# TILLAGE EFFECTS ON SOIL SURFACE CONDITIONS AND DUST EMISSION BY WIND EROSION IN SEMIARID ARAGON (NE SPAIN)

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## Abstract

Wind erosion is one of the most serious soil degradation problems in many agricultural regions of the world. 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. However, actual wind erosion data are not yet available. We report here results from a wind erosion study conducted during the summer 1995 within a single dryland field located in Central Aragón. Two consecutive field experiments investigated the effects of chisel ploughing (reduced tillage) and mouldboard ploughing (conventional tillage) on soil surface conditions and vertical dust flux. Micrometeorological data and suspended sediment samples were collected in the month following each tillage operation. Likewise, soil surface properties affecting wind erosion were determined immediately after tillage. Values of vertical dust flux varied from 0.52 to 5.03 µg $m^{-2}$ $s^{-1}$ (for a range of wind shear velocity of 0.46-0.56 m $s^{-1}$) during the first experimental period (after chisel ploughing) and from 1.45 to 11.66 µg $m^{-2}$ $s^{-1}$ (for shear velocities between 0.37 and 0.72 m $s^{-1}$) in the second experiment (mouldboard ploughing). The wind-erodible fraction of soil surface (aggregates <0.84 mm diameter) was 41% and 50% after chiseling and mouldboard ploughing, respectively. The percentage of soil cover with crop residues and clods was 15% after chiseling and only 4% after mouldboard ploughing. The frontal area of this nonerodible material and soil roughness was reduced four times after mouldboard ploughing. Although direct comparisons of tillage effects are still necessary, these first results suggest that reduced tillage, with chiseling as primary tillage, could be considered as a viable alternative for wind erosion control during the fallow period in semiarid Aragón. This study indicates, likewise, the need to consider the temporal and spatial variability of soil properties affecting wind erosion in agricultural soils.

*Keywords*: Chisel ploughing; Mouldboard ploughing; Vertical dust flux; Dry aggregate size distribution; Soil surface cover

## 1. Introduction

There is limited quantitative information of wind erosion on agricultural lands in Europe, despite the concern expressed about its environmental and economic impacts (Eppink and Spaan, 1989; Frielinghaus, 1991; Szabó et al., 1994). Rainfed arable lands in semiarid areas of the Mediterranean region are particularly prone to wind erosion due to soil moisture deficit, weak soil structure and limited vegetation cover. In Spain, where land degradation by water erosion has been well documented (Sala et al., 1991), studies on wind erosion are very scarce (Quirantes, 1989). Although different regions in Spain, among them Central Aragón (NE Spain), are mentioned as potential wind erosion areas of Western Europe (De Ploey et al., 1989), there is a lack of field studies in which wind erosion is considered as a major degradation problem for the Spanish soils.

In Aragón, about one million hectares of total rainfed arable land (1.36 million ha) have an average annual precipitation of 500 mm or less. In contrast to other semiarid regions, the rainfall regime is characterized by the absence of any well defined rainy season and in any month there is a high probability of having either an extremely low amount (<10 mm) or no rain at all (McAneney and Arrúe, 1993). Strong and dry winds (*Cierzo*) with a dominant WNW direction are frequent throughout the region. *Cierzo* events with gusts over 30 m $s^{-1}$ are not rare, especially in summer (Biel and García de Pedraza, 1962). Soils are mostly alkaline (pH >8), with low organic matter content (<20 g $kg^{-1}$), high total carbonate content (>300 g $kg^{-1}$ in many cases) and a dominant sandy loam to loam textural class (Montañés et al., 1991). Due to these characteristics, it is expected that these soils are highly susceptible to wind erosion, particularly in fallow lands. Fallowing (9-10 months), in the traditional cereal-fallow rotation in the area, may enhance wind erosion hazard because of the insufficient residues on the surface and the highly pulverized soils by multiple tillage operations. In addition, fallow lands in Aragón have increased by 40% since 1988 as a consequence of several set-aside land directives of the Common Agricultural Policy of the European Union. In the 1995-1996 growing season, the fallow land surface represented about 465,000 ha of which 29% was due to the application of these regulations (Meza and Albisu, 1995).

Although the adoption of conservation tillage practices has been encouraged as an alternative to preserve soil fertility in erodible lands (Pimentel et al., 1995; Saxton, 1995), studies on its effectiveness on wind erosion control have not been yet carried out in Spain. According to previous results on soil and crop response to conservation tillage in cereal production areas of

Aragón (López et al., 1996; López and Arrúe, 1997), reduced tillage could also be regarded as a fallow management alternative to attenuate soil losses by wind erosion in those areas.

The aim of the present work was to provide a first quantification of wind erosion in agricultural soils of Central Aragón. To this purpose, soil surface conditions and dust emission from natural winds were measured within a farm field following chisel and mouldboard ploughing as primary operations in reduced and conventional tillage systems, respectively.

## 2. Materials and methods

### *2.1. Site characteristics*

The study was carried out 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.). The soil is a loam (fine-silty, mixed, thermic Xerollic Calciorthird), according to the USDA soil classification (Soil Survey Staff, 1975). Selected soil properties in the Ap horizon (0-40 cm) are shown in Table 1. The climate of the study area is semiarid with an average annual rainfall of 340 mm and an average annual air temperature of 14.7 °C. According to the meteorological information provided by an automatic weather station, which was located in 5 km distance from the field site, the frequency of erosive winds in this area, i.e. winds with a velocity higher than 5.3 m $s^{-1}$ at 2 m height (Skidmore, 1965), is higher than 20% (Martínez-Cob, personal communication). The experimental field was nearly level, apparently uniform in terms of surface characteristics, almost free of vegetation (2% cover) and surrounded by irrigated land in the upwind edge. The field had been conventionally tilled with barley (*Hordeum vulgare* L.) grown under cereal-fallow rotation until 1993 when it was temporarily retired from agricultural production.

### *2.2. Experimental plan*

The field campaign, conducted during the dry season of July/September 1995, was aimed to determine the effects of chiseling and mouldboard ploughing on dust production. However, there was only one dust flux tower available and, therefore, simultaneous measurements under both tillage systems were not possible. Due to this constraint, the whole campaign was split into two successive experimental periods. During the first period (5/7/95-6/8/95) the effects of chisel ploughing on dust emission were studied (*Experiment I*). Chiseling was done on July 5 to 0-15 cm depth, without soil inversion and with partial retention of crop residues on soil surface. Soil ridges, with WNW-ESE orientation, were 10 cm high at 50 cm intervals. During the second experimental period (7/8/95-6/9/95) the effects of mouldboard ploughing were investigated (*Experiment II*). Thus, the same field was mouldboard ploughed on August 7 to 30-35 cm depth. In this case, soil ridges, also with WNW-ESE orientation, were 15 cm high at 80 cm intervals.

### *2.3. Field and laboratory methods*

#### *2.3.1. Micrometeorology and vertical dust flux*

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 field campaign with a data logger (Campbell Scientific, model CR10), which continuously recorded 2 min averages of data acquired at intervals of 10 s. Wind speed profile under neutral stability conditions was characterized by the Prandtl-von Kármán equation:

$$U(z) = u_*/k \ln(z/z_\circ)$$

where $U$ is the wind speed at height $z$, $z_\circ$ is the aerodynamic roughness length, $u_*$ is the wind shear velocity and $k$ is the von Kármán constant (0.4). Under non-neutral atmospheric conditions, wind profiles were corrected by using the Monin-Obukhov similarity function (Monin and Obukhov, 1954).

During the two experiments, 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 *Cierzo* winds (wind speed at 2 m height >5 m s$^{-1}$). Table 2 summarizes information about these sampling periods for both Experiment I and Experiment II. The filter samples were analysed for elemental composition (Mg, Al, Si, P, S, K, Ca, Ti, Mn and Fe) using wavelength dispersive X-ray fluorescence (XRF) spectrometry, according to the method described by Losno et al. (1987). 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:

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

where $C$ is the elemental concentration at heights $z_1$ (1 m) and $z_2$ (4 m) , $\Psi_m$ is the Monin-Obukhov stability function and $L$ is the Monin-Obukhov length.

*2.3.3. Soil surface properties*

Soil surface conditions were characterized immediately after tillage in the two field experiments. Soil samples for dry aggregate size distribution were taken from 0-2.5 cm depth using a metal frame (15 cm x 15 cm) with a cutting edge. The samples were carefully transported to the laboratory where they were air-dried and sieved using an electromagnetic sieve shaker (CISA, Barcelona). The soil was separated into fourteen size fractions: 38-12.5, 12.5-8, 8-6.3, 6.3-2, 2-1, 1-0.84, 0.84-0.5, 0.5-0.4, 0.4-0.25, 0.25-0.1, 0.1-0.08, 0.08-0.063, 0.063-0.04 and <0.04 mm in diameter. Aggregate size distribution was obtained by using the data inversion method described by Gomes et al. (1990). This fitting procedure is based on the adjustment of multimodal log-normal distributions to the measured values by minimizing the difference between the simulated and observed populations of each size class. Each mode of the mass-size distribution is characterized by three parameters: median diameter, standard deviation (SD) and amplitude (%).

Soil dry bulk density was determined in the upper 2.5 cm by the core method. Soil surface roughness was measured in three directions (270°, 292.5° and 315°) using the chain method (Saleh, 1993). Frontal and basal surface areas occupied by clods (aggregates >38 mm in diameter) and crop residues were estimated with a 10 x 10 cm grid within a 1 x 1 m frame. Additional soil surface samples were collected for particle size analysis by the pipet method (Gee and Bauder, 1986) and organic matter content, $CaCO_3$ content, pH ($H_2O$, 1:2.5) and electrical conductivity, EC

($H_2O$, 1:5) determinations by standard methods (Page et al., 1982). All above properties were measured at 2 or 3 points along a WNW-ESE transect and at two positions in each sampling point: the ridge top and the furrow.

## 3. Results

### *3.1. Vertical dust flux*

Positive $F$ (i.e., $C$ decreased with height), indicating active erosion of the field surface, was detected in 14 of the 27 sampling periods registered along the entire experimental campaign. The remaining cases corresponded to episodes showing zero $F$ (no significant concentration gradient) or, in just one case, a negative $F$ (deposition event).

Dust concentrations at 1 m height and associated $F$ for the sampling periods of dust emission during Experiments I and II are shown in Table 3. These values arise from the addition of each of the oxidized forms of the major elements present in the dust samples: Fe, Ca, K, Si, Al and Mg. Concentrations of P, Ti and Mn were under the detection limit of the analytical technique. Although S was also found, it was not considered because of the uniformity of its concentration with height. It could indicate that S was not generated locally, in the experimental field. Probably, the source of the particles containing S was a paper mill 7.5 km distance from the field site. In both experiments, Ca and Si were the two most abundant elements in all dust samples (Fig. 1). Their individual average concentration accounted for 35-40% of the total concentration. The third major element was Al with an average contribution of 15% and 12% in Experiments I and II, respectively. These elements contributed with similar percentages to dust collected at 4 m height (data not shown).

Unstable atmospheric conditions, as indicated by the Richardson number (Businger et al., 1971), were present during all samplings periods (Table 3). Wind direction remained fairly constant (average of 297°±10°), corresponding in all cases to episodes of *Cierzo* wind (Table 2). Whereas $u_*$ in Experiment I varied in a relatively narrow range (0.46-0.56 m $s^{-1}$), in Experiment II it progressively increased from an average value of 0.37 m $s^{-1}$ on the first sampling day to 0.70 m $s^{-1}$ on the last one (Table 3). However, this increase in $u_*$ with time did not always result in an increase in $F$. Thus, on August 24, average $u_*$ was 0.55 m $s^{-1}$ and this resulted in an average $F$ of 9.25 μg $m^{-2}$ $s^{-1}$. On August 28, average $u_*$ increased up to 0.71 m $s^{-1}$ but average $F$ was 8.30 μg

$m^{-2}$ $s^{-1}$, slightly lower than that on the previous sampling day. This observation is best illustrated in Fig. 2, showing the variation of *F* with $u_*$ for both experiments. The *F* values for the first five sampling periods in Experiment II ranged from 1.45 to 10.44 µg $m^{-2}$ $s^{-1}$ and increased as a significant power function of $u_*$ ($P$< 0.05). This increase was no longer observed in the remaining sampling periods, for which *F* values ranged between 6.72 and 11.66 µg $m^{-2}$ $s^{-1}$ regardless of $u_*$. Although the relationship between $u_*$ and *F* was not statistically significant for Experiment I, the data tend to conform a power regression with a similar exponent to that obtained for Experiment II (Fig. 2). In Experiment I, *F* values varied within a range of 0.52-5.03 µg $m^{-2}$ $s^{-1}$.

### *3.2. Soil surface conditions*

Table 4 shows soil surface characteristics due to tillage in Experiments I and II. The higher clay content and lower silt and organic matter contents following mouldboard ploughing reflect the soil-inverting action of this implement, bringing soil richer in clay and poorer in silt and organic matter to the surface (Table 1). On the other hand, mouldboard ploughing reduced the percentage of soil surface covered with nonerodible material (crop residues and clods) from 15% (Experiment I) to 4% (Experiment II), mainly due to a lower number of large clods (40-90 mm diameter). The small vegetative cover post-tillage in both experiments (1-2%) consisted mainly of crop residues lying on the soil surface. Soil roughness and the total frontal area of nonerodible elements was four times lower after mouldboard ploughing than after chisel ploughing. Soil surface water content immediately after tillage in both experiments was too low (11 and 22 g $kg^{-1}$ in Experiments I and II, respectively) to prevent wind erosion. With regard to sampling position, furrow relative to the ridge, in Experiment II soil water content and clay content were higher on the ridge top (29.8 and 275 g $kg^{-1}$, respectively) than in the furrow (14.4 and 232 g $kg^{-1}$). This fact was likely due to the working action of the mouldboard plough, leaving on the ridge top fine material brought from deeper layers.

Table 5 summarizes the average statistical parameters of the aggregate size distributions of soil surface samples collected at both sampling positions in both experiments. In all cases, three populations (modes) were found with median diameters ranging from 8 to 19 mm for the first population, 1.2 to 2.3 mm for the second one, and 0.18 to 0.29 mm for the third one. Amplitudes and SD varied between positions. In Experiment I, the first and second populations were the most affected by sampling position. While the first one dominated on the ridge top (46% of mass), the second one did in the furrow (44%). Probably, during furrow formation, the chisel plough breaks the largest aggregates into the smaller ones, thus increasing, the second population by 30% compared with the ridge top value. In Experiment II, at both sampling positions, the greatest proportion of aggregate mass corresponded to the second population (about 50%). A greater proportion of the smallest aggregates seemed to be present on the ridge top when compared with the furrow (44% vs. 33%). The reverse tendency occurred for the greatest aggregates (8% vs. 18%). Taking into account that a portion of the wind-erodible fraction (aggregates <0.84 mm diameter) is included in the intermediate population, the greatest proportion of erodible soil occurred in the furrow in Experiment I (47%) and on the ridge top in Experiment II (56%). The average aggregate size distribution for both experiments is shown in Fig. 3. Mouldboard plough did not affect the proportion of the smallest aggregates, remaining in about 40% of the total mass. On the contrary, this implement increased the intermediate aggregates from 29% (Experiment I) to 49% (Experiment II) due to the breakdown of the greatest ones. Finally, the wind-erodible fraction was 41% and 50% in Experiments I and II, respectively.

## 4. Discussion

The $F$ values obtained during the whole experimental period ranged from 0.52 to 11.7 μg m$^{-2}$ s$^{-1}$ for a $u_*$ range of 0.37-0.72 m s$^{-1}$ (Table 3). Comparable $F$ data for agricultural soils are scarce in the literature. In a study carried out on nine agricultural soils in Texas, Gillette (1977) reported $F$ values ranging from approximately 10 to 10$^4$ μg m$^{-2}$ s$^{-1}$ during wind erosion events with $u_*$ of 0.20-1.0 m s$^{-1}$. Using a portable field wind tunnel, Nickling and Gillies (1989) found mean $F$ of 73-488 μg m$^{-2}$ s$^{-1}$ for $u_*$ varying between 0.30 and 0.80 m s$^{-1}$ over three agricultural fields in Arizona. More recently, Nickling and Gillies (1993), collecting dust at different heights over rice (*Oryza sativa* L.) and millet (*Pennisetum glaucum* L.) fields in Mali, measured $F$ of 0.07-6 μg m$^{-2}$ s$^{-1}$ for $u_*$ between about 0.20 and 0.50 m s$^{-1}$. The fluxes computed in our environmental conditions were well below those observed in Texas and Arizona. Dust emissions in Texas were associated in almost all cases with major dust storms on large and exposed fields. In comparison, the $u_*$ values recorded in the present study, as well as those from Mali, were generally lower and, in any case, they did not correspond to dust storm episodes. Direct comparison with the Arizona data is difficult due to the different sampling equipment used. Thus, for the Arizona study, within the wind tunnel the suspended sediment was collected at 50 cm height and each measurement was made at a different location to avoid depletion of erodible grains. In addition, the three soils of Arizona and most of the soils of Texas had a dominant sand textural class (sand content >85%) and a wind-erodible fraction ranging between 53 and 99%. Therefore, different wind strength conditions and different nature of the erodible soils may explain that the magnitude of dust emissions in our experimental field differed from that of Texas and Arizona. Significant power relationships between $F$ and $u_*$ (r=0.61-0.81), with exponents ranging between 2.9 and 4.2, were also found by Nickling and Gillies (1989) for different surface types but not for agricultural fields. For these latter, the authors found a high degree of data scatter which was also noted by Gillette (1977).

The general increase in wind speed with time in Experiment II gave evidence that a decay in dust emission occurred at the end of this experiment (Fig. 2). This behaviour was likely due to a limited supply of material available for wind erosion. If large soil aggregates were not desintegrated during this period, a gradual depletion of fine particles could be expected from the first erosion events to the last ones. Unfortunately, aggregate size distribution was only determined at the beginning of each experiment. However, the above idea appears to be supported by the $z_{\circ}$ values recorded during the sampling periods (Table 3). Under the surfaces classically considered, i.e. surfaces equally erodible in extent and time (just as sand dunes), an increase in wind speed in eroding conditions must be followed by an increase in $z_{\circ}$ induced by saltating particles (Bagnold, 1941). In contrast, in the present study, $z_{\circ}$ did not show a clear increase with $u_*$. Furthermore, a slight decrease in $z_{\circ}$ with the time could be noted, indicating that the soil surface was not a continuous source of erodible material during the experimental period. These results, obtained under field conditions, support those reported previously by Scott (1995) from experiments conducted on artificial surfaces using a wind tunnel and confirm the need for taking into account the changes of surface erodibility with time in the characterisation of wind erosion processes in agricultural soils.

The chemical composition of the dust collected showed that Ca and Si were the two most abundant elements (Fig. 1). Whereas the high content in Si is a common characteristic of the soil-derived dust from different world regions (Gomes and Gillette, 1993), the abundance of Ca reflected the specific mineral composition of most soils in Aragón, soils particularly rich in calcite. The high content of $CaCO_3$ in these soils was likely an important factor of erodibility. Thus, while, in general, noncalcareous soils having a loam texture are not highly erodible, the presence of $CaCO_3$ increases their erodibility by reducing the mechanical stability of clods and producing more wind-erodible aggregates (Gillette, 1988; Breuninger et al., 1989).

Although the presence of clods and crop residues on the soil surface after tillage can be considered low in both experiments (Table 4), even small increases in soil cover can reduce significantly the levels of dust emission. Based on the mathematical relationship established by Bilbro and Fryrear (1994) from previous laboratory and field wind tunnel data, the 15% and 4% soil cover measured in Experiments I and II, respectively, would reduce soil losses, with respect to a bare soil, by 48% and 16%. That is, with only a 10% more of soil covered, wind erosion could be reduced about 30%. Likewise, the frontal surface of the nonerodible elements is an important parameter to consider in wind erosion studies because it absorbs a portion of the wind energy which will not be available to detach and transport soil particles. In the same study, Bilbro and Fryrear (1994) proposed another equation to estimate the effect of residue frontal area (also called silhouette area) on soil losses by wind erosion. In spite of the negligible amounts of crop residues in both experiments, the application of this equation predicted that the reduction of soil losses, when compared with a bare soil, was 10% higher after chiseling than after mouldboard ploughing. On the other hand, a strong relationship ($P < 0.01$) was found between the frontal area of nonerodible elements and the roughness values obtained by the chain method (Fig. 4). Although more field data are required, this good correlation suggests that values of frontal area could be predicted from those of roughness, which are faster and easier to obtain.

In principle, chisel plough seemed to be more effective than mouldboard plough in creating nonerodible aggregates from both a higher number of large clods (>38 mm diameter) and a lower wind-erodible fraction. This result does not agree with previous observations (Zobeck and Popham, 1990; Fryrear et al., 1994) reporting a better aggregation status after mouldboard ploughing. This disagreement was likely due to differences in soil moisture at the time of tillage. In our case, an average water content in the plough layer of about 60-70 g $kg^{-1}$ immediately after tillage, indicated that both chisel and mouldboard ploughing were conducted under low moisture conditions (water content at -1.5 MPa for the 0-40 cm layer was 105 g $kg^{-1}$). In general, whereas chiseling may be done when soil is dryer, mouldboard ploughing requires a certain level of soil moisture to produce soil cloddiness. Tilling under low soil moisture conditions is not exceptional in the semiarid areas of Aragón where the opportunity of tillage is critical because of the uncertain nature of rainfall distribution (López et al., 1996).

Since in our study chiseling and mouldboard ploughing were implemented one month apart, direct comparisons of tillage effects on dust emission can not be made. However, soil surface conditions after tillage could indicate a lower susceptibility of soil to wind erosion following chisel ploughing than mouldboard ploughing. This consideration appears to be supported by the values of the threshold wind shear velocity, $u_{*t}$ (i.e., $u_*$ at which soil erosion begins), estimated for Experiments I and II by using the dust emission model developed by Marticorena and Bergametti (1995), including the improved expression of shear stress partition between nonerodible and erodible elements from Alfaro and Gomes (1995). The model requires the statistical parameters of the aggregate size distributions (Table 5) and the roughness length of the surface (computed from the wind speed profile during periods with no erosion). The $u_{*t}$ values for soil conditions created by chisel and mouldboard ploughing were 0.45 and 0.38 m $s^{-1}$, respectively, indicating a lower erodibility of the soil after chisel ploughing.

In Central Aragón, where residue production is too low to provide effective ground cover, a combination of clods by tillage and residues could probably be an effective strategy in protecting the soil surface. In this respect, the preliminary results obtained in this study suggest that reduced tillage, with chiseling as primary operation, could be considered as a promising alternative to conventional tillage for wind erosion control in our region. In addition, benefits from reduced tillage may be expected to increase with time due to a progressive accumulation of crop residues and amelioration of soil structure. However, in the case of persistence of the limited supply of erodible material observed in the present study after mouldboard ploughing, the initial advantages of reduced tillage could disappear with time. Further research is needed to examine this behaviour and evaluate the effectiveness of reduced tillage on wind erosion control throughout the fallow period in rainfed cereal production areas of Central Aragón. Finally, the change in the availability of erodible material with time as well as the effect of the sampling position indicate the need to consider the temporal and spatial variability of soil properties affecting wind erosion in agricultural soils.

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## Figure legends

**Figure 1.** Relative elemental composition of soil-derived dust collected at 1 m height in (a) Experiment I (chisel ploughing) and (b) Experiment II (mouldboard ploughing). Bars indicate standard deviation.

**Figure 2.** Vertical dust flux versus wind shear velocity in Experiment I (chisel ploughing) and Experiment II (mouldboard ploughing). See text for details.

**Figure 3.** Aggregate size distribution (<38 mm diameter) of soil in the 0-2.5 cm in Experiment I (chisel ploughing) and Experiment II (mouldboard ploughing).

**Figure 4.** Relationship between surface rouhgness (chain method) and frontal area of nonerodible elements in Experiment I (chisel ploughing) and Experiment II (mouldboard ploughing).

Table 1.

Selected physical and chemical properties of the soil at the experimental site

| Depth | Particle size distribution | | | pH | EC | Organic matter | $CaCO_3$ |
|---|---|---|---|---|---|---|---|
| | Sand | Silt | Clay | | | | |
| cm | g $kg^{-1}$ | | | | dS $m^{-1}$ | g $kg^{-1}$ | |
| 0-20 | 293 | 484 | 223 | 8.3 | 0.25 | 14.6 | 432 |
| 20-40 | 279 | 460 | 261 | 8.3 | 0.28 | 13.3 | 425 |

Table 2.

Average wind direction and wind speed for dust sampling periods during Experiment I (5/7/95-6/8/95) and Experiment II (7/8/95-6/9/95)

| Experiment | Tillage operation [a] | Date | Sampling period | Wind direction (0° = North) | Wind speed at 2 m height |
|---|---|---|---|---|---|
| | | | | degrees | $m\ s^{-1}$ |
| I | Chisel ploughing | July 10 | 20:30-20:50 | 282 | 6.67 |
| | | | 20:56-21:16 | 299 | 5.37 |
| | | July 22 | 11:20-11:40 | 287 | 5.28 |
| | | | 11:47-12:07 | 292 | 5.93 |
| | | | 12:14-12:34 | 298 | 6.06 |
| | | | 16:10-16:30 | 298 | 6.93 |
| | | | 16:35-16:55 | 294 | 7.15 |
| | | | 17:01-17:21 | 291 | 7.72 |
| | | | 20:30-20:50 | 290 | 7.10 |
| | | | 20:54-21:14 | 291 | 6.63 |
| II | Mouldboard ploughing | August 8 | 12:10-12:30 | 306 | 4.93 |
| | | | 12:33-12:53 | 284 | 5.14 |
| | | | 12:57-13:17 | 302 | 5.12 |
| | | August 14 | 9:50-10:10 | 307 | 5.85 |
| | | | 10:20-10:40 | 306 | 5.60 |
| | | | 10:46-11:06 | 299 | 5.08 |
| | | August 24 | 10:25-10:45 | 309 | 7.42 |
| | | | 10:48-11:08 | 310 | 6.84 |
| | | | 11:12-11:33 | 305 | 7.04 |
| | | | 15:45-16:05 | 303 | 9.56 |
| | | | 16:08-16:28 | 304 | 9.22 |
| | | | 16:33-16:54 | 310 | 10.03 |
| | | August 28 | 12:42-13:02 | 304 | 10.98 |
| | | | 13:06-13:26 | 296 | 11.25 |
| | | | 13:30-13:50 | 290 | 10.65 |
| | | | 17:00-17:20 | 296 | 10.80 |
| | | | 17:26-17:46 | 300 | 10.82 |

[a] Chisel and mouldboard ploughing were implemented on July 5 and August 7, respectively.

Table 3.

Dust concentration ($C$), vertical flux ($F$) and meteorological conditions ($u_*$, wind shear velocity; $z_\circ$, aerodynamic roughness length; $Ri$, Richardson number) for dust emission episodes during Experiment I (5/7/95-6/8/95) and Experiment II (7/8/95-6/9/95)

| Experiment | Tillage operation [a] | Date | Sampling period | $C$ at 1 m height | $F$ | $u_*$ | $z_\circ$ | $Ri$ |
|---|---|---|---|---|---|---|---|---|
| | | | | µg m$^{-3}$ | µg m$^{-2}$ s$^{-1}$ | m s$^{-1}$ | mm | |
| I | Chisel ploughing | July 10 | 20:30-20:50 | 54.69 | 5.03 | 0.51 | 10.90 | -0.02 |
| | | July 22 | 11:47-12:07 | 16.36 | 0.52 | 0.46 | 8.62 | -0.10 |
| | | | 16:35-16:55 | 29.37 | 3.04 | 0.54 | 8.98 | -0.07 |
| | | | 17:01-17:21 | 29.23 | 1.68 | 0.56 | 7.54 | -0.06 |
| II | Mouldboard ploughing | August 8 | 12:33-12:53 | 27.50 | 3.55 | 0.38 | 5.93 | -0.18 |
| | | | 12:57-13:17 | 16.99 | 1.45 | 0.37 | 5.24 | -0.18 |
| | | August 14 | 9:50-10:10 | 28.41 | 3.06 | 0.40 | 4.98 | -0.05 |
| | | August 24 | 10:25-10:45 | 77.03 | 10.44 | 0.49 | 4.31 | -0.03 |
| | | | 11:12-11:33 | 57.44 | 6.54 | 0.46 | 4.16 | -0.05 |
| | | | 15:45-16:05 | 88.93 | 11.66 | 0.62 | 4.20 | -0.02 |
| | | | 16:33-16:54 | 59.69 | 8.34 | 0.63 | 3.37 | -0.03 |
| | | August 28 | 12:42-13:02 | 58.51 | 8.61 | 0.70 | 3.93 | -0.02 |
| | | | 13:30-13:50 | 56.48 | 9.57 | 0.72 | 5.16 | -0.03 |
| | | | 17:00-17:20 | 56.02 | 6.72 | 0.70 | 4.11 | -0.02 |

[a] Chisel and mouldboard ploughing were implemented on July 5 and August 7, respectively.

Table 4.

Soil properties in the 0-2.5 cm depth and soil surface conditions (cover and roughness) after chisel ploughing (Experiment I) and mouldboard ploughing (Experiment II)

| Experiment | Tillage operation | Particle size distribution | | | pH | EC | Organic matter | $CaCO_3$ | Dry bulk density | Soil cover | | Frontal area | | Roughness [b] |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | Sand | Silt | Clay | | | | | | Residues | Clods [a] | Residues | Clods [a] | |
| | | g $kg^{-1}$ | | | | dS $m^{-1}$ | g $kg^{-1}$ | | Mg $m^{-3}$ | % | | $cm^2$ $m^{-2}$ | | % |
| I | Chisel ploughing | 296 | 501 | 203 | 8.3 | 0.24 | 15.8 | 415 | 1.19 | 1.88 | 12.69 | 101 | 1269 | 21.0 |
| II | Mouldboard ploughing | 303 | 443 | 254 | 8.3 | 0.26 | 14.6 | 411 | 1.00 | 0.93 | 2.86 | 71 | 313 | 5.3 |

[a] Aggregates >38 mm in diameter.
[b] Average from measurements in three directions (270°, 292.5°, and 315°).

Table 5.

Statistical parameters of the aggregate size distributions (<38 mm diameter) of soil in the 0-2.5 cm depth as affected by sampling position relative to the ridge after chisel ploughing (Experiment I) and mouldboard ploughing (Experiment II).

| | | | Population 1 [a] | | | Population 2 [a] | | | Population 3 [a] | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Experiment | Tillage operation | Position | Median diameter | SD | Amplitude | Median diameter | SD | Amplitude | Median diameter | SD | Amplitude |
| | | | mm | | % | mm | | % | mm | | % |
| I | Chisel ploughing | Ridge top | 7.92 | 1.66 | 45.7 | 1.16 | 1.22 | 13.3 | 0.29 | 2.78 | 41.0 |
| | | Furrow | 16.46 | 1.71 | 23.6 | 1.38 | 3.31 | 43.6 | 0.18 | 1.96 | 32.8 |
| II | Mouldboard ploughing | Ridge top | 19.04 | 1.25 | 7.8 | 1.60 | 3.22 | 48.6 | 0.18 | 2.36 | 43.6 |
| | | Furrow | 18.00 | 1.53 | 18.5 | 2.30 | 4.13 | 48.6 | 0.18 | 2.40 | 32.9 |

[a] Each population identifies one mode of the mass-size distribution.

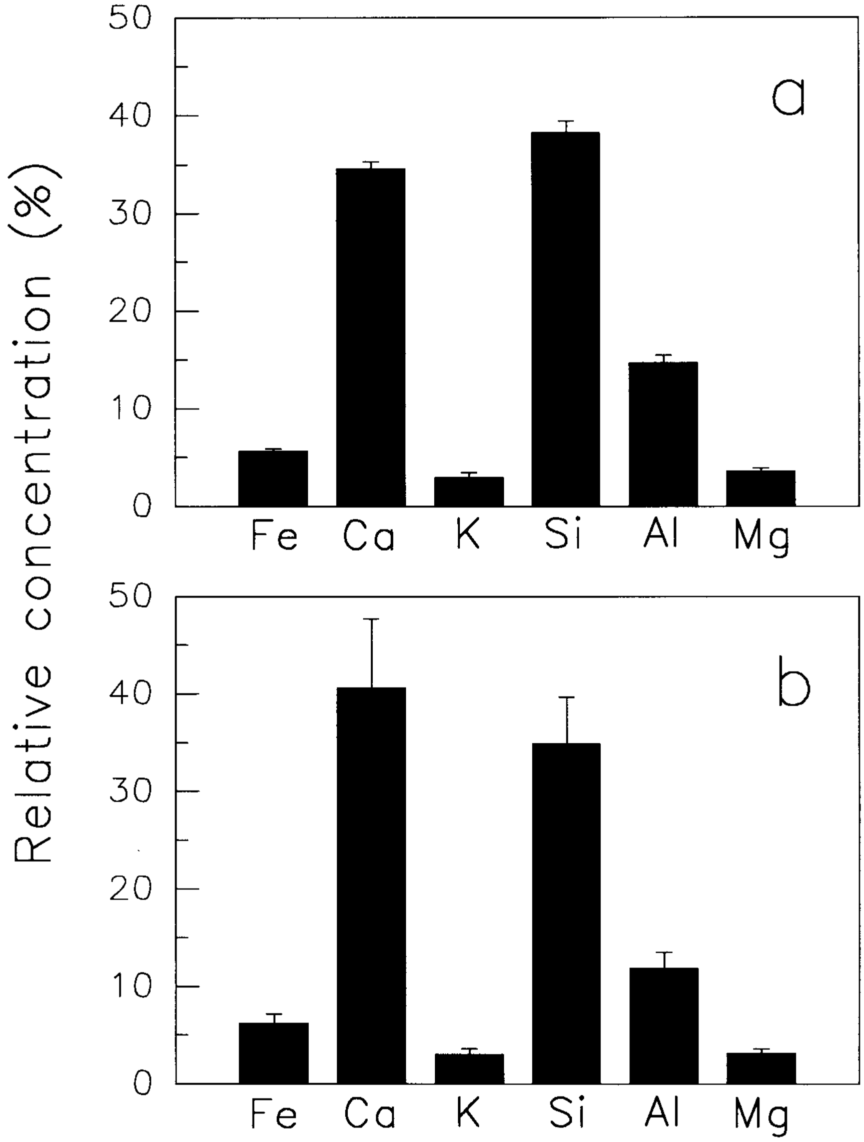



Fig. 1

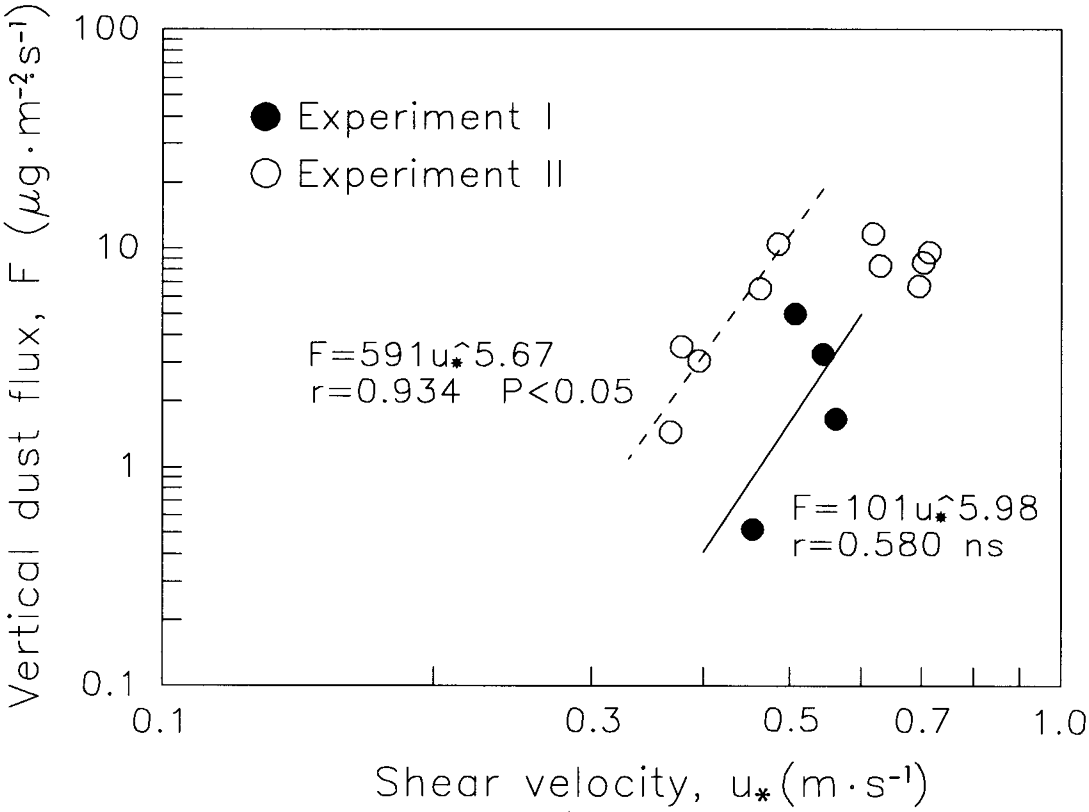
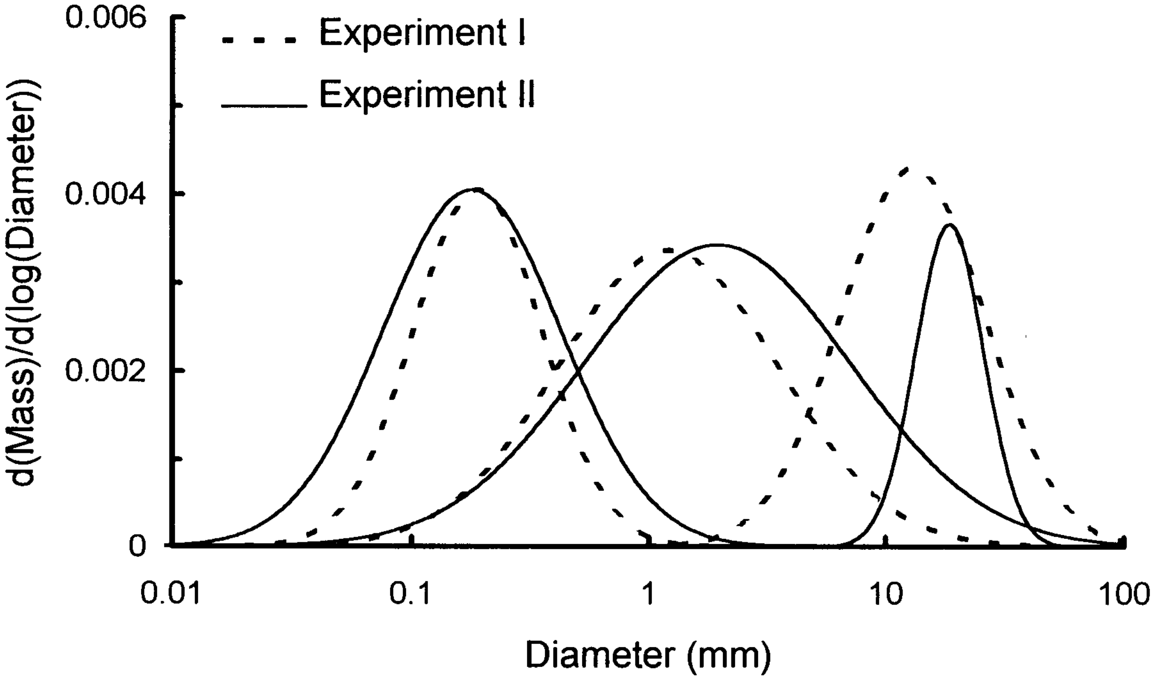
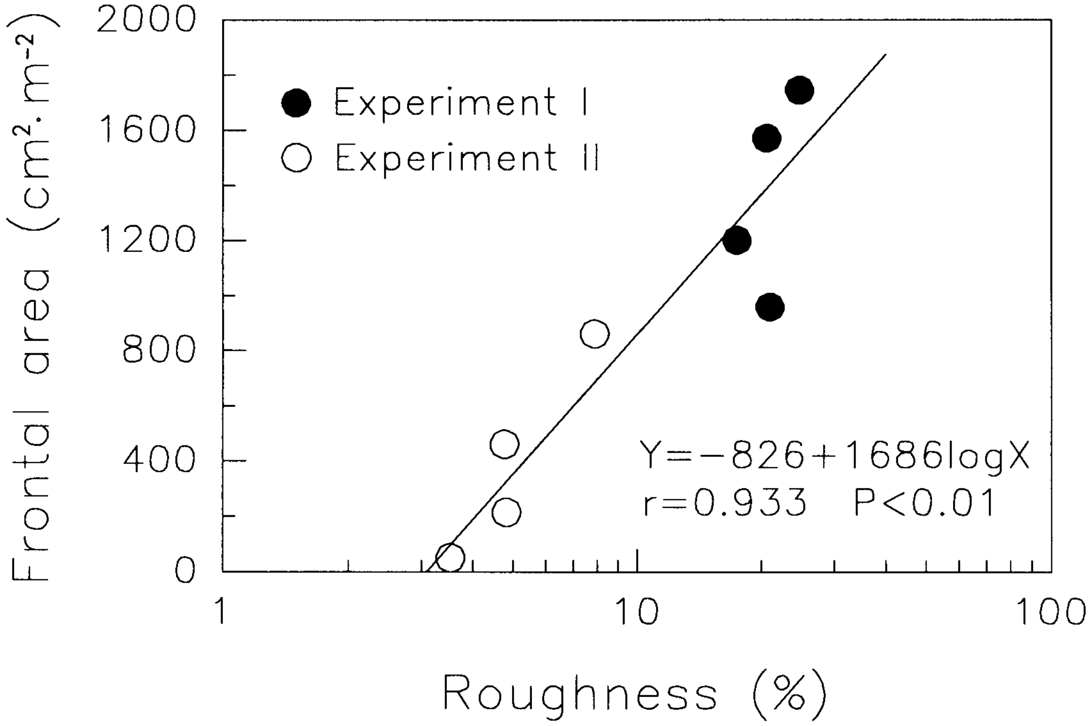

Vertical dust flux, F (μg·m⁻²·s⁻¹)
100
10
1
0.1
Experiment I
Experiment II
F=591u*^5.67
r=0.934 P<0.05
F=101u*^5.98
r=0.580 ns
0.1
0.3
0.5
0.7
1.0
Shear velocity, u*(m·s⁻¹)

Fig. 2



0.006
0.004
0.002
0
d(Mass)/d(log(Diameter))
Experiment I
Experiment II
0.01
0.1
1
10
100
Diameter (mm)


Fig. 3



Frontal area (cm².m⁻²)
2000
1600
1200
800
400
0
Experiment I
Experiment II
Y=−826+1686logX
r=0.933 P<0.01
1
10
100
Roughness (%)


Fig. 4