SALTATION TRANSPORT ON A SILT LOAM SOIL IN NORTHEAST SPAIN

G. STERK, M.V. LÓPEZ, J.L. ARRÚE

ABSTRACT: The Ebro River valley in Northeast Spain experiences regularly strong west-northwest winds that are locally known as *cierzo*. When the *cierzo* blows, wind erosion may potentially occur on unprotected agricultural lands. In this paper the first results of field measurements of soil characteristics and saltation transport in the Ebro River valley near Zaragoza are presented. An experiment was conducted on a silt loam soil in the summers of 1996 and 1997. Two plots of 135 x 180 m were both equipped with a meteorology tower, three saltiphones (acoustic sediment sensors) and ten sediment catchers. The plots were different with respect to tillage practices. One plot received mouldboard ploughing followed by a pass of a compacting roller (conventional tillage — CT), whereas the other plot only received chisel ploughing (reduced tillage — RT). Soil characterizations indicated that soil erodibility was significantly higher in the CT plots than in the RT plots. Consequently, no significant saltation transport was observed in the RT plots during both seasons. In the CT plot, four saltation events were recorded during the 1996 season and nine events during the 1997 season. Most events were preceded by rainfall during the previous one or two days, which reduced saltation transport significantly. It is concluded that the occurrence of wind erosion in the Ebro River valley depends on the timing and type of tillage, distribution of rainfall and soil-surface crusting.

Keywords: Wind erosion; saltation transport; soil surface characteristics; soil tillage

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INTRODUCTION

Rainfed arable lands in semiarid regions are often prone to wind-erosion processes. This is particularly true whenever the soil is loose, dry, bare or nearly bare and the wind velocity regularly exceeds the threshold velocity for initiation of soil particle movement (Fryrear and Skidmore, 1985). During an erosive storm, soil particles may be moved by three different transport modes (Bagnold, 1973). Saltating particles jump and bounce over the soil surface, thereby inducing creep — the rolling and sliding of larger particles, and suspension — the raising of fine soil particles. This wind-blown particle transport can create several agricultural problems: (a) it may damage crops by abrasion and burial in sediment, which reduces yields, (b) it leads to soil degradation in the source areas by the loss of fertile topsoil and (c) deposition of wind-blown material may damage structures like drainage ditches, irrigation canals, etc., and may create problems of dune formation in or at some distance from the source area.

The semiarid Ebro River valley in Central Aragón, Northeast Spain, is such a region where wind erosion potentially causes agricultural damage (López *et al*., 1998). This region is regularly invaded by strong and dry winds, which are locally known as *cierzo*. These winds are typically caused by a high-pressure zone close to the Iberian Peninsula above the Atlantic Ocean, and a low-pressure zone above the Mediterranean Sea. In the Ebro River valley, the airflow is contracted and accelerated between two mountain ranges, the Pyrenees in the north and the Iberian System in the southwest (Biel, 1963). The resulting *cierzo* winds have a dominant west-northwest direction, and gusts with wind speeds over 30 m s^{-1} are quite common (Biel and García de Pedraza, 1962).

Soils are mostly alkaline, with low organic matter contents, high total carbonate contents and predominantly of a loamy texture. The traditional farming system is a rainfed cereal—fallow rotation that allows livestock integration. The fallow year in this system is applied to conserve soil moisture for the subsequent cropping year. It may enhance soil erodibility because of the limited soil cover and the highly pulverized soils caused by multiple tillage operations. Hence, the adoption of conservation tillage systems in Central Aragón could possibly reduce wind-erosion damage and help to protect soil and water resources in the area. A preliminary quantification of soil-surface conditions and vertical dust fluxes following chisel and mouldboard ploughing suggested that chisel ploughing would be a viable alternative for wind-erosion control during the fallow period (López *et al.,* 1998).

In 1996, the project Wind Erosion and Loss of Soil Nutrients in Semi-Arid Spain (WELSONS) was initiated to determine the extent of wind-induced soil degradation in Central Aragón. The main goal of the project is to develop a nutrient emission model based on fluxes of saltation and suspension material. In addition, the project aims at testing alternative soil tillage practices that reduce soil and nutrient losses. The purpose of this paper is to describe the first results of field measurements of soil surface characteristics and saltation transport for two different tillage treatments, and to determine the severeness of wind-erosion problems in Central Aragón. Papers dealing with suspension transport, nutrient emissions and modelling will be published elsewhere.

MATERIALS AND METHODS

Site Description

The experiment was carried out in the El Saso area (40°36’N, 0°32’W), which is about 35 km east of Zaragoza (Figure 1). Average annual rainfall in the area for the period 1941—95 was 365 mm. The experimental field is about 80 ha and has a rather flat topography in an otherwise hilly landscape. The farmer applies a traditional cereal—fallow rotation, which means that half of the field is used for crop production while the other half is under fallow. The fallow and cereal areas alternate each year. The soil in the experimental field was classified as a silt loam, and some properties of the topsoil (0—0.40 m depth) are shown in Table 1.

Two intensive field campaigns were conducted from early July until the end of September in 1996 and from mid-June until the end of September in 1997. During both seasons, two plots of 135 x 180 m were selected in the fallow part of the field (Figure 1). The plots were 20 m apart and the longest axes were parallel to the dominant *cierzo* wind direction (west-northwest). Two different tillage treatments were applied: conventional tillage (CT), and reduced tillage (RT). The CT treatment consisted of mouldboard ploughing to a depth of 0.30—0.35 m, followed by a pass of a compacting roller with a cutting blade in front. This is a traditional tillage system for fallow land in the area, and is applied in spring. The RT treatment consisted of a single pass of a chisel plough to a depth of about 0.15—0.20 m, which can be considered as a type of conservation tillage (López *et al.,* 1998). All the tillage operations were done in the west-northwest direction, which is similar to the farmer's practice. In 1996, the plots were tilled only once at the beginning of the experiment (6 July). In the second year, the CT and RT treatments were carried out on 16 June. During that season, on 15 July and 3 September, the roller with the cutting blade and the chisel plough were again applied to remove surface crusts that had developed as a result of high-intensity rainfall events. Although this repeated tillage was done for experimental reasons, it is in accordance with local farmers' practices, as they often repeat tillage to remove weeds that have developed during the fallow period. The area surrounding the plots was not tilled, which created a non-erodible zone due to a dense cover of weeds.

Soil Surface Properties

Soil surface conditions were characterized immediately after the tillage treatments. The wind erodible fraction (percentage of soil aggregates <0.84 mm in diameter) was determined from soil samples taken at 0—25 mm depth using a metal frame (0.15 x 0.15 m) with a cutting edge. The samples were taken to the laboratory where they were air dried and sieved using an electromagnetic sieve shaker (CISA, Spain). The dry bulk density of soil was determined in the upper 25 mm by the core method (Blake and Hartge, 1986). Soil surface roughness was measured in the direction of the prevailing *cierzo* wind (292.5°) using the chain method (Saleh, 1993). Frontal and basal surface areas occupied by clods (aggregates >38 mm in diameter), crop residues and pebbles were estimated with a 0.10 x 0.10 m grid within a 1 x 1 m frame. All above determinations were made at six points in each plot, and at two positions at each sampling point (total number of samples is 24).

When soil crusting occurred, the wind-erodible fraction of loose material on top of the crust was collected using an ordinary vacuum cleaner. Soil crusts were also characterized in terms of thickness and penetration resistance. A crust was considered to include the thin skin of fine material on the immediate surface of the soil and the consolidated material immediately under it (Zobeck, 1991). Crust thickness was measured with a ruler, and penetration resistance was determined with a manual surface penetrometer (Type IB, Eijelkamp, The Netherlands). This type of penetrometer measures the maximum penetration resistance in the top layer over a distance of approximately 0.10 m. Normally, when no stones are encountered, the crust will cause the maximum resistance.

Saltation Transport

In both plots, an automatic weather station was installed for continuous registration of meteorological parameters. Wind speed was measured with a cup anemometer at 2.0 m, wind direction with a wind vane at 2.0 m, and precipitation with a tipping bucket ram gauge at 1. 2 m. All sensors were connected to a Delta-T logger (Delta-T Devices Ltd, UK). Average values of wind speed and wind direction, and total rainfall data were stored once every minute.

Saltation transport was quantified with saltiphones and Modified Wilson and Cooke (MWAC) sediment catchers. The saltiphone (Eijelkamp, The Netherlands) is an acoustic saltation sensor (Spaan and Van den Abeele, 1991; Sterk *et al.,* 1998) that continuously records impacts of saltating sand grains with a microphone with a membrane of 201 mm^2. The microphone is placed inside a steel tube (diameter = 0.05 m, length = 0.13 m) that protects it from severe weather conditions. The tube is mounted on a ball bearing and has two vanes at the back to keep it oriented into the wind.

During erosion, part of the saltating sand grains moving through the tube hit the microphone and create high-frequency signals. By amplifying these signals and filtering low-frequency signals, saltating sand can be distinguished from other noises like those created by wind and ram. Every amplified signal, or pulse, is cut off after 1 ms, so, theoretically, a maximum number of 1000 grains per second can be recorded. The actual number of impacts may be higher due to overlap of particle impacts during the 1 ms pulse duration.

In both plots, three saltiphones were connected to the automatic weather station and installed with the centre of the microphones positioned at 0.10 m height. The created pulses were continuously counted and stored at 1 min intervals. The output, in counts per minute, shows the temporal variability of the saltation flux, which was used to determine the exact starting time and duration of storms.

Particle mass transport was quantified with MWAC sediment catchers (Sterk, 1993; Sterk and Raats, 1996). This catcher traps aeolian material at seven heights between 0.05 and 1.00 m, which means that the material is a mixture of saltation and suspension particles. The overall trapping efficiency of the catcher is 49 per cent (Sterk, 1993). Through the seven observations of horizontal particle mass fluxes, a model was fitted to describe a vertical profile of measured mass fluxes (Sterk and Raats, 1996):

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

where *q(z)* is the horizontal mass flux (kg m^{-2} s^{-1}) at height z (m), and *a, α, b, c* and β are regression coefficients. For each catcher, a total mass transport rate (kg m^{-1} s^{-1}) of wind-blown sediment at the point of sampling was obtained by integrating Equation (1) over height from z=0 to z=1 m, and correcting for the trapping efficiency of the sampler. Multiplying by the storm duration resulted in a total mass transport value (kg m^{-1}), which is equal to the total mass of material below 1 m height that passed a strip 1 m wide and perpendicular to the mean wind direction. Hence, this value includes creep, saltation and suspension transport. However, when only particle masses are considered, the contribution of saltation transport is far more important than the contributions of the other two transport modes (Chepil, 1945; Sterk and Raats, 1996). A transect of 10 MWAC catchers was installed in both plots. Distances from the upwind boundary of the plot during *cierzo* wind were: 0, 5, 15, 30, 50, 70, 90, 110, 130 and 150 m.

RESULTS AND DISCUSSION

Weather conditions during the 1996 field campaign were unfavorable for the experiment. In July and August, 59.2 mm of ram was recorded, which is 33 per cent above the long-term average. This rainfall, and in particular the storm on 29 July which had an instantaneous rainfall intensity of 180 mm h^{-1} during one minute, caused severe soil-surface crusting. It was decided to leave the crust in the field as it represented the natural condition, but it completely protected the soil from erosion as well. Consequently, no significant erosion was observed after 29 July, despite 14 days with moderate (5—10 m s^{-1}) to strong (>10 m s^{-1}) *cierzo* wind. Only four minor events before 29 were recorded, but those were all followed by rain several minutes after erosion started. Hence, the first campaign was considered a failure in terms of wind-erosion measurements, and it was decided that tillage would be repeated if crusting happened again during the 1997 campaign. The results presented here are therefore mainly from the second year.

Table II shows soil-surface conditions immediately after the initial tillage operations in the CT and RT plots during the 1997 field experiment. The values presented are very similar to those collected during the 1996 field experiment. Chisel ploughing (RT) created a less compacted topsoil compared with conventional tillage CT, which is reflected by the significant difference in bulk density. This is obvious as CT includes the passage of a compacting roller that results in a relatively high bulk density. However, this does not mean that CT creates a less erodible soil surface. Except for the soil cover and frontal area of pebbles, all other soil surface parameters were significantly higher under RT than under CT. In particular, the soil cover created by residues and non-erodible clods was substantially higher with chisel ploughing (Table II). Using the model developed by Bilbro and Fryrear (1994), the reduction in sediment transport due to this flat surface cover of residues and clods can be calculated. In the CT plot, only 4.3 per cent of soil cover was observed. This corresponds to a 17 per cent reduction in mass transport compared with bare, erodible soil. The soil cover in the RT plot was about 25 per cent, which corresponds to a reduction of 67 per cent.

The 1997 summer was also characterized by much precipitation. A total of 138 mm of rain was recorded during the three and a half months measurement period, which again resulted in severe soil-surface crusting. The second tillage operation on 15 July removed the surface crusts in both plots that had developed during the previous month. The crusts, however, returned immediately during rainfall in the same week. On 28 July, a crust characterization was done in both plots (Table III). The thickness of the crust was more or less similar in both plots, but the penetration resistance was significantly higher in the CT plot, indicating that this crust was stronger than the crust formed in the RT plot. The penetration resistance values on 20 August had doubled (CT: 1.24 MPa; RT: 0.88 MPa) as a result of repeated cycles of wetting and drying. In addition, the total masses of aggregates and wind erodible material on top of the crust were significantly higher under CT than under RT (Table III).

A total of 17 days with moderate to strong *cierzo* wind was recorded during the 1997 field experiment. Significant saltation transport was never recorded in the RT plot on those days. Hence, chisel ploughing reduced the erodibility sufficiently to provide adequate wind-erosion protection. In the CT plot, significant saltation transport was observed on 10 days (Table IV). Four of these events were associated with c*ierzo* wind, whereas the other events were caused by unstable weather conditions or convective rainstorms. The *cierzo* wind-erosion events had durations of several hours, usually starting in the morning or early afternoon, and finishing in the evening. Figure 2 shows the temporal development of wind speed and saltation flux for one of the *cierzo* wind-erosion events. The non-*cierzo* wind-erosion events had durations varying from 15—40 min (Table IV).

Given the wet circumstances during the 1997 experiment, it is likely that saltation transport was much reduced due to high threshold wind-speed conditions and soil-surface crusting. Most wind-erosion events were preceded by rainfall. The *cierzo* events of 17 and 18 July were preceded by 18.2 mm of rain on the 15 and 16 July, while the *cierzo* events of 24 and 25 July were preceded by 24.6 mm of rain, also during the previous two days. The non-c*ierzo* events on 4, 7 and 17 August were preceded by ram as well, either on the same day or the day before.

The threshold wind-speed conditions for each event were determined from the saltiphone and wind-speed data. Figure 3 shows the saltation flux as a function of wind speed during the *cierzo* wind erosion event of 25 July. Although some saltation occurred already at wind speeds above 9 m s$^{-1,}$ it is clear that significant saltation transport occurred only at wind speeds well above 10 m s^{-1}. The threshold wind speeds for the other events varied from about 8 m s^{-1} under dry conditions, to between 9 and 10 m s^{-1} under moist conditions. One notable exception is the short wind-erosion event of 24 September which had a much lower threshold wind speed. This event will be discussed later.

The effect of surface crusting on saltation transport for this particular soil can be determined from the measured soil surface and crust characteristics. For instance, using the data in Table II it is possible to calculate the amount of wind-erodible material present at the soil surface when no crust existed. Assuming that a soil layer of 1 mm thickness represents the soil surface, the mass of wind-erodible material in the CT plot was 464 g m^{-2}. On 28 July, only 11.6 g m^{-2} was measured on top of the surface crust (Table III), which is 97.5 per cent less. As the crust was not broken during wind-erosion events, this must mean that crust formation strongly limits the quantity of wind-erodible material. Figure 2 shows that the saltation flux on 25 July was generally well below 100 cts min^{-1}, in spite of high wind speeds. Compared with the short wind erosion event of 26 July 1996 (Figure 4), the observed fluxes were almost one order of magnitude lower with similar wind-speed conditions. In addition, the saltation flux in Figure 2 decreased after 12.00 hours, while the wind speed remained above threshold until about 17.00 hours. This clearly indicates that the supply of saltation material was limited.

Saltation material in the CT plot was also trapped with the 10 MWAC sediment catchers. The bottles of the catchers were changed on 31 July 1997, and hence the material trapped was from all four *cierzo* events. The other non-*cierzo* events were too small to have sufficient material trapped. For each catcher, a mass transport value (kg m^{-1}) was calculated with Equation (1). The obtained values were plotted as a function of distance from the non-erodible boundary at the upwind edge of the field during c*ierzo* wind (Figure 5).

Saltation transport increased from zero at the non-erodible boundary to a maximum value of 9.0 kg m^{-1}, which was reached after approximately 100 m. Moreover, at certain positions along the transect, notably at 70, 90 and 130 m, saltation transport deviated from the general increasing trend. This was most likely caused by differences in erodibility in front of those catchers. Assuming that the transect of 10 catchers is representative for the whole CT plot, the loss of saltation material during the four *cierzo* wind-erosion events was calculated from a simple mass balance to be 0.5 Mg ha^{-1}. Compared with other studies, Sterk and Stein (1997), for example, reported a loss of 45.9 Mg ha^{-1} during four convective storms in the Sahelian zone of Africa, the loss was very small. This can also be attributed to the wet and crusted soil conditions during the four c*ierzo* days.

The storm of 24 September 1997 was the only dry event without a crusted surface in the plots. The recorded saltation transport was the result of wind gusts during unstable weather conditions preceding rainfall. The one-minute average wind-speed values do not reflect the short, instantaneous gusts that mainly caused erosion (Stout, 1998). The maximum average wind speed measured was 7.3 m s^{-1} while most recordings were below 4.0 m s^{-1}. The sampling period of 1 min was too long to determine the instantaneous threshold wind speed for saltation, because the gusts were generally much shorter than 1 min. However, this short event does clearly indicate that when the soil surface is dry and without a crust, soil erodibility in the CT plot is high, and hence it is possible that severe saltation transport may occur. Also, the short event of 26 July 1996 (Figure 4), which was preceded by only 5 mm of rain during the two previous days, shows that saltation fluxes exceeding 1000 cts min^{-1} may occur when the soil is bare and without a crust. This again indicates that there is a potential risk of severe saltation transport in the CT plot when a strong *cierzo* wind blows immediately following the tillage operation.

CONCLUSIONS

The Ebro River valley in Central Aragón, Northeast Spain, experiences regularly strong *cierzo* winds from the west-northwest. These winds potentially cause saltation transport on bare and freshly tilled fields that have dry, flat and non-crusted surfaces. The general practice of a fallow year for moisture conservation in the rainfed cereal production systems favours the occurrence of wind erosion, as the soil surface is generally kept clear of weeds by repeating tillage.

The two tillage types that were compared in the experiment showed that chisel ploughing resulted in a less erodible soil surface than conventional tillage, i.e. mouldboard ploughing followed by the passage of a compacting roller. Saltation transport was never measured in the plot that had received chisel ploughing, while several saltation episodes were recorded in the conventional tillage plot. Hence, chisel ploughing can be considered a type of conservation tillage.

Surface crusting due to rainfall prevents the soil from severe erosion. The formed crusts during the experimental seasons were strong enough to reduce saltation transport significantly. No saltation transport was recorded after a dense and strong crust had formed during the first season. During the second season, crusting again limited saltation transport, but some erodible material on top of the crust was removed during four *cierzo* days. This saltation transport resulted in a soil loss of 0.5 Mg ha^{-1} only, which is an acceptable level in terms of soil damage.

Finally, it is concluded that the occurrence and magnitude of saltation transport in the Ebro River valley of Central Aragón is largely dependent on the type of soil tillage, the timing of the tillage operations, the distribution of rainfall, the severeness of soil-surface crusting and the frequency of strong c*ierzo* days. The results indicate that potentially severe soil losses may occur on days with strong *cierzo* wind, and the soil is dry, bare, and recently tilled with a compacting roller.

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Table I. Physical and chemical properties of the topsoil at the experimental field

	Particle size distribution†							
Depth (m)	Sand (%)	Silt (%)	Clay (%)	Acidity (pH)	EC (dS m^{-1})	OM (%)	$CaCO_3$ (%)	Gypsum (%)
0–0·2	19·3	67·6	13·1	7·9	2·2	1·8	33·7	23·6
0·2–0·4	18·4	68·3	13·3	7·9	2·4	1·7	34·0	23·6

†Sand 50–2000 μm, silt 2–50 μm, clay < 2 μm.

Table II. Soil-surface characteristics in the conventional tillage (CT) and reduced tillage (RT) plots immediately after the initial tillage operation during the 1997 field experiment

Tillage	Bulk density ($Mg\ m^{-3}$)	Wind-erodible fraction† (%)	Soil cover			Frontal area			Roughness 292·5° (%)
			Residues (%)	Clods‡ (%)	Pebbles (%)	Residues ($cm^2\ m^{-2}$)	Clods ($cm^2\ m^{-2}$)	Pebbles ($cm^2\ m^{-2}$)	
CT	1·20 a§	38·7 a	0·18 a	4·06 a	0·03 a	6 a	216 a	4 a	6·4 a
RT	1·03 b	26·5 b	13·29 b	11·13 b	0·32 a	483 b	967 b	15 a	14·3 b

†Aggregates < 0·84 mm in diameter.

‡Aggregates > 38 mm in diameter.

§Within columns, means followed by the same letter are not significantly different at $p < 0{\cdot}05$.

Table III. Soil crust characteristics under conventional tillage (CT) and reduced tillage (RT) on 28 July 1997

Tillage	Thickness (mm)	Penetration resistance† (MPa)	Aggregate mass	
			Total ($g\ m^{-2}$)	<0.84 mm ($g\ m^{-2}$)
CT	4·76 a‡	0·61 a	84·62 a	11·63 a
RT	5·01 a	0·42 b	15·85 b	6·01 b

†Maximum penetration resistance.

‡Within columns, means followed by the same letter are not significantly different at $p < 0.05$.

Table IV. Date, time and wind characteristics of periods with significant saltation transport in the conventional tillage (CT) plot during the 1997 field experiment

Date	Time (h.min)	Wind speed ($m\ s^{-1}$)	Wind direction (degree)	Cierzo
17 July	12.00–21.00	11·26	304·0	Yes
18 July	15.00–24.00	11·02	306·3	Yes
24 July	15.00–20.00	8·27	296·1	Yes
25 July	8.30–18.30	10·59	296·6	Yes
30 July	21.43–21.55	9·52	85·1	No
4 August	16.50–17.10	8·25	261·7	No
7 August	17.00–17.35	9·09	111·9	No
17 August	23.45– 0.00	7·83	53·8	No
27 August	18.52–19.30	9·90	335·5	No
24 September	19.50–20.08	4·59	223·0	No

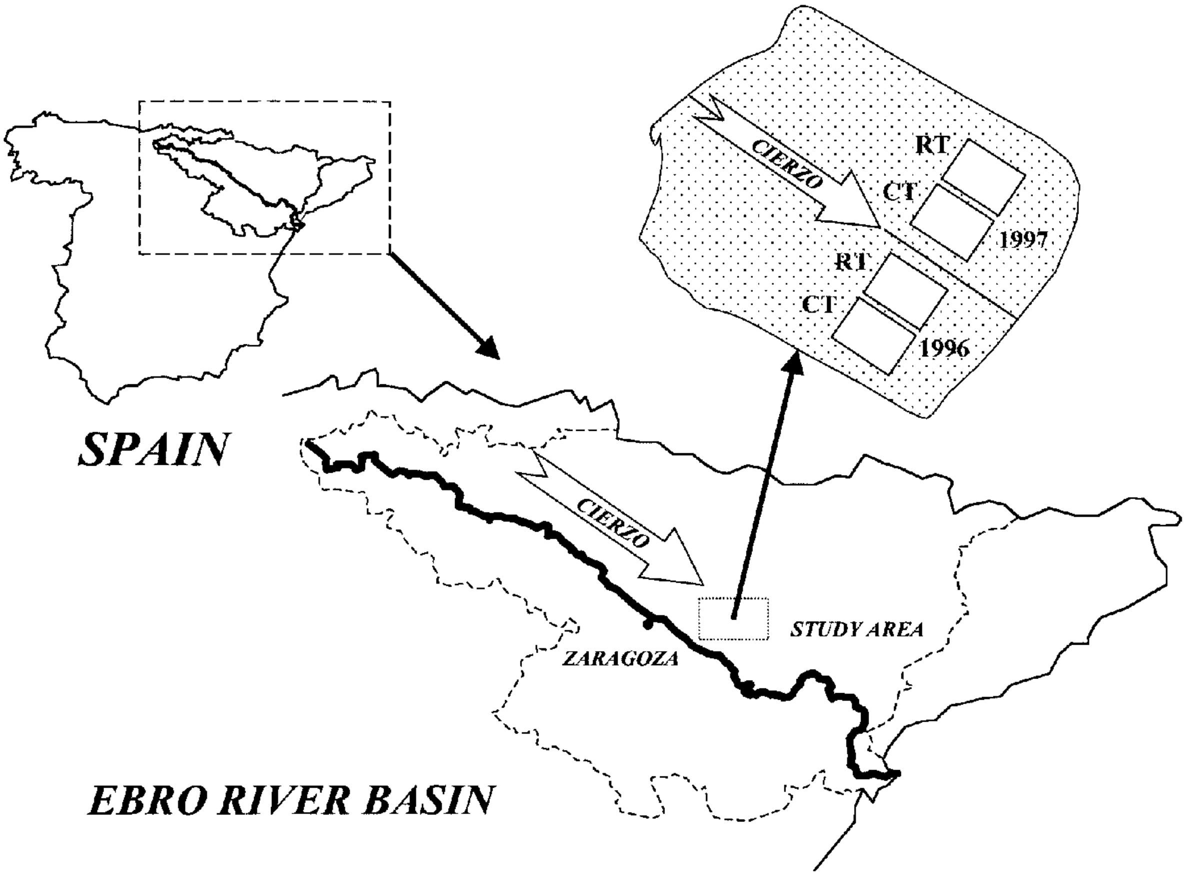

Figure 1. Location of the experimental field and layout of the field plots

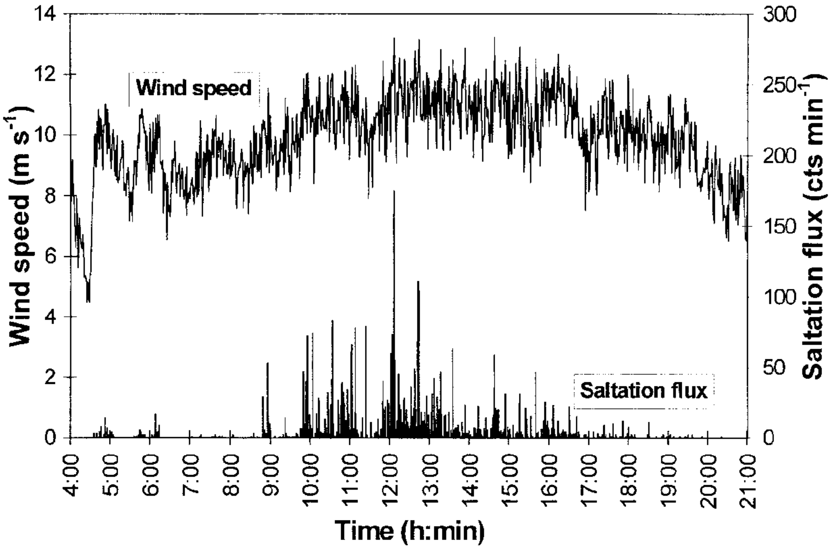

Figure 2. Wind speed at 2·0 m and corresponding saltation flux at 0·1 m in the CT plot during the *cierzo* wind-erosion event on 25 July 1997

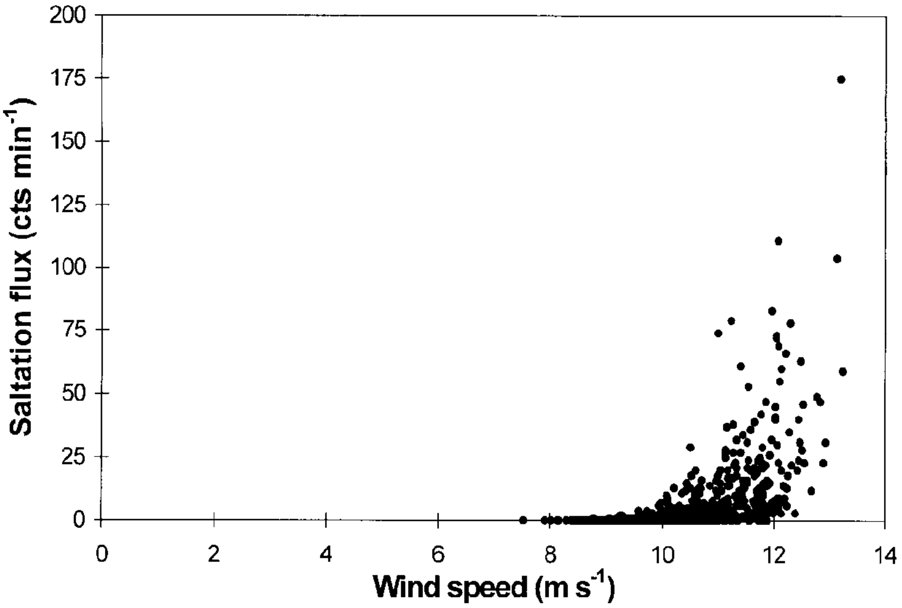

Figure 3. Relationship between wind speed at 2·0 m and saltation flux at 0·1 m in the CT plot during the cierzo wind erosion event on 25 July 1997

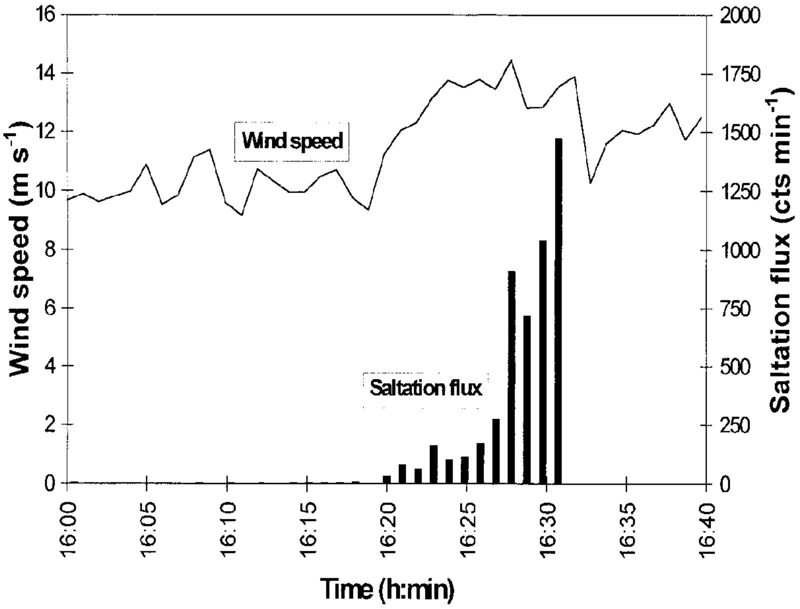

Figure 4. Wind speed at 2·0 m and corresponding saltation flux at 0·1 m preceding a convective rainstorm in the CT plot on 26 July 1996

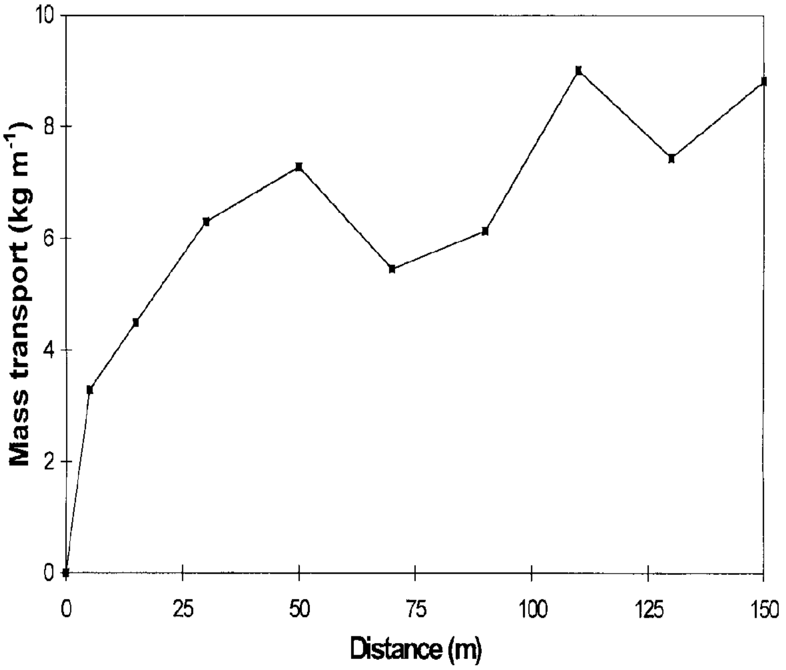

Figure 5. Total mass transport (M) during four cierzo wind-erosion events as a function of distance downwind from the non-erodible boundary of the field