1 **EFFECTS OF REDUCED TILLAGE ON SOIL SURFACE**
2 **PROPERTIES AFFECTING WIND EROSION IN SEMIARID**
3 **FALLOW LANDS OF CENTRAL ARAGÓN**

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7 **M.V. López*, R. Gracia, J.L. Arrúe**

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11 *Departamento de Edafología, Estación Experimental de Aula Dei, Consejo Superior de*
12 *Investigaciones Científicas (CSIC), POB 202, 50080-Zaragoza, Spain.*

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17 * Corresponding author. Tel.: 34 (9) 76 57 65 11; fax: 34 (9) 76 57 56 20; e-mail:
18 vlopez@eead.csic.es

Abstract

In Central Aragón (NE Spain), where strong and dry winds are frequent all year round, fallow lands are susceptible to wind erosion due to insufficient crop residues on the surface and loose, finely divided soils by multiple tillage operations. Effects of conventional tillage (mouldboard ploughing followed by a compacting roller) and reduced tillage (chisel ploughing) on soil surface properties affecting wind erosion were studied during three experimental campaigns in a dryland field of Central Aragón. Reduced tillage provided higher soil protection than conventional tillage through a lower wind erodible fraction of soil surface (on average, 10% less) and a significantly higher percentage of soil cover with crop residues and clods (30% higher). Random roughness was also higher after reduced tillage than after conventional tillage (15% vs. 4%). These results indicate that reduced tillage can be an effective soil management practice for wind erosion prevention during the fallow period in semiarid Aragón. The study shows, likewise, that significant changes in soil aggregate size distribution associated with wind erosion processes may occur in short periods of time. Thus, temporal variability of soil surface properties, including crust and clods stability, needs to be considered in wind erosion research in agricultural soils.

Keywords: Dryland farming; Fallowing; Conservation tillage; Soil erodibility by wind; Soil surface properties

1. Introduction

Achieving sustainable agroecosystems is a major challenge in semiarid regions. Due to particular soil and climate conditions and unsuitable agronomic practices, semiarid drylands of Central Aragón (NE Spain) are prone to land degradation by wind and water erosion. While soil loss by water erosion has been well documented (Benito et al., 1992; Navas, 1993; Lasanta et al., 1995), wind erosion has not been yet considered as a serious degradation problem in this region. However, recent field studies, providing preliminary results on dust emission (López et al., 1998) and saltation transport (Sterk et al., 1999), indicate that the risk of severe wind erosion could be high in agricultural soils of Central Aragón.

About three quarters (more than one million hectares) of the rainfed arable land in Aragón receive an average annual precipitation of 500 mm or less. The rainfall regime is characterized by the absence of a well-defined rainy season. In any month there is the strong probability of having either an extremely low amount (<10 mm) or no rain at all (McAneney and Arrúe, 1993). Strong and dry WNW winds (*Cierzo*) are frequent and characteristic for Central Aragón. Wind events with gusts over 30 m s^{-1} are common, especially in summer (Biel and García de Pedraza, 1962). Soils are mostly alkaline ($\text{pH} > 8$), with low organic matter content ($< 20 \text{ g kg}^{-1}$), high total carbonate content ($> 300 \text{ g kg}^{-1}$ in many cases) and a dominant sandy loam to loam textural class (Montañés et al., 1991). Because of the fragility and high susceptibility to degradation of soils in the region, particularly the gypsiferous soils (Navas, 1990), especial attention must be paid to their agricultural use and proper management during the fallow period. Long fallowing (16-17 months), in the traditional cereal-fallow rotation, may enhance wind erosion due to insufficient residues on the surface and the highly pulverised soils caused by multiple tillage operations. Consequences of wind erosion include a reduction in crop production by selective removal of the finest soil particles, rich in nutrients and organic matter, a reduction in the water-holding capacity and increased degradation of soil structure (Lowery et al., 1995; Larney et al., 1998).

All the above considerations were of major concern in planning the project Wind Erosion and Loss of Soil Nutrients in Semi-Arid Spain (WELSONS), initiated in 1996 in order to provide a predictive understanding of impacts driven by climate and land-use changes on the degradation of agricultural soils by wind erosion in Central Aragón (Gomes et al., 1996). 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), evaluation of reduced tillage as a soil management practice for wind erosion prevention in fallow lands was included among the objectives of that project. The purpose of this paper is to show the effects of tillage on soil surface properties affecting wind erosion during three intensive field campaigns in an agricultural soil of Central Aragón. Soil surface conditions following mouldboard ploughing and chiseling, as primary operations in conventional and reduced tillage systems, respectively, are compared and discussed on the basis of their temporal variability.

2. Materials and methods

2.1. Site characteristics

The study was carried out within an agricultural field in the Los Monegros area (41°36'N, 0°32'W, 280 m alt.), about 35 km east of Zaragoza (Fig. 1). The climate of the area is semiarid with an average annual rainfall of 380 mm and an average annual air temperature of 14.3 °C. The experimental field is almost level within an undulating landscape. The soil is a silt loam (coarse-loamy, gypsic, thermic Gypsiorthid) (Soil Survey Staff, 1975). Selected soil properties for two depths in the plough layer (0-20 and 20-40 cm) are shown in Table 1.

The experimental field has been conventionally tilled with barley (*Hordeum vulgare* L.) grown under cereal-fallow rotation for at least the previous 10 years. Accordingly, half of the farm field is cropped while the other half is fallowed, alternating these areas each year. Average annual cereal grain yield in Los Monegros is less than 2 t ha⁻¹ (Austin et al., 1998).

2.2. *Experimental plan*

Three intensive field campaigns were made during the summers of 1996 (July-September), 1997 (June-September) and 1998 (June-July). In 1996 and 1997, two adjacent plots of 135 x 180 m, with a separation of 20 m, were delimited in the fallow area of the field for the application of two tillage treatments: conventional tillage (CT), consisting of mouldboard ploughing to 30-35 cm depth followed by a pass of a compacting roller (a traditional practice in the study area), and reduced tillage (RT), with only a single pass of chisel plough to 15-20 cm depth, as an alternative conservation tillage system. In 1998, only the CT treatment was considered and implemented on a plot of the same dimension. All tillage operations were done in the prevailing wind direction (WNW). Fig. 1 shows the layout of the experimental plots during the study period. In 1997 and 1998, tillage operations (pass of roller on the CT plot and chisel ploughing on the RT plot) were repeated to disrupt the surface crust formed after rainfall events, as required by ongoing simultaneous experiments on dust emission and saltation processes. Repeated tillage is commonly practised by local farmers in order to remove weeds growing during the fallow period.

2.3. *Sampling and measurements*

Prior to preparation of the CT and RT plots, soil samples were taken from 0-20 and 20-40 cm depths on the experimental field in order to have a first indication of soil composition (Table 1). Particle size distribution was determined by using a light-scattering particle size analyser (COULTER LS 230). Organic matter content, CaCO₃ content, gypsum content, electrical conductivity (H₂O, 1:5) and pH (H₂O, 1:2.5) were determined by standard methods (Page et al., 1982).

Soil surface properties affecting wind erosion were measured immediately after the application of the tillage treatments. Soil samples for dry aggregate size distribution were collected from 0-2.5 cm depth using a metal frame (15 x 15 cm) with a cutting edge. The samples were carefully transported to the laboratory where they were air-dried and sieved with an

electromagnetic sieve shaker (CISA, Barcelona). The soil was separated in 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: mass median diameter (MMD), standard deviation (SD) and amplitude (% mass). In order to evaluate the temporal variation of soil erodibility, the dry aggregate size distributions from soil samples taken in the CT plot immediately after tillage on July 8 in 1998 were compared with those collected on July 16 following a dry and windy period. To detect more efficiently differences between dates, soil samples from July 16 were shallower (0-1 cm) than those from previous samplings (0-2.5 cm). Assuming that, immediately after tillage, the aggregate size distribution of the soil in the upper 2.5 cm and 1 cm is the same, direct comparisons between dates are possible.

Soil surface roughness was measured in the WNW direction (random roughness) using the chain method (Saleh, 1993). Frontal and basal areas occupied by clods (aggregates >38 mm in diameter), crop residues and pebbles were estimated with a 10 x 10 cm grid within a 1 x 1 m frame. Frontal area refers to the lateral surface of these elements exposed to dominant wind per unit of ground cover and basal area to their horizontal surface expressed as percentage of total soil surface. In 1997 and 1998, soil crust was characterized in terms of thickness, maximum crust penetration resistance, measured by a hand surface penetrometer (Type IB, Eijkelkamp, The Netherlands), and amount of loose aggregates lying on the crust by using an ordinary vacuum-cleaner.

All above determinations were made at twelve points randomly selected in each plot. Hourly values of meteorological parameters (precipitation, air temperature, wind speed and wind direction, relative humidity and global solar radiation) were registered through the whole

experimental period with an automatic weather station (CAMPBELL Scientific, datalogger CR10) installed in the experimental field.

3. Results

Total rainfall received during the experimental periods of 1996, 1997 and 1998 was 60, 171 and 62 mm, respectively (Fig. 2). As compared with the long-term average precipitation (1965-1995) registered for the same seasonal periods at the Monegrillo pluviometric station (about 10 km distant from the site), the rainfall in the 1996 and 1998 campaigns was 17% lower and 23% higher than average, respectively, while in 1997 it was well-above average (61% higher). Frequent showers and rainstorms, particularly in 1997, affected to a large extent the course of the wind erosion experiment due to soil surface crusting, as detailed below. In addition, many of the days with high wind speed were preceded by rainfall during the previous one or two days (Fig. 2). Wind speed varied among months and experimental campaigns. On the basis of the number of hours per month with a mean wind speed equal to or higher than 5 m s^{-1} at 2 m height, the month with the highest frequency of erosive winds was July 1998 (35% of time). The least windy months were August and September of 1997 with wind speeds higher than 5 m s^{-1} for only 4-5% of time.

Table 2 shows the soil surface conditions after CT and RT for the different dates of tillage operations during the experimental period. With the exception of the second date in 1997, the wind erodible fraction (aggregates $<0.84 \text{ mm}$ in diameter) was significantly higher ($P<0.05$) after CT (40%) than after RT (30%). In the RT plot, additional chiseling applied on September 3 increased the fraction of erodible aggregates to that of CT. In all cases, the aggregate size distribution was characterized by three populations (modes) with mass median diameters (MMD) ranging from 12 to 17 mm for the first, 1.2-3.2 mm for the second and 0.17-0.31 mm for the third population, respectively. As can be seen in Fig. 3, corresponding to the aggregate distribution after tillage on June 16 in 1997, the MMD was slightly higher after RT than after CT for the three populations. On the other hand, in terms of amplitude (% mass), the third population was, in

1 general, the most affected by tillage with a fraction of the smallest aggregates about 6% higher
2 under CT than RT. However, the major differences between treatments concerned soil surface
3 cover and roughness created by crop residues and clods; the presence of pebbles was negligible in
4 both treatments. Thus, RT provided a more protective soil surface than CT, with a percentage of
5 soil cover in all cases significantly higher under RT than under CT (on average, 30% higher)
6 (Table 2). This difference was attributed to both a higher presence of residues and a higher
7 number of large clods (4-10 cm diameter). On the other hand, the frontal surface of these
8 roughness elements can result in an effective soil protection factor during wind erosion events by
9 reducing wind energy and trapping soil erodible particles. RT provided a total frontal area of
10 nonerodible material almost 20 and 7 times higher than CT, after the initial tillage operations of
11 1996 and 1997, respectively. This difference between treatments was greatly increased after the
12 repeated tillage in September 1997 (Table 2). In 1997 and 1998, an extra pass of the compacting
13 roller over the CT plot considerably reduced the low soil protection provided initially by this
14 treatment.

15 Table 3 shows the characteristics of the soil crust formed after intermittent rainfalls received
16 at the end of June and during July in 1997 and after the rainfall on July 1 in 1998 (Fig. 2). In the
17 two years, a thin and consolidated crust was formed, with higher values of penetration resistance
18 and mass of both total and erodible aggregates in the CT treatment.

19 The average statistical parameters of the mass-size distributions for soil aggregates collected
20 on July 16 and July 8 in 1998 to evaluate the temporal variation of soil erodibility are summarised
21 in Table 4. Although the three populations (modes) remained with time, clear differences in their
22 contributions were observed. Thus, the proportion of the first population increased from 13% to
23 27% from the first to the second date and the reverse occurred for the third population (from 26%
24 to 12%). The wind erodible fraction was significantly reduced from 48% to 31% ($P<0.05$).

4. Discussion

In a previous study on a different agricultural soil of the Zaragoza province, López et al. (1998) have observed more favourable soil surface conditions against wind erosion after RT than after CT. Although further comparisons with the present study are difficult, because in the field experiment from López et al. (1998) chiseling and mouldboard ploughing were implemented consecutively in the same plot, in both cases the lower erodibility of the soil under RT was based on reducing the wind erodible fraction of soil surface but, especially, on creating a rough and protective ground cover. Horning et al. (1998), using field wind tunnel data, have established a mathematical relationship to estimate the combined effect of residue surface cover and random roughness on soil losses by wind erosion. Application of this equation to data reported here (Table 2) indicates that the potential reduction of these losses, relative to flat, bare soil, is 30 to 70% higher in RT than in CT. These results agree with those of López et al. (1998), who reported about 50% less dust emission by wind (vertical dust flux) after chiseling than after mouldboard ploughing for erosion episodes with a mean wind speed ranging from 5 to 8 m s⁻¹ at 2 m height. Likewise, saltation transport data recorded in the experimental field of Los Monegros during the 1996 and 1997 campaigns (Sterr et al., 1999) support the general observation of a lower susceptibility of soil to wind erosion with RT than with CT. Although wind erosion was likely limited due to exceptional wet conditions and soil crusting during the experimental periods, saltation flux was registered in the CT plots during several *Cierzo* wind events but never in the RT plots (Sterr et al., 1999).

A more resistant soil condition against wind energy could have been achieved by tilling perpendicularly to the dominant wind direction. In this case, the surface roughness provided by clods and residues (random roughness) is increased in that due to the ridges produced by tillage (oriented roughness). This is possible for RT since chisel ploughing created ridges 10 cm high at 50 cm intervals, but not for CT where the compacting roller eliminates the oriented roughness left by the mouldboard plough. In any case, and regardless of the kind of tillage implements

commonly used in a given area, farmers in the region do not take into account the tillage orientation with respect to *Cierzo*. In fact, only 15 out of a total of 66 agricultural fields surveyed in semiarid Aragón, had tillage operations perpendicular to the prevailing wind direction. The range in the direction of ridges in these fields was between 0° (north) and 45° (north-east) (unpublished data).

As discussed by Sterk et al. (1999), the occurrence of saltation transport at the study site was strongly influenced by the intensity and distribution of rainfall during the experimental period. This was mainly due to soil surface crusting rather than to soil moisture because of high evaporation during the summer season. The low presence of loose material lying on the surface under RT, in spite of a lower crust resistance to abrasion as compared with CT (i.e., smaller crust strength), was likely due to the protective effect of crop residues and roughness on the underlying particles. However, regardless of tillage, the initial protection from wind erosion provided by crusting, as well as by cloddiness, can be temporary. The surface of both crust and clods can, with time, become a significant source of erodible material from the abrasive action of wind-blown soil particles (Cahill et al., 1996; Mirzamostafa et al., 1998). Soil texture has a large influence on the dry aggregate and crust stabilities, with the coarse-textured soils less resistant to breakdown (Potter, 1990; Skidmore and Layton, 1992). In this respect, the high content of CaCO₃ in our soils is probably an important factor of erodibility to add to the fragile nature of a gypsiferous soil. While noncalcareous soils with a silt loam texture are not, in general, highly erodible, the presence of CaCO₃ increases their erodibility by reducing the mechanical stability of clods and producing a more disaggregated surface (Gillette, 1988; Breuninger et al., 1989).

The temporal variability of soil conditions must be also taken into account in wind erosion studies when the surface of agricultural soils is bare and loose. Furthermore, López (1998) indicated that significant changes in soil erodibility associated with wind erosion processes may occur in short periods of time, it being possible to reach a situation of limited supply of particles available for erosion. This temporal variation can be evaluated from changes in soil aggregate size

distribution after a dry and windy period, as it occurred in our study period (July 8-16, 1998). During this period, no rainfall was received and the average daily wind speed was near or higher than 5 m s^{-1} in 5 of these 8 days, ranging the maximum average hourly wind speed registered each day between 5.1 and 11.4 m s^{-1} (Fig. 2). The changes observed in soil aggregate mass-size distribution, that is, an increase in the fraction of the greatest aggregates, at the expense of a decrease in that of the smallest ones, with a reduction in the wind erodible fraction (Table 4), reflect a progressive depletion of fine particles from the soil surface and exposure of nonerodible aggregates under significant *Cierzo* wind episodes. These results show that, under the influence of the wind erosion process itself, soil erodibility in agricultural fields can substantially change in relatively short periods of time.

5. Conclusion

Results from the characterisation of soil surface conditions after tillage showed that chiseling, as primary tillage operation, was more effective than mouldboard ploughing followed by a pass of compacting roller in both creating a protective ground cover against wind erosion, through a combination of clods and crop residues, and reducing the wind erodible fraction of the soil surface. The lower soil erodibility by wind under RT indicates that this tillage system can be considered as a suitable soil management practice to prevent wind erosion during the fallow period in the study area. Reduction in the number of tillage operations and the consideration of tillage orientation with respect to the prevailing wind direction should also be recommended.

On the other hand, since soil crusting is a common feature of soils in the area, further research on crust stability is needed to assess its temporal character as a protecting element against wind erosion on fallow land. Similarly, clods created by tillage should be studied as a potential source of erodible particles via breakdown and abrasive action of saltating particles during wind erosion events. In this sense, this study shows that significant changes in the soil aggregate size distribution associated with wind erosion processes may occur in short periods of time. Therefore,

- 1 the temporal variability of soil surface properties must be considered in wind erosion research in
- 2 agricultural soils to correctly assess the extension of the problem and to design adequate control
- 3 measures.

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Figure legends

Figure 1. Location of the study area and layout of the experimental plots (CT, conventional tillage; RT, reduced tillage) with respect to the prevailing *Cierzo* wind direction.

Figure 2. Daily precipitation and average daily wind speed at 2 m height measured at the field site during the experimental periods.

Figure 3. Dry aggregate mass-size distribution (<38 mm diameter) of soil in the 0-2.5 cm depth after conventional tillage (CT) and reduced tillage (RT) on June 16, 1997.

Fig. 2
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Fig. 2.

Fig. 3

Table 1

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

	Depth (cm)	
	0-20	20-40
Particle size distribution (g kg^{-1})		
Sand ($2000 < \phi < 50 \mu\text{m}$)	208	219
Silt ($50 < \phi < 2 \mu\text{m}$)	633	623
Clay ($\phi < 2 \mu\text{m}$)	159	158
pH (H_2O , 1:2.5)	8.1	8.1
Electrical conductivity (1:5) (dS m^{-1})	2.0	2.1
Organic matter (g kg^{-1})	15.9	14.8
CaCO_3 (g kg^{-1})	352	354
Gypsum (g kg^{-1})	171	177

Table 2

Soil surface characteristics as affected by tillage (CT, conventional tillage; RT, reduced tillage)

Field campaign	Tillage date	Tillage treatment	Wind erodible fraction (%) ^a	Soil cover (%)		Frontal area (cm ² m ⁻²)		Random roughness (%) ^c
				Residues	Clods ^b	Residues	Clods ^b	
1996	July 8	CT	43a ^d	0.80a	1.24a	80a	65a	3.5a
		RT	33b	25.21b	24.78b	1970b	739b	13.1b
1997	June 16	CT	39a	0.18a	4.06a	6a	216a	6.4a
		RT	27b	13.29b	11.13b	483b	967b	14.3b
	Sep. 3	CT	40a	0.09a	0.25a	2a	15a	2.0a
		RT	37a	9.33b	12.58b	323b	954b	16.7b
1998	June 22	CT	43	3.42	4.63	103	243	2.6
	July 8	CT	48	1.00	2.15	16	9	1.4

^aMass of aggregates <0.84 mm in diameter (0-2.5 cm depth). ^bAggregates >38 mm in diameter.^cMeasured in the WNW direction (292.5°). ^dAt the same date, means followed by the same letter are not statistically different at $P<0.05$.

Table 3

Soil crust thickness, maximum crust penetration resistance and amount of loose aggregates on the crust surface under conventional tillage (CT) and reduced tillage (RT)

Field campaign	Date	Tillage treatment	Thickness (mm)	Penetration resistance (N cm ⁻²)	Aggregate mass (g m ⁻²)	
					Total	<0,84 mm
1997	July 28	CT	4.76a ^a	61a	84.62a	11.63a
		RT	5.01a	42b	15.85b	6.01b
1998	July 7	CT	7.40	79	54.19	17.70

^aMeans followed by the same letter are not statistically different at $P<0.05$.

Table 4

Statistical parameters of the aggregate mass-size distributions (<38 mm diameter) of soil surface immediately after conventional tillage (July 8, 1998) and eight days later (July 16, 1998)

Date	Population 1 ^a			Population 2			Population 3		
	MMD (mm) ^b	SD ^c	Amplitude (%)	MMD (mm)	SD	Amplitude (%)	MMD (mm)	SD	Amplitude (%)
July 8	11.49	1.50	13.2	1.91	4.15	60.4	0.17	2.29	26.4
July 16	9.06	1.59	27.5	1.79	4.03	60.7	0.11	1.48	11.8

^aEach population identifies one mode of the mass-size distribution.

^bMass median diameter.

^cStandard deviation.