1996) equation 4. The modified model takes the form,

$$q(z) = a(z + 1)^{-b} + c\exp(-dz). \tag{5}$$

The functions were fit using a nonlinear estimation module in the *Statistica* statistical software package using a quasi-Newtonian minimization method with convergence criteria of .0001. The results were not dependant on initial values of regression coefficients. The modified Vories and Fryrear (1991) exponential function (equation 5) provided a better fit than other models, although we did find that when fitting actual data, the exponential function played a minor role in the development of the mass flux profiles. This is probably partly due to not having data below 10 cm, but Scott et al. (1995) supported the concept that the power function generally contributes most to the concentration profile.

Total discharge of sediment measured by the trap towers was determined by separate integration of the two terms in equation 5. In this way the power function is used to determine sediment load in the upper part of the profile and the exponential function estimated sediment load in the lower part (Fryrear and Saleh, 1993). We employed the TSS (transition height between saltation and suspension) presented by Fryrear and Saleh (1993) to determine the transition point between the saltation and suspension expressions. The TSS represents the point where the product of the exponential term is identical to the product of the power term and represents the average maximum height of saltating grains (Fryrear and Saleh, 1993). The TSS was determined by setting the saltation and suspension equations equal to one another, and solving for the height value, *z*. The height value determined by the TSS was then used as the lower limit of integration in the power function to describe suspended load, and as the upper limit of integration in the exponential equation for saltating load. Following this method, equation 5 can be expressed as,

$$c\int_0^{TSS} e^{-dz}dx + a\int_{TSS}^{2.2} \frac{1}{(z + 1)^{-b}}dx \quad . \tag{6}$$

Fryrear and Saleh (1993) reasoned that the separate integration of the terms would yield values of bedload and suspended load. Sterk and Raats (1996) tested this theory by sieving trapped sediment to obtain mass percentages of suspended and saltating material. Suspended transport was identified as sediment <63 μm in diameter and the saltation load was determined from grains >63 μm in diameter. The measured results were compared with their model and they found that separate integration, although useful for curve fitting, did not accurately yield separate saltation and suspension values. The saltation was underestimated with the model and the suspension portion was overestimated (Sterk and Raats, 1996). It might have been simplistic to use the sand/silt break as the measure of saltation and suspended load since the 63 μm break does not inherently control transport characteristics, but the finding does suggest caution is warranted when trying to separate saltation load from suspension load with vertical trap data.

RESULTS AND DISCUSSION

Wind Event 1

Meteorological conditions. On February 26, 2002, a warm front passed across the study area in the midday. Wind speeds began to increase during the morning from an average of 2.9 m/s to 7.2 m/s by 1100 hr. The average wind speed remained above 5 m/s for about 12 hr. Winds blew out of the south-southwest with an average wind direction of 203°, ranging from about 230° to 198°. Temperatures during the wind event averaged 19°C, ranging from 13°C to 23°C. The average relative humidity during the event was 47%. Surface soil on the field was visibly dry to a depth of about 2 cm to 4 cm. The front did not produce rain at the study site. The most recent precipitation event was five days earlier with about 6 mm of rain. No other rain events were recorded for 16 days prior to the wind event. Despite the high wind and dry conditions, the surface soil had a crust over it, which prevented significant soil erosion. The crust did not begin to break down until near the end of the wind event.

Spatial variations. The MWAC traps showed a large spatial variation in transport of sediment on the field, with total vertically integrated rates varying from 0.2 kg/m to 34 kg/m (Table 1). The highest concentrations were found in traps 6 to 12 located on the southern edge of the field where the fetch length was shortest (Fig. 2). Traps 10 to 12 were located about 2 m from the southern ditch and traps 6 to 9 were placed about 2 m from an unplowed area. Earlier, on February 2, 11, 17, and 18, unmeasured events with northerly winds had moved a substantial amount of sand to the south edges of the field and into the ditch (Fig. 4A). Saltating grains caught in the lower traps came almost exclusively from the 2-m section of wind-blown sand that had been deposited at the field edge. Sediment was actively moving on the field to the south of the study field (Fig. 2), but the ditch acts as a very effective trap preventing the exchange of sand grains from one field to another. Although the fetch was small (2 m of field edge), the grains were presorted and lacked cohesion, making them very mobile. The highest transport rate (34.2 kg/m) was at tower 11 where the greatest concentration of loose wind-blown sand existed. Tower 9 had the second highest transport rate (32.1 kg/m). This is probably also due to the presence of the loose sand along with a longer fetch created by the southwest wind.

Fig. 4. Photographs of study field conditions. Figure 4A shows conditions along the south edge of the field just prior to the February 26 event. The loss sand was deposited by four previous wind events, but primarily on February 18. Figure 4B shows the field conditions during the February 27 event. Notice the high concentration of suspended material and the ripples developed on the bed.

Vertical transport and model fit. Overall the model presented in equation 5 fits the data for mass transport measured on February 26 (Figs. 5A and 5B). Curves shown in Figure 5A have relatively standard profiles and high R^2 values. The R^2 values are not meant to represent a statistical result and are presented only to gage the goodness-of-fit of the model. The lower part of the curve, near the bed, is relatively steep and the segment above the inflection, representing suspended load, is rather

Table 1. Dust mass and mass flux values from MWAC traps for wind events on February 26 and 27, 2002

Dust flux estimates from 0 to 220 cm					
MWAC Sediment data for February 26, 2002			MWAC Sediment data for February 27, 2002		
MWAC tower	Total trapped sediment mass (g)	Average mass/length (g/m)	MWAC tower	Total trapped sediment mass (g)	Average mass/length (g/m)
1	1.24	163.38	1	—	—
2	2.05	269.18	2	—	—
3	2.46	323.21	3	—	—
4	2.39	313.88	4	—	—
5	4.02	527.81	5	—	—
6	7.64	1,003.24	6	962.73	126,339.22
7	11.90	1,562.15	7	173.72	22,796.67
8	35.37	4,641.75	8	36.31	4,764.71
9	244.76	32,119.31	9	18.43	2,418.22
10	13.06	1,714.03	10	200.91	26,365.89
11	260.68	34,209.52	11	49.74	6,527.29
12	38.93	5,108.56	12	75.59	9,920.23
Total estimated erosion from field = 67.6 kg			Total estimated erosion from field = 6,097.11 kg		
Total estimated flux off of field = 13.7 kg/ha			Total estimated flux off of field = 3,070 kg/ha		

flat. These shaped curves suggest that bedload was the dominant contributor to the sediment profile and that suspended load was fairly evenly distributed vertically. The curves shown on Figure 5B are not standard vertical profiles of eolian transport and the model did not fit the data as well. The upper part of those curves slope in the opposite direction of what would be expected and the lower sections decay quickly to the bed. These shapes indicate that suspended load dominated the sediment load and that the concentration of suspended dust increased with height.

The upper parts of the curves, representing finer grain dust material, have near horizontal profiles showing the concentration did not decrease with height as would be expected. For traps on the southern edge of the study field, the field to the south supplied the suspended sediment. The ditch has no impact on suspended material and the short 2-m section that supplied sand was already sorted and contained no fine material for suspension. The near horizontal slope is the result of the suspension cloud having time to become nearly homogeneous throughout the 2.2 m height. With these curves (Fig. 5A) it is easy to determine an approximate transition between saltation and suspension based on the curve inflection, particularly with tower 12. Curves shown in Figure 5B exhibit unique profiles generated by a combination of source areas. These towers were located on the north edge of the field (Fig. 2) where transport concentrations were lowest (Table 1). A mixture of saltating and suspended material derived from the study field generated the values for the lower traps. However, the soil had a crust until near the end of the event so it was only marginally active, and much less active than surrounding fields. In fact,

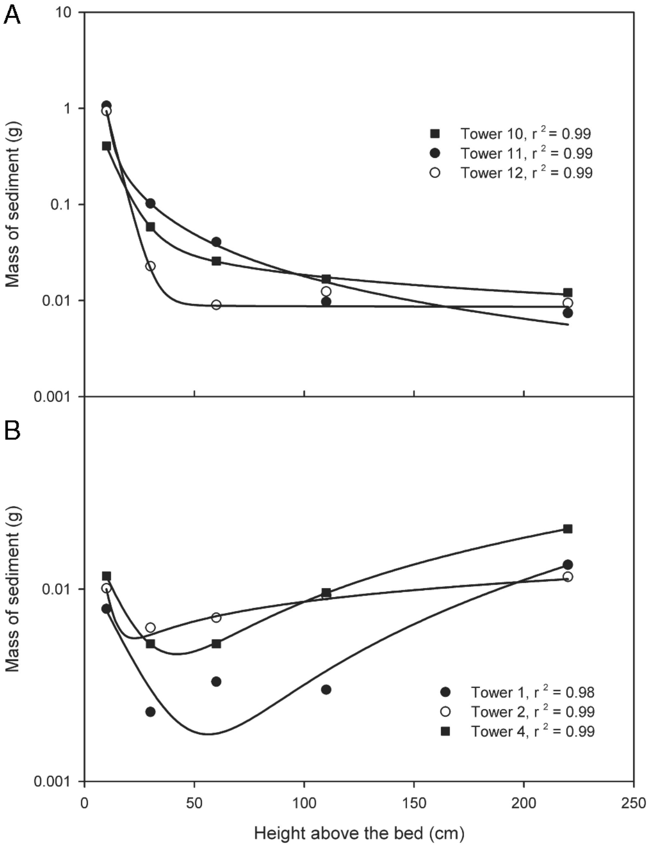

Fig. 5. Examples of curves representing the vertical dust concentration in towers from the February 26, 2002, event. Figure 5A represents towers located on the southern edge of the field whereas Figure 5B shows those located on the northern edge. R^2 values do not represent a statistical function and are included only to indicate how well the model represents the data.

most material suspended from the field presented as small, low-level dust clouds and sand streamers. The upper segments of the curves represent partially dust clouds that were produced from the study field and partially dust blown from the field to the south across the study field. That cross-field supply of suspended sediment caused the increase in material at higher elevations. The profiles in Figure 5B confirm the importance of dust erosion from the fields in that dust is more easily lost from the source than is saltating bedload. The crust on the field, combined with the loose sand at the southern edge, explains why the traps with shorter fetch lengths showed higher rates of transport.

Total soil loss. Estimates of total transport were calculated from the bed to 2.2 m. The estimates of flux at each tower were converted to mass per unit length (g/m) and used to calculate the total flux off the field. Mass flux varied greatly between towers, ranging from 0.16 kg/m to 34.2 kg/m (Table 1). Towers 1 through 5 were used to calculate the sediment flux off the field because they were positioned at the downwind edge of the field. The total mass of sediment moved off the north end of the field was estimated at 68 kg. Using the effective field area determined by wind direction, the average soil loss from the field was estimated to be 14 kg/ha. The caveat is that not all of the material was derived from the study field. The contributing area of the field to the south of the study site adds roughly 50% to the total area calculations, making the loss rate approximately 8.9 kg/ha.

The estimated values represent a small amount of erosion, but it is important to note that this was a small event because of the soil crust and that almost all of the loss is in finer grained material in suspension. Also, noting the shapes of the curves on Figure 5B, it is clear that most material lost during this event was the nutrient-rich fine grain sediment.

Wind Event 2

Meteorological conditions. On February 27, 2002, a cold front passed across the study area in the midday. Winds associated with the front began to increase from about 3.6 m/s in the early morning to 5.4 m/s by 1100 hr. Transport was visible on the field as early as 1000 hr. Wind speed throughout the event averaged 6.6 m/s and remained above 5 m/s for about 8 hr. Wind direction ranged from 284° to 303° and averaged a west-northwesterly flow from 293°. Temperatures averaged 5°C, ranging from 3°C to 6°C and the mean relative humidity was 30%. Surface soil was visibly dry to a depth of about 4 cm to 6 cm. The front did not produce rain at the study site.

Spatial variation. As with the previous day, the traps revealed significant spatial variability in transport concentrations, ranging from 2 kg/m to 126 kg/m (Table 1). Towers 1, 2, and 3 had no sediment in the traps and tower 4 and 5 had small, but insignificant amounts because the towers along the north ditch had no fetch length over the field. The order of magnitude difference between the values obtained from these two successive days can be attributed to the breaking down of the soil crust that was prevalent on the 26th. On the 27th, most of the field became active and transport was significant enough to develop ripples on the field surface (Fig. 4B). The spatial variations observed on the 27th are thought to be caused by soil inconsistencies, which change across the field even within a single soil class, and fetch length. Observationally, some areas—in particular the center of the field—are known to be consistently more active during wind events than others. We do not know the specific reasons for this, but suspect that it is a combination of grain characteristics, soil moisture, or topography. Tower 6 recorded the highest sediment transport rate (126 kg/m) and tower 7 recorded the third highest value (22.8 kg/m) (Table 1). These towers had the longest fetch lengths, and with the west-northwesterly wind, they were downwind of the center of the field. The lower values from towers 8 and 9, however, suggest that much of the sediment represented in towers 6 and 7 was eroded from the east side of the field, near to their position.

Vertical transport and model fit. The model presented in equation 5 fits the data for mass transport measured on February 27 well (Fig. 6). Curves shown in Figure 6 have standard, well-fit profiles and high R^2 values. Figure 6 shows the vertical

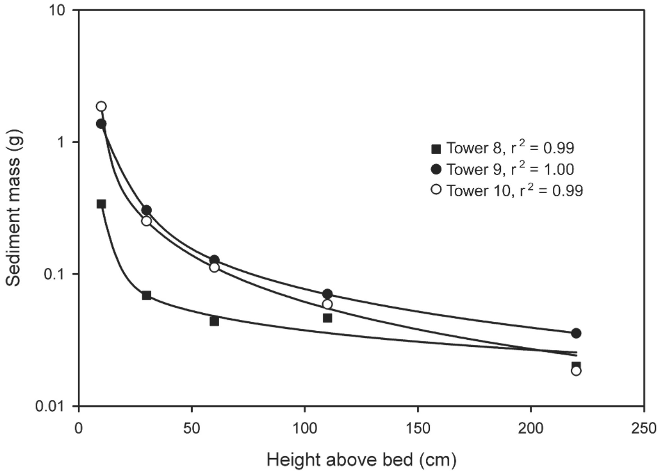

Fig. 6. Examples of curves representing the vertical dust concentration in towers from the February 27, 2002, event.

profiles for towers 8 to 10, which were located on the southern edge of the field (Fig. 2) about 2 m from the southern ditch. The lower portions of the curves show somewhat shallow slopes that extend gently toward the bed, indicating significant bedload transport. The upper sections of the curves are steep but show a steady decrease in dust concentration with height. These curves represent an expected profile with bedload dominant and a decrease in dust load with height.

Total soil loss. Only towers 6 to 12 were used to calculate the sediment flux off the field because towers 1 to 5 measured no transport. The total mass of sediment lost from the field for this event was estimated at 6697 kg. Using the effective field area determined by wind direction, the average soil loss from the field was estimated to be 3070 kg/ha. These values are much larger than those collected the previous day, even though the wind speeds were slightly lower. This demonstrates the importance of soil surface and the stabilizing ability of crust. They also demonstrate that importance of wind erosion on the North Carolina coastal plain.

High-volume sampler. During the February 27, 2002, event, two high-volume vacuum samplers were placed on the downwind side of the field (Fig. 2; Table 2). The vacuum samplers ran for two 45-min periods. The first run was from 1415 to 1500 hr. The filter was removed and replaced and the second run was from 1530 to 1615 hr. For each sampler, there are very close similarities between the two 45-min runs. Sampler 1, which was positioned on the downwind side of the field (Fig. 2), had values of 58,815 μgm^{-3} and 57,054 μgm^{-3}, respectively. The values recorded by sampler 2, located west of sampler 1 were significantly lower, but still consistent within the location at 23,451 μgm^{-3} and 24,254 μgm^{-3}. The mean values of 57,935 μgm^{-3} and 23,853 μgm^{-3} are a clear indication of the spatial sensitivity of wind erosion on agricultural fields since the distance between the samplers, normal to the wind flow, was only 28 m (Table 2). Sampler 1, positioned farther downwind in this

Table 2. Suspended Dust Concentration Values from High-Volume Traps for February 27, 2002, and 1999 Dates

	High-volume sampler data				
Date	Dust concentration (μg/m^3)	Dust flux (gm^{-2}hr^{-1})	Mean wind direction (deg)	Mean wind speed (m/s)	Sampling duration
February 27, 2002					
Sampler 1	57,935	1,251	293	6.6	1415–1615
Sampler 2	23,853	497			
April 9, 1999					
Sampler 1	8,600	263	222	8.5	1855–2030
April 15, 1999					
Sampler 1	2,085	46.8	202	6.2	1745–1930
Sampler 2	2,722	60.3			
April 23, 1999					
Sampler 1	1,808	46.7	212	7.2	1700–1920
Sampler 2	2,417	62.2			

event, had much higher values, indicating an importance of fetch length and possibly local erosion.

The high-volume sampler data were compared to the MWAC data by converting values to horizontal dust flux by multiplying the suspended concentration by wind speed (Goossens and Offer, 2000). This was problematic because our data-logger failure prevented us from having accurate wind data at 1 m. The Kinston AgNet data are collected at 10 m. We approximated the average wind speed at 1 m from the Kinston data. Although this estimate is a gross approximation, we believe it to be reasonable because the results of the calculation for horizontal dust flux are not overly sensitive to changes in wind speed.

Sampler 2 was closely positioned to tower 8 and its opening was about 1 m above the bed surface and the estimated horizontal dust flux was 496.8 gm^{-2}hr^{-1}. The MWAC data can also be expressed in these units by dividing by the area of the trap opening and multiplying by the event duration. Using these values, the horizontal dust flux estimated at 1.0 m from tower 8 data was calculated at 519.2 gm^{-2}hr^{-1}. The two values are very similar, showing a strong correlation. Goossens and Offer (2000) also noted a high correlation in measured dust concentrations during field tests between MWAC samplers and a high-volume sampler nearly identical to ours. High-volume sampler 1 was not directly adjacent to a tower. Sampler 1 yielded at horizontal dust flux of 1251 gm^{-2}h^{-1}.

The high concentrations of dust also have implications for air quality. Revised 1997 EPA standards on particulate matter set the mean annual exposure levels of PM10 particles (particulate matter with a diameter $\geq$10 μm) at 50 μg/m^3 of air, and 150 μg/m^3 of air for the 24-hr exposure, not to exceed one exposure per year (EPA, 1997). Data in this study far exceed the 24-hr exposure limits. The equipment used does not separate the PM10 from total particulate matter, but just the shear magnitude of the concentration over the EPA limits suggests serious concern for local air quality.

Previous Dust Measurements

Erosion measurements carried out during the spring of 1999 used only the high-volume samplers. The data do not permit estimates of erosion, but help to demonstrate the annual nature of wind erosion in the region. Three events are presented here, although six significant events—including one that qualitatively is thought to have been substantially larger than the February 27, 2002, event—were observed during that spring.

An event measured on April 9, 1999, occurred a few days after a corn crop was planted. Wind conditions, sampling duration, and dust concentrations are presented on Table 2. One high-volume sampler was set out near what appeared to be the central area of activity during that event (Fig. 2). That placement provided a measure of the concentration of dust erosion at the source. The mean dust concentration was 8600 $\mu g/m^3$ of air. The calculated horizontal dust flux was 263.2 $gm^{-2}h^{-1}$. Wind erosion can damage young crops. Visual examination showed that, on about 15% to 20% of the field, the soil mounds had been eroded to expose the seeds. The seeds had been planted at an average depth of 12 cm, indicating that much soil truncation had occurred on portions of the field.

On April 15, 1999, an event was measured with two high-volume samplers; one placed near the site of maximum activity and the second off the field edge, downwind of the first (Fig. 2). That configuration allowed a comparison between source concentration and downwind diffusion. Sampler 1, placed on the field, showed a mean dust concentration of 2085 $\mu g/m^3$ of air whereas sampler 2 on the field edge measured a concentration of 2722 $\mu g/m^3$ of air (Table 2). The relative horizontal dust flux was 46.8 $gm^{-2}h^{-1}$ and 60.3 $gm^{-2}h^{-1}$. We think the lower concentration at the source is from a lack of diffusion because the dust cloud had not yet fully risen to the 1-m height of the sampler. It could also be that the additional fetch length allowed for addition dust to be entrained, which offset any diffusion.

During an event on April 23, 1999, samplers were placed on the north edge of the field to measure the flux of sediment off the field (Fig. 2). Sampler 1, on the west side, measured a dust load of 1808 $\mu g/m^3$ with a horizontal dust flux of 46.7 $gm^{-2}h^{-1}$. The east sampler measured 2417 $\mu g/m^3$ with a horizontal dust flux of 62.2 $gm^{-2}h^{-1}$ (Table 2). Like the values measured on February 27, 2002, these showed significant spatial variation in dust production from the field. This instance was particularly interesting because much of the fetch length for the eastern sampler occurred over the Rains soil, which has not been observed to be active during wind events. This means the high dust load was generated from a smaller area south of the Rains soil. This event occurred after the corn seedlings (5 cm to 8 cm high) had sprouted. At the end of the 2.5-hr event, which was the weakest of the three measured during that year, abrasion of the corn leaves was noticeable. The long-term impact on the plant yield is not known, but clearly such damage is a concern.

The April 23, 1999, event yielded lower dust loads than other events because the soil was slightly moist. The moisture did not, however, completely prevent erosion.

Instead of continuous erosion the field eroded in pulses. As the wind event progressed, the surface would dry to a shallow depth at which time a pulse of transport would occur until the surface eroded down to a still moist layer. Then transport would cease until another layer would dry and the process continued.

DISCUSSION AND SUMMARY

The two wind events monitored during February 2002 yielded 14 kg/ha and 3070 kg/ha of soil removed from the field site, respectively. The individual MWAC towers showed spatial variability of two orders of magnitude, controlled by fetch length and variations in soil erodability. The two most active areas of erosion seem to be the very center of the field, where B-horizon soil is exposed, and the eastern center of the field. High-volume vacuum samplers showed dust concentrations in excess of 58,000 μg/m^3. High-volume samples from 1999 also showed high dust values, ranging from about 1800 μg/m^3 to 8600 μg/m^3. Although preliminary, these data strongly suggest that wind erosion is a significant process on the North Carolina coastal plain, despite its humid climate. Air quality was not a focus of this study, but the dust concentrations recorded by the high-volume samplers give a clear indication of the potential health impact that agricultural environments can have at off-site locations.

Soil erodability measured in this study is comparable to other areas that have been studied. The range of values, given in erosional mass per field length, for the two wind events averaged 6.8 kg/m and 28.4 kg/m respectively. These values compare favorably with mass erosion at four study sites: Big Spring, Texas (50.5 kg/m); Crown Point, Indiana (159.8 kg/m); Sidney, Nebraska (23.9 kg/m); and Eads, Colorado (15.89 kg/m; Fryrear and Saleh, 1993). These four locations are substantially more arid than eastern North Carolina. Even though eroding wind events in North Carolina are not likely to occur as frequently as in more arid environments, the process warrants further study because of the potential loss in crop productivity, both from soil sterilization and crop abrasion.

Wind erosion also may have implications in a larger geomorphic context for the region. Phillips et al. (1999a, 1999b) hypothesized that eolian erosion in the North Carolina coastal plain might be, in part, responsible for widespread soil truncation. Phillips et al. (1999a) noted a large disparity between upland soil erosion and the concentration of sediment delivered to and transported by streams on the coastal plain. One of the suggested contributors to soil loss was eolian erosion. This contention was reinforced by the discovery of soil ridges of eolian origin along forested field edges in the Littlefield area (Phillips et al., 1999a). Results of this study support those ideas because dust readily leaves the system making it difficult to account for its removal in a sediment budget.

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