

A study on the fragmentation of saltating particles along the fetch distance during wind erosion

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ABSTRACT

PM₁₀ emission largely depends on the characteristics of the saltation process, which involves the movement of aggregate and isolated particles. Studies analyzing the relationship between the fragmentation of saltating aggregates and the dust emission along the fetch distance are very scarce. The objective of the present study was to analyze, on a loamy texture soil, the changes in the size distribution of the eroded sediment along the fetch distance under field conditions. Changes in the particle size distribution of the transported material were measured at four different heights above the soil surface every 25 m on a 200 m plot, during three strong wind erosion events. Statistically significant differences were found both for particle size distribution and aggregation when comparing the eroded sediment at the windward and leeward sides of the experimental plot. A greater proportion of coarser particles was found as the distance traveled by the eroded sediment increased. From the change in average particle size distribution at the beginning and at the end of the 200 m experimental plot, it was estimated that around 12% of the particles smaller than 62.5 μm were lost by vertical transport (dust plume) producing an average concentration of 48 μg m⁻³ at 2 m height and 200 m fetch. Under the conditions of this experiment, a soil aggregate transported by saltation was fragmented at a rate of 38% every 100 m traveled ($R^2 = 0.88$; $p < 0.001$). Particle size analysis of the eroded sediment and open-air PM₁₀ concentration measurements indicated that the fragmentation of aggregates during saltation can be considered as the main mechanism of dust emission on this soil.

1. Introduction

The wind erosion of the soil involves two main mechanisms of transport of the eroded material: saltation, which represents more than 85% of the total erosion of the soil (Bagnold, 1941), and suspension, which produces dust clouds (Shao, 2008) and can also comprise ≥90% of total erosion in some regions of the world (Sharratt et al., 2007). A complex interaction exists between both processes (Whicker et al., 2014).

It is widely accepted that PM₁₀ emission largely depends on the characteristics of the saltation process (e.g., Houser and Nickling, 2001; Kang et al., 2011; Singh et al., 2012). PM₁₀ emission is produced by the transference of the kinetic energy of saltating particles to the soil aggregates lying on the soil surface (Gillette, 1974; Shao et al., 1993; Alfaro et al., 1997; Kok et al., 2012), producing their abrasion and fragmentation (Kun and Herrmann, 1999). On the other and, some studies have shown that the direct emission of PM₁₀ from crusted

surfaces may be important in certain environments (Kjelgaard et al., 2004a, 2004b). Several theories have been developed that try to explain the processes and mechanisms of aeolian dust emission (e.g., Marticorena and Bergametti, 1995; Shao, 2008; Kok, 2011), and they all agree that sandblasting and fragmentation of the aggregates is generally the main process for dust emission. Kok (2011) proposed the “Brittle Fragmentation Theory” in which he argues that the emission of fine particulate matter (dust) is produced mainly by the fragmentation of soil aggregates and which are in saltation. The author makes an analogy between the fragmentation processes of aggregates with the fragmentation of fragile materials such as glass, deriving from an analytical expression for the size distribution of emitted dust. Also, he adduces that the process of fragmentation of aggregates is the main mechanism of emission of fine particles from the soil. Avecilla et al. (2016) found that for fine textured soils, the relative capacity of emitting PM₁₀, considering the total amount of eroded material, is greater than in coarser soils. Similar results were found by Hagen et al. (2010)

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and Aymar et al. (2012). It is well-known that the transport by saltation destroys soil aggregates, initiating in this way the suspension of dust (Alfaro et al., 1997; Shao, 2008). The amount of emitted PM_{10} can increase as a function of the energy transferred to the soil surface, but this increment should also depend on the amount and composition of the aggregates involved in the saltation process. There are very few studies conducted under field conditions that analyze the relationship between the fragmentation of the saltating aggregates and the dust emission along the fetch distance.

It is known that on agricultural soils of Argentina the wind erosion process can cause a decrease in the proportion of the finer size fractions (silt and clay) due to deflation (Iturri et al., 2016). The same trends were found by Zhao et al. (2006) on agricultural sandy soils of northern China. Although there are studies that have discussed mainly the changes in particle size with height (Shao and Mikami, 2005; Li et al., 2008), little is known about the changes in the composition of the material transported by saltation along the fetch distance (distance from the upwind margin of an erodible surface to a point of interest; Delgado-Fernandez, 2010). On finer, well-aggregated soils, the aggregates transported by saltation can be progressively destroyed as the transport distance increases, hence the proportion of aggregates present in the saltation fraction should decrease to some extent along the fetch distance.

The aim of the present study was to make a first attempt to describe and analyze the changes in the size composition of the eroded sediment along the fetch distance under field conditions, considering its possible implications as a link between the wind erosion and the dust emission process.

2. Materials and methods

2.1. Study site and soil properties

This study was performed at the Anguil Experimental Station of the National Institute of Agricultural Technology (INTA, 36° 32' 27" S, 63° 59' 29" W), Argentina. The soil at the experimental plot is an Entic Haplustoll with a loamy texture (Soil Survey Division Staff, 1993). The main characteristics of the soil are presented in Table 1.

The mean annual rainfall of the study region is 760 mm and the accumulated annual evaporation is 1577 mm. The mean annual wind velocity is 2.4 m s^{-1} , and peak wind speeds take place between August and December. Maximum wind velocity can exceed 16 m s^{-1} (Casagrande et al., 2012).

Four subsamples (2.5 cm topsoil) were collected every 50 m along the length of the experimental plot. The samples were mixed to obtain a representative, unique sample. On this sample the following parameters were determined: textural composition by means of wet sieving and the Robinson pipette method (Gee and Bauder, 1986), organic matter (OM) content by means of the Walkley and Black (1934) and the free lime content (CaCO_3) by calcimetry (Schlichting and Blume, 1966).

The grain size distribution of a sample from the topsoil (2.5 cm) was also determined with a Malvern Mastersizer laser particle counter (Model 2000) under two conditions: with previous dispersion (D), and

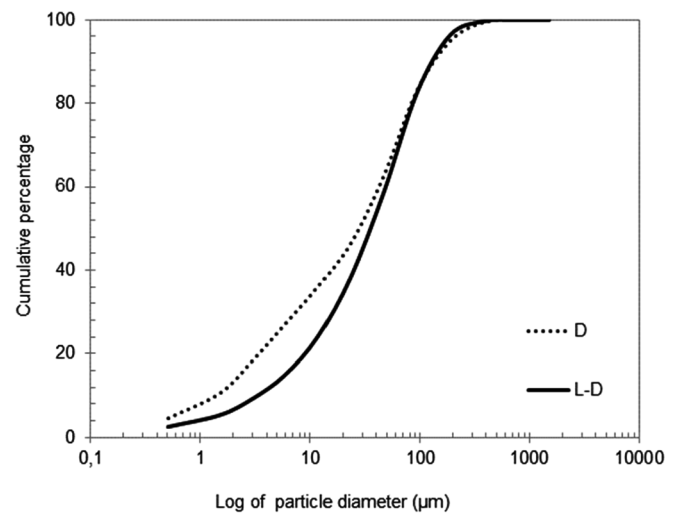


Fig. 1. Particle size distribution determined with the laser counter on dispersed (D) and less-dispersed (LD) soil samples.

with less previous dispersion (LD). The D treatment comprised the destruction of the free carbonates with 6% acetic acid and of the organic matter with hydrogen peroxide, and an ultrasound treatment during 20 s. The LD treatment consisted of placing the samples in water only, without additional modifications. (Fig. 1).

Fig. 1 shows the particle size distribution curves obtained with dispersion (D) and with less dispersion (LD) of the soil surface samples. Note that for particle size range between 0.5 and $60 \mu\text{m}$, the curves differ because of the effect of different dispersion treatments. These results indicate that within this range, aggregates could be potentially destroyed also under natural conditions (saltation), to produce finer particles (dust).

Additionally, during each wind-erosion event, samples were taken with a wide shovel without disturbing the topsoil (2.5 cm) and then they were placed in a $30 \times 30 \text{ cm}$ tray to be air-dried until they were completely dry. Then the macro-aggregate size distribution (Fig. 2) was then determined by means of a rotary sieve (Chepil, 1962).

2.2. Experimental design

An $80 \times 200 \text{ m}$ plot (Fig. 3) was delimited, with the longer side oriented N-S, which is the prevailing wind direction in this region (Casagrande et al., 2012). The plot was tilled with a disc plow and

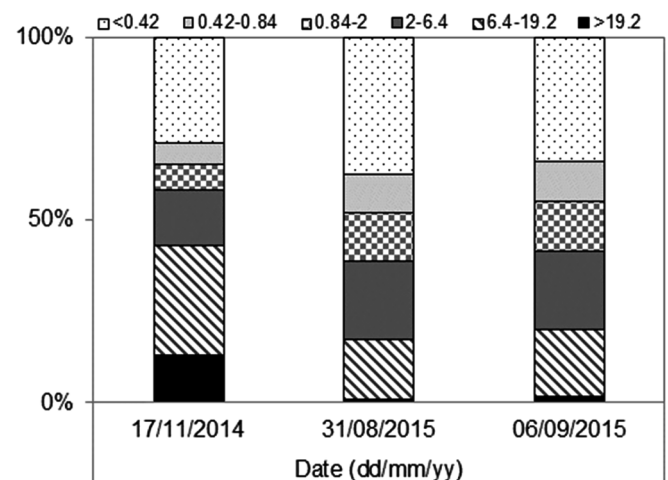


Fig. 2. Macro-aggregate size distribution of the 2.5 cm topsoil for each wind-erosion event.

Table 1
Main characteristics of the studied soil.

Grain size distribution (g kg^{-1})	Clay ($< 0.002 \text{ mm}$)	171.6
	Silt ($0.002\text{--}0.053 \text{ mm}$)	355.5
	Very fine sand I ($0.053\text{--}0.074 \text{ mm}$)	129.3
	Very fine sand II ($0.074\text{--}0.105 \text{ mm}$)	129.1
	Fine sand ($0.105\text{--}0.250 \text{ mm}$)	173
	Medium and coarse sand ($0.250\text{--}2 \text{ mm}$)	41.5
OM (g kg^{-1})		28.2
CaCO_3 (g kg^{-1})		8.8

OM = Organic matter.

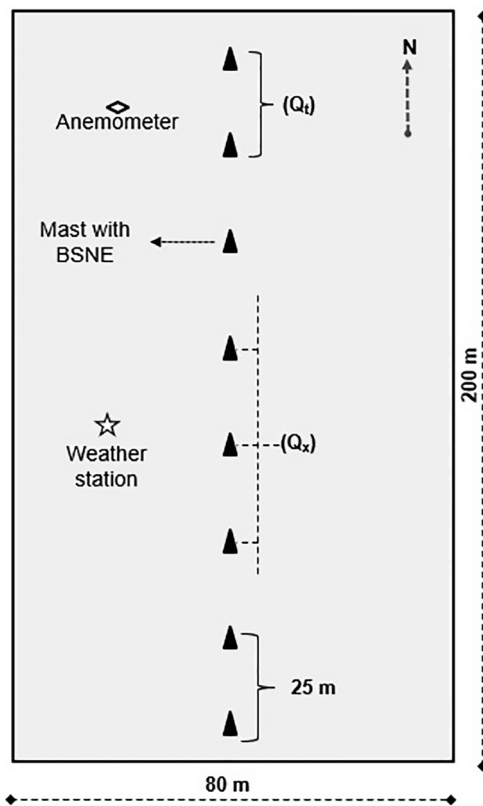


Fig. 3. Experimental plot lay-out. Q_t is the horizontal mass transport measured at leeward border of the plot and Q_x is the horizontal mass transport measured at each sampling point (25, 50, 75, 100, 125, 150, 175 and 200 m).

rotary tiller in order to maintain the surface with minimal roughness and without vegetation cover. The plot was surrounded by permanent plant cover (herbaceous vegetation and straw with an average height of 0.5 m), so as to guarantee that sediment movement occurred only within the experimental plot boundaries.

Three high intensity wind-erosion events were selected (Table 2). Wind-eroded sediment was collected with BSNE clusters located at 8 points along an N-S transect within the plot. The sampling points were separated by 25 m (Fig. 3). At each sampling point, 4 BSNE samplers were placed at 0.135, 0.2, 0.5 and 1 m height each, on a mast with a wind vane. Herein, eroded sediment is defined as the particles (aggregated and isolated particles) that were collected from 0.135 to 1 m above the soil surface during the erosion events.

2.3. Calculations

The horizontal mass transport (Q) at each sampling point was calculated by integrating an exponential curve, previously fitted to the mass transport values (q) across the height, using the Curve Expert® 1.3

program (Hyams, 2005) Eq. (1).

$$Q = \int_0^1 q^{bz} dz \quad (1)$$

where, Q is the horizontal mass transport in kg m^{-1} , q is the horizontal mass flux (kg m^{-2}), and b represents the decay rate across the height. Details on this method and the convenience of applying it under field conditions are described in Panebianco et al. (2010).

The total horizontal mass transport (Q_t) measured during an erosion event (Table 2) was determined by averaging the values measured at the two leeward clusters (175 and 200 m). Two points were used for reducing a possible “border effect” on the mass transport near to the plot boundary.

PM_{10} concentration was measured at the entrance (windward side) and at the exit (leeward side) of the plot at a height of 2 m (Table 2) using a Kanomax digital light scattering dust monitor (model 3443). The Kanomax 3443 dust monitor measures PM_{10} in a range of 0.001 to 10000 mg m^{-3} with an inflow of 1 L min^{-1} .

A wireless weather station at the center of the plot recorded the average wind velocity, the maximum wind speed, the wind direction, the air temperature and the air relative humidity, the values were recorded at a frequency of 5 min at 2 m height. Soil temperature was measured at 0.05 m depth at a frequency of 10 min (Table 2).

During each wind-erosion event, topsoil samples (2.5 cm) were taken, and soil water content was determined by gravimetry. Topsoil water contents did not exceed 4% (Table 2). These values are considered to have only limited effects on erosion and PM_{10} emission (Fecan et al., 1999; Clausnitzer and Singer, 2000; Sharratt et al., 2013). The presence or absence of superficial crusts (crust occurrence) was observed visually (Table 2).

The duration of an erosion event was determined as the period during which the wind velocity exceeded 5 m s^{-1} at 2 m high (Fryrear et al. 1998). Measurement periods did not exceed 24hs for avoiding wind direction deviations from the direction of the sampling transect located along the center line of the plot.

Fig. 4 shows the frequencies of the wind directions during each wind-erosion event. This figure confirms that the wind direction was aligned parallel with the main axis of the plot.

2.4. Disaggregation of the eroded sediment along the distance

To examine the changes in the aggregation rate of the eroded sediment along the fetch distance, a granulometric analysis was performed with a Malvern Mastersizer laser particle counter (Model 2000). It was necessary to make a combined sample by adding the content of the BSNE clusters at each sampling point (mast), because the amount of mass collected at each height was not enough to be read separately in the particle counter. Two treatments were made to the sediment samples before reading them with the particle counter: fully dispersed (D) and less dispersed (LD). The dispersion procedure was described in section 2.1. For the fully dispersed analysis (D), the sample was sonicated, and the organic matter and free carbonates were previously eliminated. But for the less dispersed analysis (LD) the samples were

Table 2
Values of the variables measured during the wind-erosion events.

Event Date (dd/mm/yy)	Duration (minutes)	W _a (m s ⁻¹) (SD)	W _m	D _w	S _{wf} (%)	T _{soil} (°C)	T _{air}	RH (%)	Crto	Q _t (kg m ⁻¹)	PM ₁₀ concentration Windward Leeward (µg m ⁻³)	
17-11-2014	430	10.1(1.5)	17(1.9)	N(0°)	2.7	27	36	21	Yes	19.7	11	90
31-08-2015	395	9.3(1.0)	15(1.1)	S(180°)	3.7	16	18	43	No	3.1	5.7	21
06-09-2015	445	8.6(1.4)	16(1.8)	N(0°)	2.8	16	22	37	No	4.1	3.7	54

W_a : average wind velocity; W_m : maximum wind velocity; SD: standard deviation; D_w : predominant wind direction; S_{wt} : soil water contents; T_{air} : air temperature; RH: air relative humidity; T_{soil} : soil temperature at 0.05 m depth; Crto: crust occurrence; Q_t : total horizontal mass transport. PM_{10} concentration: average values recorded during the measurement period of the erosive event.

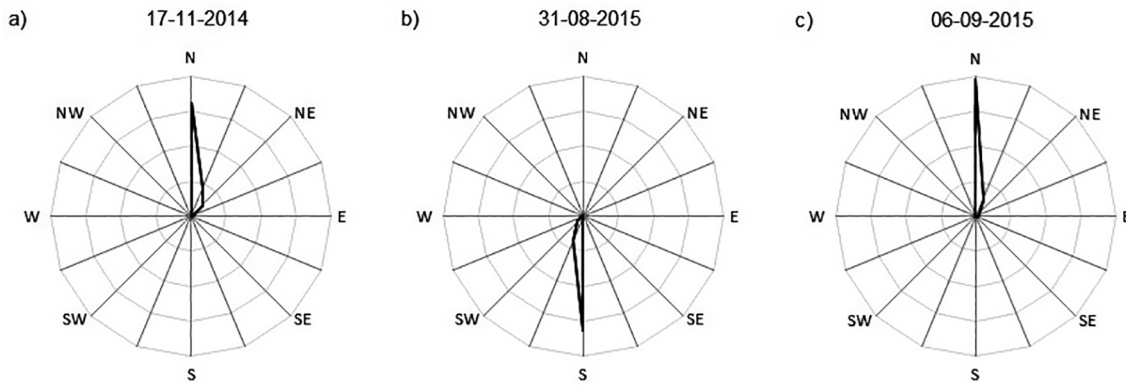


Fig. 4. Frequencies of wind directions during the wind-erosion events: a) 17-11-2014, b) 31-08-2015, and c) 06-09-2015.

only introduced in water before being read, without extra modifications, for measuring the approximate size distribution of the aggregates that were present in the eroded sediment. Comparing these two analysis, produces an estimation of the potential disaggregation of the sediment at different points and moments of an erosion event. This methodological approach was already used in previous studies (Avecilla et al., 2015, 2016, 2017; Panebianco et al., 2016). The Malvern Mastersizer was also used in other studies (Ojelede et al., 2012; Klose et al., 2017). Although the method has the disadvantage of reading the samples a liquid medium, the organic matter and free carbonates act as binders within the aggregates, reducing the disaggregation produced by the effect of the water. Results obtained with this method for this soil and others of contrasting textures can also be seen in Avecilla et al. (2015, 2016). Unfortunately, we do not have any device for dry sieving, that allow us to obtain a detailed aggregate size distribution, such as the micromesh sieves (Stout and Zobeck, 1996; Hagen et al., 2010) that can be compared to the laser counter in terms of accuracy, especially for the finer fractions. The method proposed within this work focuses on trying to generate contrasting dispersion conditions, for comparing the fully-dispersed to the non-dispersed particle size distribution, which is a theoretical proportion used in dust emission models. However, this proportion is generally considered for isolated particles from soil surface samples but not for the saltating particles under real wind-erosion conditions, as we did herein.

The relative proportion of particle sizes before and after dispersion of the eroded sediment was compared using the following equation:

$$\text{Agr}_{(x)} = (\text{clay}_D - \text{clay}_{LD}) + (\text{silt}_D - \text{silt}_{LD}) \quad (2)$$

where, $\text{Agr}_{(x)}$ is the aggregation (%) of the material collected at point x ; clay_D and clay_{LD} are the clay-sized particle (0–3.9 μm , in %) content in the sample after D and LD; and silt_D and silt_{LD} are the silt size particle (3.9–62.5 μm , in %) content after D and LD. The fractions of both clay and silt were taken to determine the aggregation of eroded sediments due to the fact that some authors (Buschiazzo et al., 1995; Iturri and Buschiazzo, 2014) have found that on loess soils of the central region of Argentina, enriched with volcanic ash, the electrochemical properties that can improve aggregation are enhanced not only by clay, but also by silt.

Additionally, a relative aggregation index was calculated at each sampling point, as the ratio between the aggregation of the saltation fraction collected and the horizontal mass transport measured ($\text{Agr}_{(x)}/Q$).

Actually, there are no standardized procedures for determining and comparing fully-dispersed to non-dispersed samples in the wind erosion research area. In the worst case, as many other methods, the method presented here does not need to be considered as an absolute measurement, but it can be used as an approximation for comparing samples that have received the same dispersion and non-dispersion treatments (relative measurement).

2.5. Statistical analysis

The correlation between variables was analyzed using linear regression. The differences between the particle size distribution of eroded sediment and the aggregation at different locations were analyzed using a test for comparison of mean values using the LSD Fisher test ($\alpha = 0.1$). To perform this analysis we used the INFOSTAT software (Di-Rienzo et al., 2002; FCA-UNC, Córdoba, Argentina).

3. Results and discussion

3.1. General pattern of mass fluxes at different heights along the fetch

Fig. 5 shows the horizontal mass flux (q) at each sampling height and the horizontal mass transport at each distance (Q) during all the events. Hence the average horizontal mass transport (Q) increased exponentially with the distance ($R^2 = 0.91$; $p < 0.01$). The horizontal mass flux (q) at every sampling height increased with the fetch distance, fitting linearly to the fetch distance at every height above the soil surface ($R^2 = 0.86, 0.86, 0.94$ and 0.86 for $0.135, 0.3, 0.5$ and 1 m respectively, $p < 0.001$). However, the amount of eroded material increased along the fetch distance but at different rates depending on the height above the soil surface. The slope of the correlation equation that fits q to the fetch distance at 0.135 m above the soil surface was 30 times greater than the one for 1 m height, 10 times greater than the one for 0.5 m height and 4 times the one for 0.3 m. This fact is related to the maximum transport capacity of the wind. The transport capacity of the wind increases with height because of the greater wind speed and the lighter sediment load, and therefore the distance at which the carrying capacity of the wind is saturated also increases with height above the soil surface. Considering a continuous process under relatively stable conditions (smooth surface and high wind speed and gustiness), this difference produces the typical development of a dust plume that can be observed on eroding fields, where the horizontal movement of the particles predominates on the lower heights (below the saltation layer), and the vertical one is progressively more visible away from the soil surface and downwind from the beginning of the eroding area. As the entrainment of finer particles into the wind flux above the saltation layer is more efficient away from the soil surface, particles move forwards and upwards through the boundary layer producing a dust column that evolves more or less diagonally depending on the atmosphere conditions: forward due to the direction of the wind, and up due to the vertical gradient of the transport capacity of the wind.

The concept that relates the maximum transport capacity of the wind and the distance is the critical fetch distance. It is generally considered that at this point, the wind is saturated and the mass load does not increase with the distance further from this point. However, this theoretical concept is still very controversial.

The concept of equilibrium-saltation and critical fetch distance has

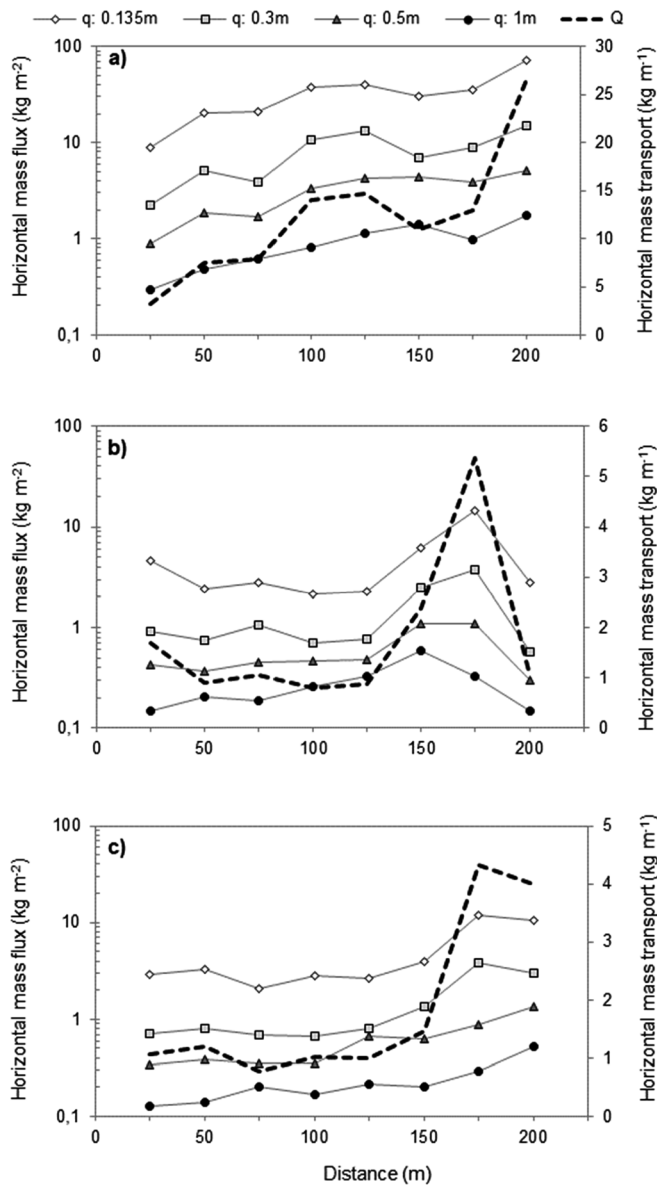


Fig. 5. Horizontal mass flux (q) at four measured heights (0.135, 0.3, 0.5 and 1 m) and horizontal mass transport (Q) as a function of the fetch distance during three different wind erosion events: a) Nov. 17, 2014, b) Aug. 31, 2015 and c) Sep. 06, 2015.

also been discussed and questioned by many authors, because it strongly depends on the soil texture, the surface conditions (Gares et al., 1996; Stout and Zobeck, 1997; Jackson et al., 2006; Duran et al., 2011) and the wind speed (Shao and Raupach, 1992; Selmani and Valance, 2018). Moreover, especially under field conditions it is almost impossible to achieve stationary conditions both for the surface and for the wind speed. The wind is considered the main driver of the saltation-emission process, but wind speed over an eroding field is prone to turbulent fluctuations that occur in a very short time scale (Kok et al., 2012), and this gustiness produces a high intermittency of the saltation process (Stout, 1990; Stout and Zobeck, 1997). Hence, the equilibrium of the saltation process can change constantly during an erosion event (Duran et al., 2011; Valance et al., 2015), also affecting other stationary-condition related concepts, as the critical fetch distance.

In a thorough review made by Irene Delgado-Fernandez (2010) about the fetch distance problem, an attempt was made to distinguish between studies made under equilibrium and disequilibrium conditions. This classification included the type of transport system (supply

limited or not), and the time and the space involved in the study. However, the author collects critical fetch-distance values from many studies, ranging from negligible to more than 50 m, and also some equations for describing the critical fetch, that stretch from linear and exponential to sinusoidal functions. Again, this thorough review concludes that primary factors determining the critical fetch (or “stationary transport” distance) are sediment-supply dependent, and that there is no concluding description of the critical fetch distance, even for beaches which are characterized by much more homogeneous conditions than agricultural soils. Natural transport systems driven by the wind are generally supply-limited (Shao, 2008), but despite the many works cited and discussed herein, the discussion generally lacks the inclusion in the transport system analysis of the combination between the sampling time and the wind speed, which is also crucial for determining the distance traveled by the wind-eroded sediment and the moment (time and distance) where the supply limitation becomes determinant.

Concerning the critical-fetch distance or stationary-saltation problem related to the mass transport (Q), the results presented herein are within the range of the results and values found by other authors, but we emphasize in the different increment rates of the mass flux (q) across the height along the sampling field. Hence, critical distances or stationary state conditions, are also sampling height-dependent, at least under this 200 m agricultural field conditions and on a typical, daily wind-erosion event.

3.2. Changes in particle size distribution of the eroded sediment along the fetch in the dispersed samples

Fig. 6 shows the particle size distribution of the dispersed samples of the eroded sediment at the beginning (windward side) and the end (leeward side) of the plot, for the three wind-erosion events. The amount of fine particles ($< 62.5 \mu\text{m}$) was higher at the windward side than at the leeward side. Significant statistical differences ($p < 0.1$) between windward and leeward side were found for the particle size between 1.5 and $100 \mu\text{m}$.

The amount of particles between 500 and $2000 \mu\text{m}$ was negligible, due to the low content of particles of this size range in the topsoil (Table 1, Fig. 1). Moreover, the particles in this size range move mainly by creep (Dong et al., 2002), below the lower sampling height used in this study.

At the beginning of the plot (windward side) between 67 and 76% of the eroded sediment were particles smaller than $62.5 \mu\text{m}$ (76.3% for Nov.17, 2014; 72.4% for Aug. 31, 2015; 67.3% for Sep. 06, 2015),

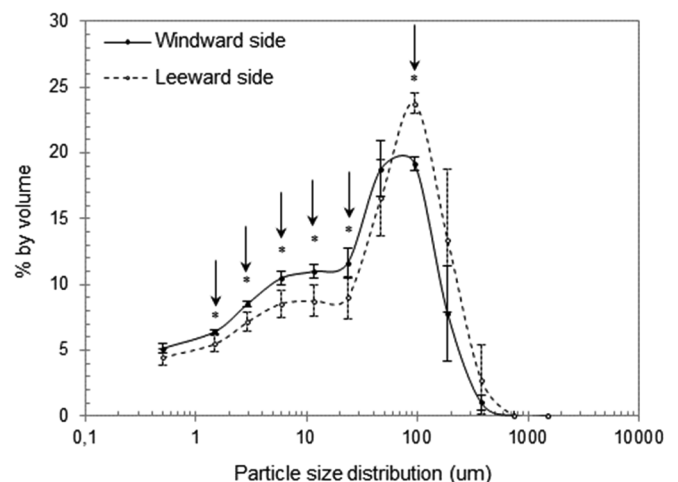


Fig. 6. Particle size distribution of the eroded sediment at the beginning (windward side) and the end (leeward side) of the plot during three events (dispersed samples). The asterisks indicate significant statistical differences ($p < 0.1$) between windward and leeward for the same particle size.

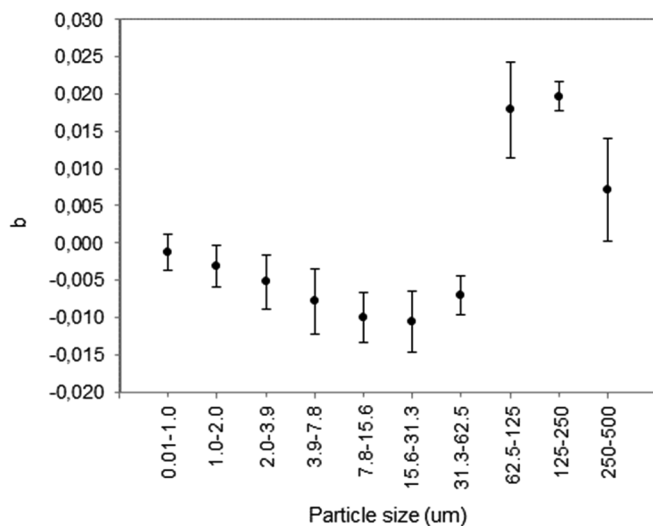


Fig. 7. Slope (b parameter) of the linear regressions between the content (%) of the different particle sizes and the fetch distance during three wind-erosion events. Error bars represent standard deviations.

while between 23 and 34% were particles were bigger than 62.5 μm. At the end of the plot (leeward side) between 50 and 66% were particles smaller than 62.5 μm (65.7% for Nov.17, 2014, 64.3% for Aug. 31, 2015, 50% for Sep. 06, 2015), and between 34 and 50% were particles bigger than 62.5 μm.

The difference between the particle sizes found at the beginning and at the end of the plot indicate that there was a decrease of 10.6, 8.1 and 17.3% (12% on average) of the particles smaller than 62.5 μm for the events of Nov.17, 2014, Aug. 31, 2015 and Sep. 06, 2015 respectively. Of course, there was an increase of the same proportion of particles bigger than 62.5 μm (sand grains). Considering that particles smaller than 50 μm are considered transportable by suspension (Gillette and Walker, 1977; Tegen and Lacis, 1996; Zender et al., 2003), it can be assumed that on average, 12% of the fraction smaller than 62.5 μm was entrained into suspension while moving along the plot during the wind-erosion events.

Fig. 7 shows the slopes of the linear regressions between the particle size distribution of the eroded sediment and the fetch distance. A higher slope value indicates a larger change of the proportion of a certain size fraction along the fetch distance. The correlation coefficient of the linear regression was not statistically significant in some cases ($p > 0.001$). Therefore, the slope of the adjusted line was considered only as an indicator of the general change in the particle size distribution of the eroded material along the fetch.

The value of the slope was negative for particle sizes smaller than 62.5 μm, indicating a decrease in the proportion of this size fractions as the distance traveled by the eroded sediment increased. However, the average decrease differed along the distance according to particle size: 0.13% for the 0.01–1.0 μm range, 0.52% for 2.0–3.9 μm range and 1.06% for the 15.6–31.3 μm range. The lower decrease of the size range between 0.01 and 3.9 μm (0.32% on average), as compared to the fraction 3.9–62.5 μm (1 per cent on average), can be attributed to the strong cohesive forces that keep the smaller particles attached to other particles (Castellanos, 2005; Merrison, 2012). This effect hinders the transport of these size fractions as isolated particles.

Detachment and release of fine particles occurs during saltation, because of the impact of the aggregates with the soil surface (Alfaro et al., 1997; Bullard et al., 2004; Hagen, 2004). According to the literature (Zender et al., 2003; Kok et al., 2012), and the results presented in 3.2, the particles smaller than 50 μm can be easily transported by suspension, above one meter height, which is the sampling height used herein. For this reason, the content of this size fraction in the samples

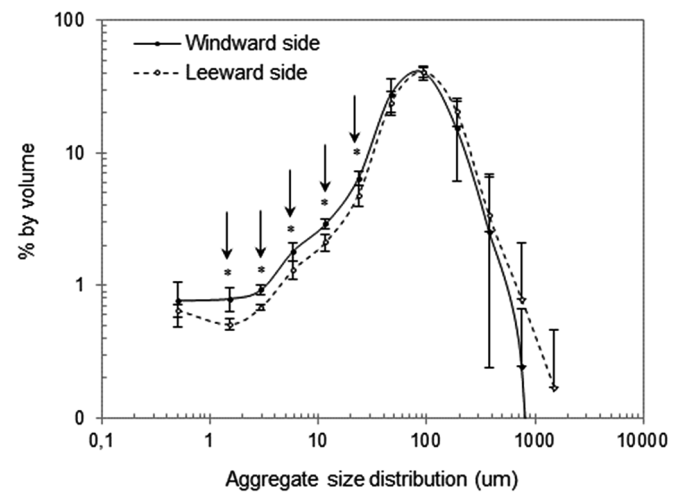


Fig. 8. Aggregate size distribution of the eroded sediment at the beginning (windward side) and the end (leeward side) of the plot during three events (non-dispersed samples). The asterisks indicate significant statistical differences ($p < 0.1$) between windward and leeward for the same aggregate size.

decreased along the fetch distance. On the contrary, there was an increase of the proportion of particles bigger than 62.5 μm along the fetch distance: 1.79% for the 62.5–125 μm range, 1.97% for the 125–250 μm range and 0.71% for the 250–500 μm range

3.3. Changes in the aggregate size distribution of the eroded sediment along the fetch in the less dispersed samples

When analyzing the aggregate-size distribution curve determined from less dispersed samples, we consider the particles mostly as aggregates, but it should be considered that the values can comprise both aggregates and isolated mineral particles as well. The Fig. 8 shows the aggregate size distribution of the eroded sediment (aggregates and particles in their natural condition) at the windward and at the leeward side of the plot. There was a statistically – significant greater proportion of aggregates between 1 and 30 μm ($p < 0.1$) at the windward side. Although no statistically significant differences were found for the coarser fractions, we observed an increasing trend in the proportion of large – sized aggregates along the fetch distance. However, as shown in the dispersed samples (Fig. 7), the sediment accumulated at the end of the plot was mainly sand grains, not aggregates.

As shown in Fig. 8, results presented herein were statistically significant for the finer fraction only. However, it should be taken into account that minor differences in the particle and aggregate size distributions between events can occur due to the variable physical condition of the soil surface. Additionally, it must be highlighted that on the field the avalanches of sediment and the consequent dust plumes are not a continuous process as in a wind tunnel, but produced by the intermittent wind gusts (Stout and Zobeck, 1997), which produce a repetitive “sweeping effect” over the plot. This effect differs between and within erosion events, producing variability in mass transport patterns. Moreover, it is well known that wind erosion of agricultural soils is a complex process that involves many variables. To show the differences between the studied wind-erosion events, each one of them is described in detail below.

During Aug. 31 and Sep 6, 2015 the soil surface was loose as a consequence of a recent tillage operation (Fig. 9b and 9c; Fig. 2), hence this condition favored the movement of coarser particles. On the contrary, during the Nov. 17, 2014 event (Fig. 9a; Fig. 2), the soil surface was or crusted, favoring the movement of finer particles. Particularly, during the Nov 17, 2014 a physical crust was present on the soil surface because of a previous rain. Under these special conditions, a high proportion of fine particles (7.8–31.3 μm) were transported by the

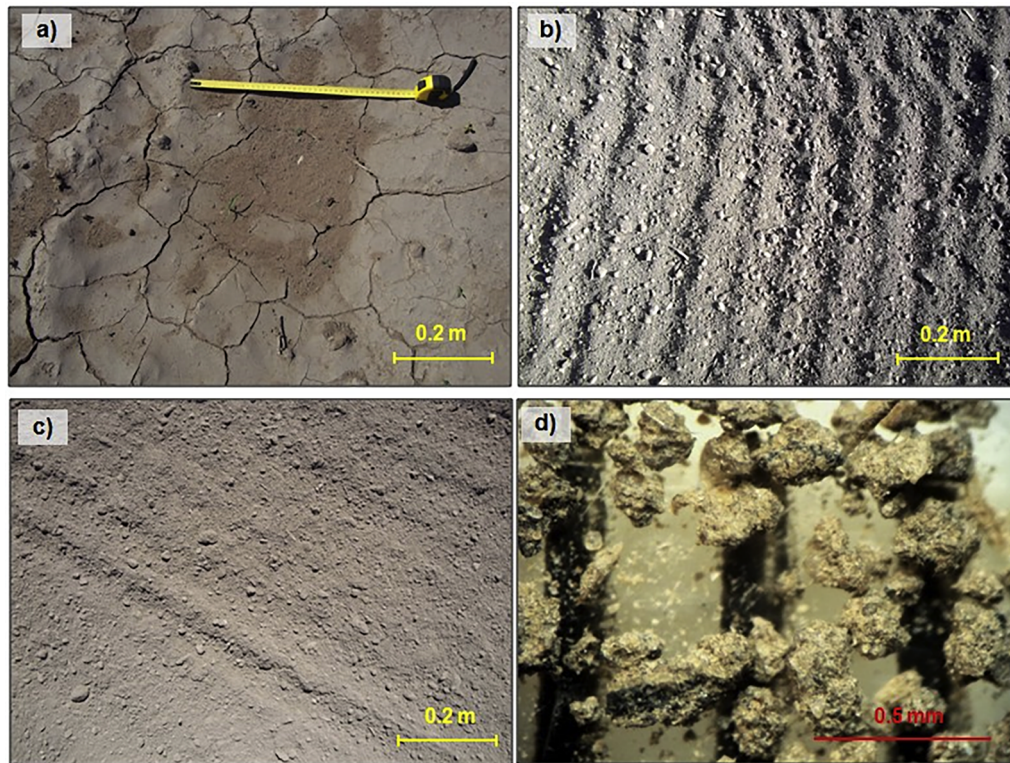


Fig. 9. Soil surface conditions during the events: a) Nov. 17, 2014, b) Aug. 31, 2015, c) Sep. 06, 2015, and d) Microphotography of the saltation fraction of the soil (200–500 μm).

wind. It could be observed, although unfortunately it was not quantified, that patches of loose sand-sized particles remained on the crust formed (Fig. 9a). On crusted surfaces, the abrasion caused by these loose sand particles seems to play a fundamental role in the production of dust and consequent emission. The physical crusts are formed as a result of the breakage of the aggregates and the dispersion of clays by the effect of rainwater (Sharratt and Vaddella, 2014), having fine material in the sealed surface and a skeleton formed mainly by sands (Valentin and Bresson, 1992). Zobeck (1991) showed that a very close relationship is established between the formation of surface crusts, erosion and the emission of dust due to the impact of the saltating particles. The role of surface bombardment by particles found in saltation is recognized as the main driver of sustained release of fine material from these surfaces (Rice and McEwan, 2001). The surface crusts protect the soil against wind erosion until they are degraded by the particles transported by saltation, which abrade the surface of the soil. A proportion of this type of material, called “loose erodible material” by Zobeck (1989), remains on the surface of the soil after the crusts have formed. This material is frequently formed by particles of 0.1–0.5 mm in diameter (Potter, 1990), which can be retransported by the wind by saltation. Zobeck (1991) and Rice et al. (1996) showed that a greater kinetic energy of the particles that impact on the crust produces greater destruction of the crust and, consequently, greater erosion. On the other hand, some studies have shown that the direct emission of PM_{10} from crusted soils can be important in certain environments (Kjelgaard et al., 2004b). However, direct emission of PM_{10} occurs in fine soils in which the process of saltation is limited.

From the comparison between both the fully dispersed and the less dispersed samples of the eroded sediment along the fetch distance, the results found suggest that the aggregates from the soil surface are progressively disintegrated along the fetch distance and the resulting fragments are entrained into the horizontal air flux above the saltation layer and transported also vertically. However, for the coarser fractions it is likely to be necessary a greater distance for this process to occur.

Supporting this explanation, the PM_{10} concentrations measured with a dust monitor (Table 2) were consistently lower at the windward ($3.7\text{--}11 \mu\text{g m}^{-3}$) than at the leeward side of the plot ($21\text{--}90 \mu\text{g m}^{-3}$). These measurements show the relatively low PM_{10} background concentration at the beginning of the plot, indicating that most of the dust was emitted from within the plot boundaries. Considering the results presented previously, this dust must have come mainly from the fragmentation of saltating aggregates.

3.4. Fragmentation of the saltating aggregates along the fetch distance

The correlation between the relative aggregation index of the eroded sediment and the fetch distance is presented in Fig. 10. Higher values of the aggregation index indicate a higher proportion of aggregates in the collected sample at a given distance. The relative aggregation index fluctuated between 3.8 at 25 m and 0.3 at 200 m. These results indicate more aggregation ($p < 0.1$) of the eroded sediment at the beginning (windward side) of the plot than at the end (leeward side) of it. Assuming a homogenous distribution of the aggregate sizes on the surface of the plot at the beginning of each event, this difference was due to the progressive fragmentation of the saltating aggregates along the fetch distance during wind erosion. As shown in Fig. 10, the fragmentation increased at an average rate of 38% along 100 m.

From the linear regression shown in Fig. 10, it can be deduced that under the conditions of this study, aggregates up to $62.5 \mu\text{m}$ moving over an eroding field can be considered totally fragmented after traveling a distance of 260 m. As discussed previously, a universal critical fetch distance is impossible to determine. However, the result found herein can be related to the fetch distances measured under similar agricultural-field conditions by other authors. Critical fetch distances of up to 150 m have been observed by Fryrear and Saleh (1996), Gillette et al. (1996) and Fryrear et al. (2001), and about 250 m by Stout and Zobeck (1996) and Hagen et al. (2010), and even more than 300 m was suggested by Stout (1990). According to our results, if enough wind

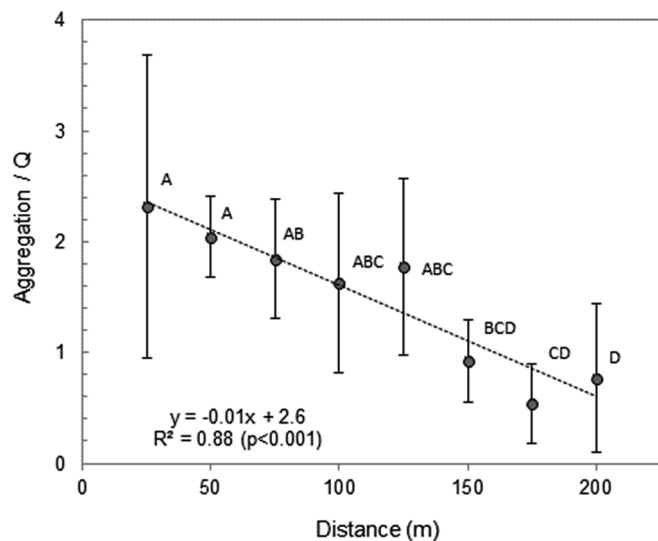


Fig. 10. Correlation between the relative aggregation index (Aggregation/Q) of the eroded sediments and the fetch distance for the three events (average for three events). Error bars represent standard deviations. Different letters indicate differences between the aggregation index with the distance ($p < 0.1$).

energy is applied over a sufficiently long and smooth loamy agricultural soil, every 260 m a complete disintegration of the aggregates of the transport system will occur. At this point, in average terms most of the eroded material within that area would have entered into suspension. In other words, most of the saltating material would be gradually depleted until that distance, producing a turning point in the measurements every 260 m because at this point, saltation could be exhausted and the main transport mode would be suspension. However, over longer fields, at this point the process of avalanching would start again, giving rise to a new cycle of saltation-fragmentation-suspension for another 260 m. Of course, the result of this analysis depends partially on the reference point taken as the start of the transport system and the length of the sampling transect. Considering a non-erodible boundary, in a shorter sampling transect the process would not be fully developed, whereas in a longer transect the process would be sampled again from 260 m on, producing an overlap of the measurements and hence a variable relation between the mass transport and the distance, that can also depend on the reference starting point. Again, the results found herein suggest the presence of a turning point around a windward distance of 260 m. Nevertheless, evidence found in the literature strongly suggest that the point of stationary-transport conditions, usually called critical fetch distance, is very variable depending on surface conditions that control the sediment availability and sort, and also on variability, intensity and duration of the wind.

4. Conclusions

This study provides a first quantification of the movement and alteration of saltating aggregates along the fetch distance under field conditions on a loamy agricultural soil. Measurements were carried out under ideal conditions for the occurrence of wind erosion on a 200 m long experimental plot.

Statistically significant differences were found both for particle size distribution and aggregation when comparing the eroded sediment at the windward and leeward sides of the experimental plot. A greater proportion of coarser particles was found as the distance traveled by the eroded sediment increased. From the change in average particle size distribution at the beginning and at the end of the 200 m experimental plot, it was estimated that around 12% of the particles smaller than $62.5\mu\text{m}$ were lost by vertical transport (dust plume) producing an average concentration of $48\mu\text{g m}^{-3}$ at 2 m height and 200 m fetch.

Under the conditions of this experiment, an average eroded soil aggregate ($62.5\mu\text{m}$) was fragmented at a rate of 38% every 100 m traveled ($R^2 = 0.88$; $p < 0.001$). Particle size analysis of the eroded sediment and open-air PM_{10} concentration measurements indicated that the fragmentation of aggregates during saltation can be considered as the main mechanism of dust emission on this soil. Results found show that, the finer the material transported by the wind, the lower the rate of mass transport increase along the fetch distance, suggesting that the critical fetch distance (distance at which maximum transport is reached) can be affected by the sampling height and sediment type and availability. Moreover, the results found also suggest the presence of a turning point around 260 m downwind where saltation can be exhausted due to the fragmentation of the saltating aggregates. It is discussed if this finding could be also related to the critical fetch distance concept.

Wind erosion and dust emission from agricultural soils are complex and highly variable processes that are difficult to quantify and describe. More studies are needed to expand knowledge about the relation between the soil surface characteristics, the saltation fraction composition and dust emission.

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