1 **WIND EROSION IN AGRICULTURAL SOILS: AN EXAMPLE OF LIMITED**
2 **SUPPLY OF PARTICLES AVAILABLE FOR EROSION**

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Abstract

Soil erosion by wind is a complex process since many interacting factors are involved. In addition, wind erosion can show a considerable spatial and temporal variability associated with changes in soil surface conditions. During a wind erosion experiment conducted in August 1995 within an agricultural field of Central Aragón (NE Spain) (López et al., “in press”), a decay in dust emission (vertical dust flux) with an increase in wind speed was observed at the end of the experimental period. A further analysis of the evolution of the vertical flux with time in response to changes in soil erodibility is shown in the present study. The analysis is based on the comparison of the measured flux with the potential flux predicted for identical wind conditions assuming that the supply of erodible material at the soil surface was unlimited. The potential flux was estimated by using the dust emission model developed by Marticorena and Bergametti (1995). The model is based on the parameterization of the threshold wind shear velocity as a function of the aggregate size distribution and the roughness length of soil surface. The results indicate that the observed reduction in soil erodibility with time was probably due to variations in the aggregate size distribution and, more precisely, to a limited supply of erodible particles at the soil surface. This study underlines the need to consider the temporal variability of the surface conditions in wind erosion research and derived models.

Keywords: Vertical dust flux; Dry aggregate size distribution; Roughness length; Tillage; Modeling

1. Introduction

Wind erosion is one of the most serious problems in many agricultural regions of the world. Although it is not a new phenomenon, it is now when the current knowledge of its environmental and economic impacts claims appropriate measures for soil protection (Pimentel et al., 1995; Saxton, 1995). The design and evaluation of wind erosion control techniques requires a detailed understanding of wind erosion processes.

Most of the wind erosion research in agricultural soils has been based on experiments with portable wind tunnels (Fryrear, 1984; Nickling and Gillies, 1989; Findlater et al., 1990; Leys and Raupach, 1991; Lyes et al., 1996). Wind tunnels provide a controlled environment, allowing the repeatability of experiments. However, the limited space of the wind tunnel section as well as the short testing time make difficult the extrapolation of the results to natural conditions. Wind erosion on a field-scale can show a considerable spatial and temporal variability. Spatially, aspects such as the avalanching effect and differences in soil properties and surface roughness across the field (Stout and Zobeck, 1996; Sterk and Stein, 1997) are difficult to simulate in a wind tunnel. Temporally, changes in soil surface conditions during wind erosion events, such as abrasion of aggregates and crusts, armouring and saltation avalanching (Stetler and Saxton, 1996; Stout and Zobeck, 1996) are minimised or even ignored in wind tunnel studies. Thus, to assess the extent of wind erosion in a realistic way and prescribe effective control methods, wind erosion must be studied in all its complexity through direct field observations.

Due to particular soil and climate conditions and inappropriate agricultural practices, Central Aragón (NE Spain) is a semiarid region prone to land degradation by wind erosion. A field study was conducted during the summer 1995 to provide a first quantification of wind erosion in agricultural soils of this region (López et al., “in press”). Soil surface properties and dust emission from natural winds were measured within a farm field following chisel and mouldboard ploughing. In this paper we focus on the mouldboard ploughing experiment, analysing in detail changes in vertical dust flux with time in response to changes in soil surface erodibility. The discussion is

based on the comparison between the measured vertical dust fluxes and potential fluxes for the same wind conditions assuming that soil surface remains equally erodible with time.

2. Material and methods

2.1. Field experiment

The study was carried out in the summer 1995, within an agricultural field of about 1.5 ha located at the Consejo Superior de Investigaciones Científicas experimental farm in the Zaragoza province (41°44'N, 0°46'W, 270 m alt.). Site and soil characteristics, field sampling equipment and analytical techniques have been previously described in detail (López et al., “in press”); therefore, only aspects relevant to this paper are repeated here. The soil is a loam (fine-silty, mixed, thermic Xerollic Calciorthird), according to the USDA soil classification (Soil Survey Staff, 1975). Mouldboard ploughing, as primary operation in the conventional tillage system in the region, was implemented on August 7 in the direction of prevailing wind to 30-35 cm depth. Soil ridges, with WNW-ESE orientation, were 15 cm high at 80 cm intervals. Selected soil surface properties and conditions determined immediately after tillage are shown in Table 1. Likewise, dry aggregate size distribution (<38 mm diameter), obtained by using the data inversion method described by Gomes et al. (1990), is presented in Figure 1. Details about the sieving method and the statistical fitting procedure are found in López et al. (“in press”).

Micrometeorological data and suspended sediment samples were collected in the month following tillage. A 4-m tower, equipped with meteorological devices and suspended sediment samplers, was installed in the downwind edge of the field to maximise the fetch effect. Cup anemometers were mounted at 0.75, 1, 2 and 4 m above the ground and a wind vane at 2 m height. Temperature and relative humidity sensors were placed at heights of 1 and 2 m. Micrometeorological parameters were monitored during the whole experimental period with a data logger (Campbell Scientific, model CR10), which continuously recorded 2 min averages of data acquired at intervals of 10 s.

Suspended sediment samples were collected at 1 and 4 m height by using an isokinetic low-volume filtration system. The filter system used a polycarbonate membrane with 0.4 µm pore size diameter (Nuclepore filters). Pumps drew air at a flow rate of 18 L min⁻¹. Dust samples were collected over finite periods of 20 min during episodes of high winds (wind speed at 2 m height >5 m s⁻¹).

2.2. Wind profile and vertical dust flux calculations

Wind speed profile under neutral stability conditions was characterised by the Prandtl-von Kármán equation:

$$U(z) = u_*/k \ln(z/z_o) \quad (1)$$

where U is the wind speed at height z , u_* is the wind shear velocity, k is the von Kármán constant (0.4) and z_o is the surface roughness length. Under non-neutral atmospheric conditions, indicated by the Richardson number (Businger et al., 1971), wind profiles were corrected by using the Monin-Obukhov similarity function (Monin and Obukhov, 1954) as follows:

$$U(z) = u_*/k (\ln(z/z_o) - \Psi_m(z/L)) \quad (2)$$

where Ψ_m is the Monin-Obukhov stability function and L is the Monin-Obukhov length. Values of u_* and z_o were calculated for 20 min periods.

Vertical flux of wind-blown dust (F) was computed from the suspended element concentrations (oxidized forms) and micrometeorological data by using the flux equation derived by Gillette (1977) and modified by Sabre (1997) for the stability correction as follows:

$$C(z_1) - C(z_2)$$

$$F = u_* k \frac{C(z_2) - C(z_1)}{\ln(z_2/z_1) - \Psi_m(z_2/L) + \Psi_m(z_1/L)} \quad (3)$$

where C is the elemental concentration at heights z_1 (1 m) and z_2 (4 m). Total F was obtained from the addition of the elemental fluxes of the major elements present in the dust samples: Fe, Ca, K, Si, Al and Mg. The elemental mass was determined using wavelength dispersive X-ray fluorescence (XRF) spectrometry, according to the method described by Losno et al. (1987).

3. Results and discussion

Table 2 summarises information about the dust sampling periods registered after tillage. Wind direction remained fairly constant (average and standard deviation of $297^\circ \pm 10^\circ$), corresponding in all cases to episodes of *Cierzo*, the WNW wind prevailing in the region. Wind speed increased progressively during the experimental period from an average value of 5 m s^{-1} at 2 m height on the first sampling day to 11 m s^{-1} on the last one. Unstable atmospheric conditions, as indicated by the Richardson number, were present during all sampling periods. Therefore, wind profiles and vertical fluxes were calculated for stability corrections using equation (2) and (3), respectively. Positive F (i.e., dust concentration decreased with height), indicating active erosion of the field surface, was detected in 11 of the 18 sampling periods registered along the entire experimental campaign (Table 2). The remaining cases corresponded to episodes showing zero F (no significant concentration gradient).

Figure 2 shows the variation of F with u_* for the sampling periods of dust emission. The general increase in u_* with time, caused by successive increases in wind speed with each event, gave evidence that a decay in dust emission occurred at the end of the experimental period. The F values for the first five sampling periods ranged from 1.45 to $10.44 \text{ } \mu\text{g m}^{-2} \text{ s}^{-1}$ and increased as a significant power function of u_* for a range of 0.37 - 0.49 m s^{-1} ($P < 0.05$). This increase was no longer observed in the remaining cases, for which F varied between 11.66 and $2.03 \text{ } \mu\text{g m}^{-2} \text{ s}^{-1}$ for u_* ranging between 0.62 and 0.72 m s^{-1} . While an increase in F with u_* , generally as a power function, has been widely described for different soil surfaces types (Gillette, 1977; Nickling and

Gillies, 1989; 1993), a reduction of F with u_* has been rarely indicated for field observations. Stetler and Saxton (1996), collecting dust at different heights over agricultural fields on the Columbia Plateau of the USA, found a negative power function between F and u_* ($r^2=0.91$). Among the probable causes indicated by the authors for this inverse relation, it is a fast depletion of fine particles from the soil surface under high wind speeds. Shao et al. (1996), studying streamwise sand flux after cultivation of agricultural soils in south east Australia, measured lower fluxes than those expected for the weather conditions prevailing at that moment. The authors attributed this behaviour to a selective removal of fine particles from the surface during previous erosion events.

In our study, the F decay with time was probably also due to a limited supply of material available for wind erosion. If large soil aggregates were not disintegrated during the experimental period, a gradual depletion of fine particles and exposition of protective nonerrodible aggregates could be expected from the first erosion events to the last ones. Unfortunately, aggregate size distribution was only determined at the beginning of the experiment. However, the coincidence of the increase in wind speed with time during the experimental period makes this study a good opportunity to analyse more accurately the evolution of soil erodibility under the influence of the wind erosion process itself. This analysis can be based on the comparison of the measured F with the potential F predicted for identical wind conditions assuming that the supply of erodible material at the surface was unlimited. For this purpose, values of potential F were estimated using the model developed by Marticorena and Bergametti (1995), including the improved expression of shear stress partition between nonerrodible and erodible elements from Alfaro and Gomes (1995). This model is based on the parameterization of the threshold wind shear velocity, u_{*t} (i.e., minimum u_* at which particle movement begins) as a function of the aggregate size distribution and the roughness length of the surface, z_o :

$$u_{*t}(D_p, z_o, z_{os}) = u_{*ts}(D_p)/f(z_o, z_{os}) \quad (4)$$

where D_p is the particle diameter, z_{os} is the smooth roughness length (i.e., uncovered erodible

surface), u_{*ts} is u_{*t} for the erodible part of the surface and $f(z_o, z_{os})$ is the stress partition coefficient defined by Alfaro and Gomes (1995). In the model, the u_{*t} expression has been included in a size-dependant formulation of the horizontal mass flux, G (i.e., flux of material in the saltation layer) as:

$$G(D_p) = E (\rho_a/g) u_*^3 (1+R) (1-R^2) \quad (5)$$

where E is the ratio of erodible to total surface, ρ_a is the air density, g is the gravitational acceleration and $R = u_{*t} (D_p, z_o, z_{os})/u_*$. The total G is then defined as the sum of the individual size class contributions weighted by their area abundance. A detailed description of this physical scheme and its validation can be found in Marticorena and Bergametti (1995) and Marticorena et al. (1997).

The strategy followed to obtain the potential F was, first, to compute from the model the G values for ideal conditions and, second, to estimate the corresponding F values from the F/G ratio of the first sampling day, as will be explained below. In order to compute G , the statistical parameters of the aggregate size distribution determined immediately after tillage (Fig. 1) and the z_o value for each of the four sampling days were introduced in the model. Although soil surface roughness did not apparently change during the experimental period, a monitoring of z_o was made to assess that the variation in z_o with time was not responsible for the observed reduction in soil erodibility. The mean and standard deviation values of z_o for the four sampling days were 3.94 ± 1.15 , 3.71 ± 0.79 , 3.38 ± 0.99 and 2.89 ± 0.77 mm. These values indicated a slight reduction in z_o during the experimental period which can not be expected to highly affect G . Thus, taking into account this change in z_o , the model predicted G values varying between $1.56 \cdot 10^6$ and $4.59 \cdot 10^7 \mu\text{g m}^{-1} \text{s}^{-1}$ for the u_* range recorded in the field study (0.37 - 0.72 m s^{-1}). If z_o was stable with time, predicted G should range from $1.56 \cdot 10^6$ to $4.50 \cdot 10^7 \mu\text{g m}^{-1} \text{s}^{-1}$, indicating that the variation in z_o

involved a maximum increase of 2% in G . Anyway, the observed F decay could be only explained from an increase in z_o but not from a decrease.

In the second step, potential F was obtained from the computed G assuming that F is a constant fraction of G , as previously demonstrated by Shao et al. (1993) from wind tunnel experiments. This fraction was calculated from the ratio of measured F to estimated G for the first dust emission episode registered on August 8 (12:33-12:53). It seems reasonable to expect that at that moment (only one day after tillage) the actual G was optimum and, therefore, equal to the G estimated from the model. Thus, the F/G ratio of $1.77 \cdot 10^{-6} \text{ m}^{-1}$ was used to estimate the potential F for the remaining episodes. The F values estimated in this way ranged from 2.76 to $81.1 \mu\text{g m}^{-2} \text{ s}^{-1}$ (Fig. 3). Figure 3 shows clearly that the measured and potential F were in a good agreement for the first five episodes and in a gradual discrepancy for the remaining cases. These results demonstrate that the observed behaviour of F with time was due to changes in the aggregate size distribution at the soil surface, thus confirming the hypothesis of a limited supply of erodible particles in the soil.

The reduction in soil erodibility during the study period must be reflected in an increase in u_{*t} . Values of u_{*t} were estimated for each sampling period by fitting equation (5) to the G values derived from the actual F (Table 2) through the ratio of $1.77 \cdot 10^{-6} \text{ m}^{-1}$. As it is shown in Table 3, u_{*t} increased progressively from a value of 0.35 m s^{-1} on August 8 to 0.70 m s^{-1} on August 28. This result indicates that significant changes occurred in the size distribution of soil particles during the erosion events and, consequently, different new threshold conditions were present within a month. The threshold wind shear velocity, u_{*t} , is a important parameter in wind erosion research because it comprises all factors affecting soil erodibility, determining, at the same time, both the frequency and intensity of erosion episodes. To assess how realistic the u_{*t} estimations were, a visual approach to determine actual u_{*t} was made by comparing u_* for the sampling periods with and without dust emission (Table 2). For example, on August 8, u_{*t} must be between 0.35 and 0.37 m

s⁻¹. Thus, a mean value of 0.36 m s⁻¹ was considered as u_{*t} for the first day. Table 3 compares the u_{*t} values deduced in this way with those estimated from the model. The strong correlation found between the two u_{*t} data sets (Fig. 4) provided a validation of the model predictions. Furthermore, since the applicability of this model has been established up to now for desert soils, results from the present study seem to demonstrate its suitability also for dryland agricultural soils.

From experiments conducted on artificial surfaces in a wind tunnel, Scott (1995) outlined a simple method to characterise the erosion process over short periods of time based on the analysis of the wind profile. More precisely, that author showed that the type of wind erosion process may be determined from the response of the saltation roughness length, z_o' (i.e., z_o in eroding conditions) to the increase in u_* . Following this approach, wind erosion was described for selected periods with a gradual increase in u_* . Thus, hourly averages of z_o' and u_* were calculated from 10:00 to 18:00 on August 24 and from 8:40 to 16:40 on August 28 by using equation (2). Over the first period, u_* increased from an average value of 0.45 to 0.62 m s⁻¹ and, on the contrary, average z_o' decreased from 4.81 to 3.14 mm (Fig. 5a). The significant relationship found between $\ln z_o'$ and $1/u_*$ ($P < 0.01$) was contrary to that expected for the surfaces classically considered, i.e. surfaces equally erodible in extent and time (just as sand dunes). Thus, on non supply-limited soils, an increase in wind speed in eroding conditions must be followed by an increase in z_o' induced by saltating particles (Bagnold, 1941). Our results, obtained under field conditions, indicated that the soil surface was not a continuous source of erodible material, supporting the previous observations of Scott (1995) from experiments in wind tunnel. Over the period of August 28, u_* increased from an average value of 0.44 to 0.73 m s⁻¹. However, in contrast to August 24, z_o' significantly increased with u_* (Fig. 5b), following a similar trend to that predicted from the analytical expression of z_o' proposed by Raupach (1991):

$$z_o' = (A u_*^2 / 2g)^{1-r} z_o^r \quad (6)$$

1 where A is a constant (0.38) and $r = u_{*t}/u_*$. In this case, z_o was fixed in 2.89 mm and u_{*t} at 0.60 m
2 s⁻¹. After this period, u_* progressively decreased until the end of day. However, the fast reduction
3 in F recorded for the last sampling period (Table 2 and Fig. 2) cannot be due only to the decrease in
4 wind speed, but also to a new supply-limited condition to which F must have adapted.

6 **4. Conclusions**

7 This study shows that, under natural field conditions, significant changes in soil erodibility
8 associated with wind erosion processes may occur in a month and, even on the order of hours. More
9 precisely, results reported here provide a wind erosion example in which the available supply of
10 fine particles becomes progressively depleted and the soil surface increasingly armoured. These
11 results underline the need to consider the evolution of soil properties in wind erosion research and
12 derived models. If the temporal variability is not taken into account, erosion measurements and
13 predictions could be erroneously used to assess the extent of wind erosion and design appropriate
14 control methods.

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References

- Alfaro, S.C. and Gomes, L., 1995. Improving the large-scale modeling of the saltation flux of soil particles in presence of nonerodible elements. *J. Geophys. Res.*, 100: 16,357-16,366.
- Bagnold, R.A., 1941. *The Physics of Blown Sand and Desert Dunes*. Morrow, New York, 265 p.
- Businger, J.A., Wyngaard, J.C., Izumi, Y. and Bradley, E.F., 1971. Flux profile relationships in the atmospheric surface layer. *J. Atmos. Sci.*, 28: 181-189.
- Findlater, P.A., Carter, D.J. and Scott, W.D., 1990. A model to predict the effects of prostrate ground cover on wind erosion. *Aust. J. Soil Res.*, 28: 609-622.
- Fryrear, D.W., 1984. Soil ridges-clods and wind erosion. *Trans. ASAE*, 27: 445-448.
- Gillette, D.A., 1977. Fine particulate emissions due to wind erosion. *Trans. ASAE*, 20: 890-897.
- Gomes, L., Bergametti, G., Dulac, F., Ezat, U., 1990. Assessing the actual size distribution of atmospheric aerosols collected with a cascade impactor. *J. Aerosol Sci.* 21, 47-59.
- Leys, J.F. and Raupach, M.R., 1991. Soil flux measurements using a portable wind erosion tunnel. *Aust. J. Soil Res.*, 29: 533-552.
- Leys, J., Koen, T. and McTainsh, G., 1996. The effect of dry aggregation and percentage clay on sediment flux as measured by a portable field wind tunnel. *Aust. J. Soil Res.*, 34: 849-861.
- López, M.V., Sabre, M., Gracia, R., Arrúe, J.L. and Gomes, L., 1998. Tillage effects on soil surface conditions and dust emission by wind erosion in semiarid Aragón (NE Spain). *Soil Tillage Res.* (in press).
- Losno, R., Bergametti, G. and Mouvier, G., 1987. Determination of optical conditions for atmospheric aerosol analysis by X-ray fluorescence. *Environ. Tech. Lett.*, 8: 77-87.
- Marticorena, B. and Bergametti, G., 1995. Modeling the atmospheric dust cycle: 1. Design of a soil-derived dust emission scheme. *J. Geophys. Res.*, 100: 16,415-16,430.
- Marticorena, B., Bergametti, G., Gillette, D. and Belnap, J., 1997. Factors controlling threshold friction velocity in semiarid and arid areas of the United States. *J. Geophys. Res.*, 102: 23,277-23,287.

- 1 Monin, A.S. and Obukhov, M.A., 1954. Dimensionless characteristics of turbulence in the surface
2 layer. Akad. Nauk. USSR, Geofiz. Inst. Tr. No. 24, pp. 163-187.
- 3 Nickling, W.G. and Gillies, J.A., 1989. Emission of fine-grained particulates from desert soils. In: M.
4 Leinen and M. Sarnthein (Editors), *Paleoclimatology and Paleometeorology: Modern and Past*
5 *Patterns of Global Atmospheric Transport*, Kluwer Academic Publishers, pp. 133-165.
- 6 Nickling, W.G. and Gillies, J.A., 1993. Dust emission and transport in Mali, West Africa.
7 *Sedimentology*, 40: 859-868.
- 8 Pimentel, D., Harvey, C., Resosudarmo, P., Sinclair, K., Kurz, D., McNair, M., Crist, S., Shpritz, L.,
9 Fitton, L., Saffouri, R. and Blair, R., 1995. Environmental and economic costs of soil erosion and
10 conservation benefits. *Science*, 267: 1117-1123.
- 11 Raupach, M.R., 1991. Saltation layers, vegetation canopies and roughness lengths. *Acta Mech.*, 1
12 (Supp.): 83-96.
- 13 Sabre, M., 1997. Etude dynamique du processus d'émission de poussières désertiques: Impact sur le
14 fractionnement physico-chimique entre sol et aérosol. Ph.D. diss. Univ. of Paris VII, France.
- 15 Saxton, K.E., 1995. Wind erosion and its impact on off-site air quality in the Columbia Plateau—An
16 integrated research plan. *Trans. ASAE*, 38: 1031-1038.
- 17 Scott, W.D., 1995. Measuring the erosivity of the wind. *Catena*, 24: 163-175.
- 18 Shao, Y., Raupach, M.R. and Findlater, P.A., 1993. Effect of saltation bombardment on the
19 entrainment of dust by wind. *J. Geophys. Res.*, 98: 12,719-12,726.
- 20 Shao, Y., Raupach, M.R. and Leys, J.F., 1996. A model for predicting aeolian sand drift and dust
21 entrainment on scales from paddock to region. *Aust. J. Soil Res.*, 34: 309-342.
- 22 Soil Survey Staff, 1975. *Soil taxonomy: a basic system of soil classification for making and*
23 *interpreting soil surveys*. USDA-SCS Agric. Handb. 436, U.S. Gov. Print. Office, Washington,
24 D.C., USA.
- 25 Sterk, G. and Stein, A., 1997. Mapping wind-blown mass transport by modeling variability in space
26 and time. *Soil Sci. Soc. Am. J.*, 61: 232-239.

- 1 Stetler, L.D. and Saxton, K.E., 1996. Wind erosion and PM10 emissions from agricultural fields on
- 2 the Columbia Plateau. *Earth Surface Proc. Landforms*, 21: 673-685.
- 3 Stout, J.E. and Zobeck, T.M., 1996. The Wolfforth field experiment: a wind erosion study. *Soil Sci.*,
- 4 161: 616-631.

Figure legends

Figure 1. Aggregate size distribution (<38 mm diameter) of soil in the 0-2.5 cm depth after tillage. Statistical parameters for each of the three modes of the mass-size distribution are indicated (MMD, mass median diameter; SD, standard deviation; Amp, amplitude).

Figure 2. Vertical dust flux versus wind shear velocity measured after tillage.

Figure 3. Comparison of measured and potential vertical dust flux estimated for ideal conditions of unlimited supply of erodible material at the soil surface.

Figure 4. Model estimations of threshold wind shear velocity (u_{*t}) versus u_{*t} deduced from observations of wind shear velocity registered for different dust sampling periods. See text for details.

Figure 5. Relationship between wind shear velocity (u_*) and saltation roughness length (z_o') on (a) August 24, between 10:00 and 18:00, and (b) August 28, between 8:40 and 16:40. The type of representation is based on the procedure given by Scott (1995). Also shown is the analytical expression of $z_o'(u_*)$ given by Raupach (1991) (equation (6) in the text).

Table 1.

Soil properties in the 0-2.5 cm depth and soil surface conditions after mouldboard ploughing.

Particle size distribution			pH	EC	Organic matter	CaCO ₃	Dry bulk density	Soil cover		Frontal area		Wind-erodible fraction ^b
Sand	Silt	Clay						Residues	Clods ^a	Residues	Clods ^a	
———— g kg ⁻¹ ———				dS m ⁻¹	———— g kg ⁻¹ ———		Mg m ⁻³	———— % ———		—— cm ² m ⁻² ——		%
303	443	254	8.3	0.26	14.6	411	1.00	0.93	2.86	71	313	50.0

^a Aggregates >38 mm in diameter.

^b Mass of aggregates <0.84 mm in diameter.

Table 2.

Vertical dust flux (F) and meteorological conditions (Ri , Richardson number; u_* , wind shear velocity) for dust sampling periods after tillage on August 7

Date	Sampling period	Wind direction (0° = North)	Wind speed at 2 m height	Ri	u_*	F
		degrees	m s ⁻¹		m s ⁻¹	µg m ⁻² s ⁻¹
August 8	12:10-12:30	306	4.93	-0.18	0.34	-
	12:33-12:53	284	5.14	-0.18	0.38	3.55
	12:57-13:17	302	5.12	-0.18	0.37	1.45
August 14	9:50-10:10	307	5.85	-0.05	0.40	3.06
	10:20-10:40	306	5.60	-0.07	0.39	-
	10:46-11:06	299	5.08	-0.09	0.35	-
August 24	10:25-10:45	309	7.42	-0.03	0.49	10.44
	10:48-11:08	310	6.84	-0.05	0.46	-
	11:12-11:33	305	7.04	-0.05	0.46	6.54
	15:45-16:05	303	9.56	-0.02	0.62	11.66
	16:08-16:28	304	9.22	-0.04	0.57	-
August 28	16:33-16:54	310	10.03	-0.03	0.63	8.34
	12:42-13:02	304	10.98	-0.02	0.70	8.61
	13:06-13:26	296	11.25	-0.02	0.71	-
	13:30-13:50	290	10.65	-0.03	0.72	9.57
	17:00-17:20	296	10.80	-0.02	0.70	6.72
	17:26-17:46	300	10.82	-0.02	0.70	-
	17:50-18:10	297	10.91	-0.02	0.71	2.03

Comparison of model estimations of threshold wind shear velocity (u_{*t}) with those deduced from observations of the wind shear velocity for different dust sampling periods (Table 2). See text for more details.

Date	Sampling period	u_{*t} estimated	Observation	u_{*t} observed
————— m s ⁻¹ —————				
August 8	12:33-12:53	0.35	0.34 < u_{*t} < 0.37	0.36
	12:57-13:17	0.35	"	0.36
August 14	9:50-10:10	0.37	0.39 < u_{*t} < 0.40	0.39
August 24	10:25-10:45	0.43	u_{*t} ~ 0.46	0.46
	11:12-11:33	0.42	"	0.46
	15:45-16:05	0.58	0.57 < u_{*t} < 0.62	0.59
	16:33-16:54	0.60	"	0.59
August 28	12:42-13:02	0.68	u_{*t} ~ 0.70	0.70
	13:30-13:50	0.69	"	0.70
	17:00-17:20	0.68	"	0.70
	17:50-18:10	0.70	"	0.70

Fig 1

Fig. 1

Fig. 2

Fig. 3

Fig 4

Fig. 5