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Meteorological conditions during dust (PM_{10}) emission from a tilled loam soil: Identifying variables and thresholds

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A R T I C L E I N F O

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A B S T R A C T

Soil wind erosion and consequent PM_{10} emission is a complex process that has been related to surface properties and meteorological conditions. Most of the studies have emphasized on the relationship between the surface conditions and the dust emission, in general on deserts and dry lakes or playas. Little is known about the influence of meteorological variables on PM_{10} emission from agricultural soils. The objective of this study was to identify the most important meteorological variables involved in the emission of PM_{10}, identify their threshold values, and to analyze their interaction with the soil surface conditions. Measurements were made on a loam soil (Entic Haplustoll) in the semiarid Argentinian Pampa. Horizontal mass transport (Q) and PM_{10} emission were measured during two years on a bare and flat surface that was tilled periodically. The meteorological variables measured were: average and maximum wind speed, wind direction, air temperature, relative humidity and soil temperature. In 30% of the events, the PM_{10} concentration at 1.8 m height exceeded the average values allowed by the World Health Organization (50 $\mu g\ m^{-3}$ for a 24 h period). Maximum values exceeded 1000 $\mu g\ m^{-3}$. The slope of the PM_{10} concentration gradient changed between spring − summer and autumn − winter periods. Threshold values of the studied variables were set when PM_{10} concentration values at 1.8 m height were consistently above the 50 $\mu g\ m^{-3}$ limit. The highest PM_{10} emission rates were observed when relative humidity values were below 20% and the air temperature was higher than 30 °C. In addition when the wind speed exceeded 8 $m\ s^{-1}$, dust emission increased significantly. From a multiple regression analysis, results indicated that PM_{10} emission was well correlated ($p < 0.001$) with maximum wind speed, relative humidity, and air temperature. Maximum wind speed and relative humidity conditioned the PM_{10} emission in a synergistic way. However, the regression explained only 32% of the variability. Although higher average PM_{10} emission values were measured during events with a crusted surface, lower average values of Q were measured during events with a crust. Field observations indicated that the complex interaction between the weather conditions and soil surface properties such as soil crusts, aggregate size distribution, soil moisture and even the soil condition when the tilling is done, can produce a high variability and unpredictability, of the PM_{10} emission from bare agricultural soils.

1. Introduction

The emission of particles ≤10 μm in diameters (PM_{10}), during wind erosion of agricultural soils, has become relevant in recent years. Fine particles transported by suspension can produce environmental pollution and trigger respiratory and heart diseases (Pope et al., 1995; Ghio and Devlin, 2001). The translocation of fine particles can also affect the dynamics of nutrients and the biochemical cycle in terrestrial ecosystems (Herut et al., 2001). Fine particles can also affect climate in different ways (Seinfeld and Pandis, 1998; McConell, 2007). Shao et al. (2011) mention that "dust as an aerosol significantly impacts on the energy balance of the Earth system through the absorption and scattering of radiation in the atmosphere and the modification of the optical properties of clouds and snow or ice surfaces". Dust carries organic matter contributing directly to the carbon cycle, and also iron, that is vital to ocean productivity and ocean − atmosphere CO_2 exchange.

Most of the studies regarding dust emissions have been developed on surfaces of ephemeral lakes or deserts (Draxler et al., 2001; Hoffmann et al., 2008) and to a lesser extent on soils used for agriculture (Sharratt et al., 2007; Li et al., 2015). Different studies have shown that the anthropogenic sources, which include land use for agriculture and livestock, can contribute significant amounts of dust to

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the total dust suspended in the atmosphere (Ginoux et al., 2001). Korcz et al. (2009) found, for natural areas in Europe, a PM_{10} emission factor of 0.021 mg km^{-2}, while in agricultural and anthropogenic areas the values were 0.157 and 0.118 mg km^{-2}, respectively.

Numerous studies have been carried out as attempts to determine the factors affecting PM_{10} emissions from soils. Generally, they have been made under laboratory conditions, and focused on the relationship between the intrinsic properties of the soil: texture, organic matter, distribution and aggregate stability and soil moisture (Funk et al., 2008; Alfaro, 2008; Aimar et al., 2012). However, little is known about the effect of meteorological variables in PM_{10} emissions from agricultural soils. It is known that the wind speed is a major factor in the generation of dust, acting in combination with the vegetation cover and the soil structure (Zobeck, 1991; Yin and Nickovic, 2007). Several studies, conducted mainly in wind tunnels, have shown that the threshold wind speed that initiates the process of wind erosion depends on the air humidity, because it affects the moisture content of the soil surface, affecting thereby the cohesion strength between particles (Ravi et al., 2004, 2006; Neuman and Sanderson, 2008). Gregory and Darwish (1989) suggested that meteorological variables such as temperature and humidity could be used more easily as predictors of soil erosion than the surface soil moisture, due to the difficulties in measuring precisely the surface soil moisture. In addition, other studies have found that the air temperature is correlated with dust concentration. Hussein and Karppinen (2006) investigated the dependence of the concentration of fine particles in the air on local meteorological parameters and they reported that both wind speed and air temperatures were the most important variables. On the other hand, it is known that the conditions of the soil surface (disturbed − undisturbed surface, crust occurrence, size of aggregates and plant cover) can produce variability of the wind erosion and PM_{10} emission processes (Goossens, 2004; Baddock et al., 2011; Brungard et al., 2015).

In the Semiarid Central Region of Argentina (SCRA) one of the largest sources of dust emission are agricultural soils due to their susceptibility to wind erosion, and also because they occupy a large area (10 million hectares). This region is affected by both the anticyclone of the Pacific Ocean and the anticyclone of the Atlantic Ocean (Panebianco et al., 2016), whereby the dust emission from this area could potentially affect the air quality in surrounding regions. In this region the soils generally remain uncovered (bare soil or very low coverage with plant canopy or plant residues) during winter and spring, when the wind speeds are high and there is potential susceptibility to erosion processes and PM_{10} emissions (Buschiazzo et al., 2007; Panebianco et al., 2008; de Oro and Buschiazzo, 2009, Aimar et al., 2012; Avecilla et al., 2016).

The study of the meteorological conditions that lead to the emission of fine dust (PM_{10}) in the SCRA can contribute to the knowledge of the amount of dust emitted from agricultural soils under field conditions, and to the understanding of the relation between climate, soil and dust emission. The aim of this study was to assess the PM_{10} emission process under field conditions and to evaluate the effect of meteorological variables on dust emission by wind from a loam agricultural soil.

2. Materials and methods

2.1. Study area and sampling scheme

A loam soil (Entic Haplustoll) (Soil Survey Division Staff, 1993) was selected at the Experimental Station located of the INTA Anguil “Ing. Agr. Guillermo Covas”, near Santa Rosa city, Argentina (36° 35′ 59″S; 63° 57′ 39″W), at 165 m AMSL (Fig. 1, Table 1).

The annual average wind speed (measured at 1.5 m height) is 8.6 km h^{-1}. The prevailing direction of the winds is N-S (Fig. 1). The annual average precipitation at the study site is 760 mm, with an annual cumulative evaporation (Class A evaporation pan) of 1583.4 mm (Fig. 2). The annual average air temperature is 15.3 °C, and the maximum average is 30.4 °C in January. The annual average soil temperature, measured at 0.05 m depth, is 17.4 °C. The annual average relative humidity is 67%. Monthly averages are shown in Fig. 2.

Measurements were made during two years on an 80 m wide and 200 m long experimental plot, disposed parallel to the prevailing wind direction. The plot was tilled regularly (24/09/2014, 21/10/2014, 14/06/2015, 31/08/2015) with a disc plow in order to maintain the surface with minimal roughness and vegetation cover. There were periods in which the soil was partially covered by weeds. Measurements were made only during high wind speed events. The duration of an erosive event was defined as the period during which the wind speed exceeded 5 m s^{-1} at 2 m height. This wind speed is considered the average threshold for wind erosion (Fryrear et al., 1998). The period of measurement of each event did not exceed 24 h, in order to avoid changes of the wind direction that could interfere with the analysis of the data.

2.2. Soil surface parameters

Composite samples were taken from the topsoil (2.5 cm). The sampling scheme consisted of four subsamples randomly distributed in a homogeneous area of 100 m^2. The texture was determined by the combined method of wet sieving and pipette (Gee and Bauder, 1986), organic matter (OM) was determined by the method of Walkley and Black (1934) and the content of free carbonate ($CaCO_3$) was determined with the Scheibler calcimeter method (Schlichting and Blume, 1966) (Table 1).

The erodible fraction (EF) and dry structural stability of the aggregates (DSS) were determined with a rotary sieve (Chepil, 1962). This device is a set of concentric cylindrical sieves whose openings are 0.42, 0.84, 2, 6.4 and 19.2 mm. The percentage of aggregates < 0.84 mm, the erodible soil fraction (EF), was calculated by means of Eq. (1) (Colazo and Buschiazzo, 2010):

$$EF = \frac{W<0.84}{IW} X\ 100 \quad (1),$$

where EF is the erodible fraction (%), W < 0.84 is the weight (g) of the aggregates < 0.84 mm, and IW is the initial weight (g) of the total sample. The dry structural stability of the aggregates (DSS) was evaluated making a second dry sieving of each aggregate size class after the first sieving (Skidmore et al., 1994), and then using Eq. (2):

$$DSS = \left[1 - \frac{W<0.84_2}{W>0.84_1}\right] x\ 100 \quad (2),$$

where $W < 0.84_2$ is the weight (g) of the aggregates that passed through the 0.84 mm sieve after the second sieving, and $W > 0.84_1$ is the weight (g) of the aggregates retained by the 0.84 mm sieve after the first sieving.

Additionally, the size distribution of the soil particles was analyzed with a particle counter (Malvern Mastersizer 2000) on dispersed and less dispersed samples (Fig. 3). The content of PM ≤ 10 μm in the soil that could potentially be emitted (dispersed samples) was 327.3 g kg^{-1} according to these measurements. The dispersion treatment included the destruction of free carbonates and organic matter, agitation in water and ultrasound. The less dispersion treatment consisted of placing the samples in water only, without additional modifications.

During each event, samples were taken in the form of a block with a wide shovel without disturbing the topsoil (5 cm) and were placed in a tray of 30 × 30 cm for drying in the air. The aggregate size distribution was then determined by means of the rotary sieve. Additionally, samples were taken from the 2.5 cm topsoil to determine soil moisture by oven drying (105–110 °C).

When present, the vegetation cover (alive or dead plants) was determined taking randomly 3 digital photos, perpendicular to the soil surface and from a height of 150 cm. This photos covered an area of 1 m^2 each. The photographs were downloaded to a PC, and a grid of 108 intersection points was superimposed on them using the Paint Shop Pro 7 software. The soil cover was calculated as the ratio between the

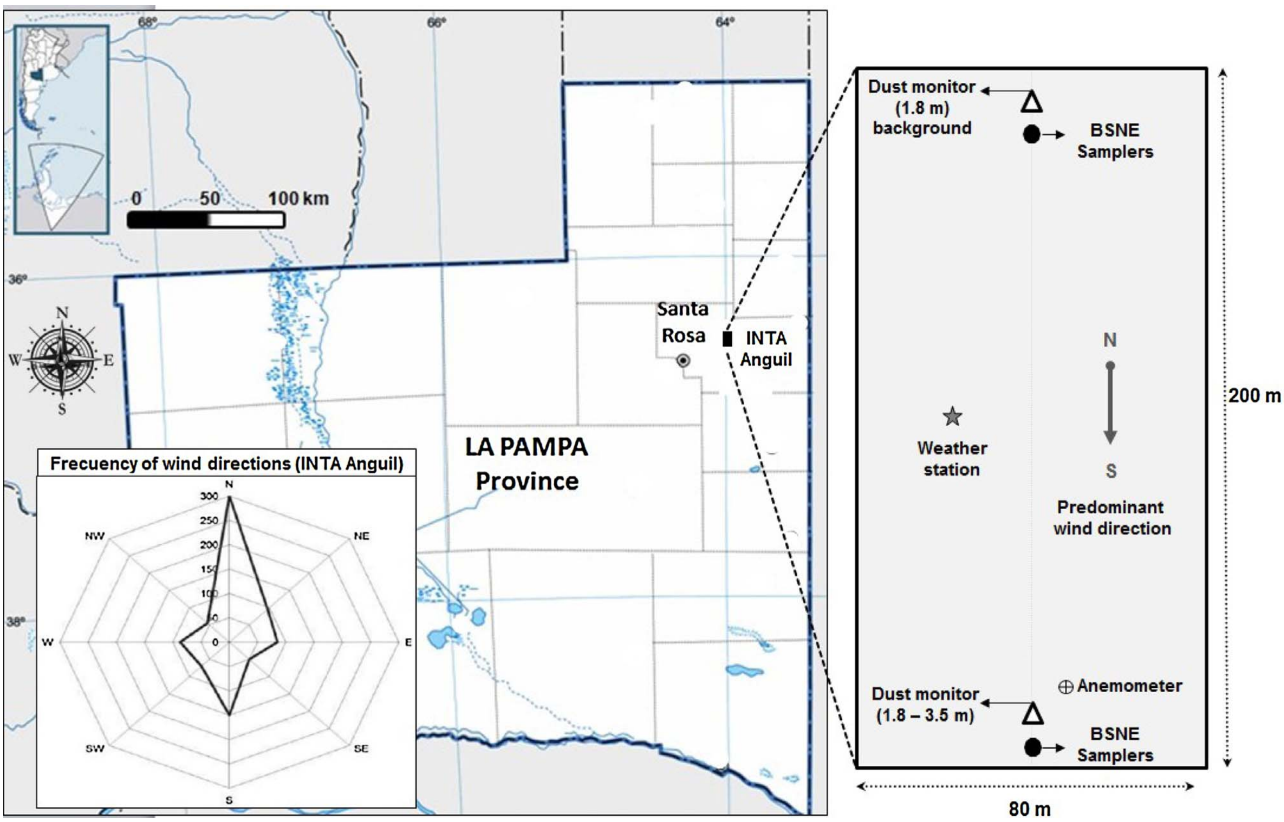

Fig. 1. Geographical location of the study site and design of experimental plot.

Table 1
Main characteristics of the studied soil. Values expressed in g kg^{-1}.

Grain size distribution (g kg^{-1})	Clay (< 0.002 mm)	171.6
	Silt (0.002-0.053 mm)	355.5
	Very fine sand I (0.053-0.074 mm)	129.3
	Very fine sand II (0.074-0.105 mm)	129.1
	Fine sand (0.105-0.250 mm)	173
	Medium and coarse sand (0.250–2 mm)	41.5
OM (g kg^{-1})		28.2
$CaCO_3$ (g kg^{-1})		8.8
EF (%)		21.2
DSS (%)		95.7

OM: organic matter; EF: erodible fraction; DSS: dry structural stability of aggregates.

intersection points showing plant coverage and the total points of the grid (Mendez and Buschiazzo, 2010).

The presence or absence of superficial crusts was observed visually. During some of the events, crusts were present due to precipitations occurred in previous days. Because this condition could affect the processes of wind erosion and PM_{10} emission, this parameter was taken into account for the analysis and description of the superficial conditions.

2.3. Weather data and wind profiles

The meteorological variables measured were: average (Wa) and maximum (Wm) wind speed, wind direction, air temperature (T_air) and relative air humidity (RH), the values were recorded at a frequency of 5 min, at 2 m height. For these measurements, a wireless, automatic weather station installed in the plot was used (Davis Vantage Pro2 Plus). Additionally, soil temperature was measured at 10 cm depth (T_soil) at a frequency of 10 min. The latter dataset was taken Agrometeorological System for Information and Management from INTA (National Institute for Agricultural Technology, Argentina. siga2.inta.gov.ar, viewed on October 28, 2015), located in the proximity of the plot.

The mean wind profile was measured hourly during the erosive events, with portable anemometers (Windmaster 2, Kaindlelectronic) at four heights: 0.1, 0.5, 1 and 2 m to be able to calculate the friction velocity (Roney and White, 2006) according to the equation:

$$U_z = \frac{\mu_*}{k} \ln\left(\frac{Z}{Z_0}\right) \quad (3),$$

where U_Z is the wind speed at height Z, μ_* is the friction velocity, k is the Von Karman's constant (0.4), and Z_0 is the aerodynamic roughness height.

Fig. 4 shows the average wind profiles recorded during four high-wind events. In accordance with Eq. (3), these profiles exhibit the typical logarithmic form that is usually expected within a surface boundary layer over low-roughness surfaces during the daytime.

2.4. Dust emission

Herein, dust is defined as particles with an aerodynamic diameter ≤ 10 µm. This definition conforms to the criteria used to describe particles as pollutants within the air quality standards regulations (US. EPA, 1995). To determine the amount of dust that went into suspension during the erosive events, a mast was placed 20 m away from the southern or the northern edge of the plot (depending on the wind direction during the event) in order to obtain a 180 m fetch distance (Fig. 1). On each mast, two Kanomax dust monitors (model 3443) were mounted at 1.8 and 3.5 m high, respectively. The Kanomax dust monitor is a light scattering digital dust monitor measuring particles in a range from 0.1 to 10 µm. It measures in a concentration range of 0.001–10000 mg m^{-3} with an intake flow of 1 L min^{-1}. Measurements were taken at a frequency of 1 min during the duration of the event. A third dust monitor was placed at 1.8 m height at the windward edge of the plot for measuring the background dust concentration (Fig. 1). The

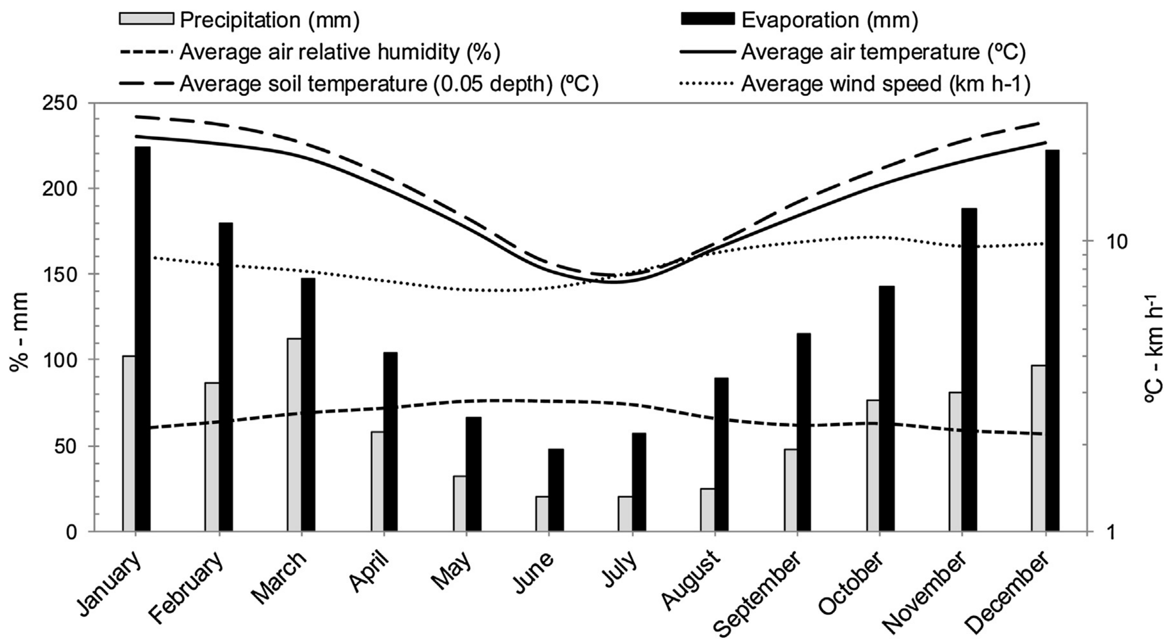

Fig. 2. INTA Anguil agro-meteorological variables (Casagrande et al., 2012).

vertical flux of PM_{10} (F_vPM_{10}), from now on the PM_{10} emission, was calculated with the widely-used equation proposed by Gillette (1977) in mg $m^{-2} s^{-1}$ (López et al., 1998; Kjelgaard et al., 2004; Singh et al., 2012):

$$F_VPM_{10} = \frac{k \cdot \mu_* \cdot (C_1 - C_2)}{\ln(Z_2/Z_1)} \tag{4}$$

where k is the Von Karman's constant (0.4); μ_* is the friction velocity in m s^{-1}; C_1 and C_2 are the PM_{10} concentrations at heights Z_1 and Z_2 (herein 1.8 and 3.5 m). Z_0 was determined from the velocity profiles before the dynamic saltation threshold, and μ_* was derived from the slope of the profiles (Roney and White, 2006).

2.5. Mass transport

To collect the material transported by saltation, BSNE sediment samplers (Fryrear, 1998) were installed at the southern and the northern edge of the plot (Fig. 1). At each sampling point, four BSNE were placed on masts at 13.5; 30; 50 and 100 cm height. A wind vane attached to the mast oriented the sampler inlet towards the wind direction. After each event, samples were weighed with analytical balance up to the fourth decimal place. The horizontal mass transport Q (kg m^{-1}), was determined by integrating an exponential curve, previously fitted to the mass flux values across the height:

$$Q = \int_0^1 a^{bz} dz \tag{5},$$

where Q is the horizontal mass transport in kg m^{-1}, a is the mass flux (kg m^{-2}) at height zero (z = 0), and b represents the decay rate across the height. Details on this method are described in Panebianco et al. (2010).

2.6. Estimated parameters and statistical analysis

PM_{10} emission values and meteorological variables were averaged in ten-minute intervals. For obtaining a value of PM_{10} every ten minutes with Eq. (4), a value of u_* every ten minutes was also needed. Unfortunately, we did not have automatic anemometers for measuring the instant wind profiles. For estimating the ten-minute u_* (u_*pred) from the hourly u_*

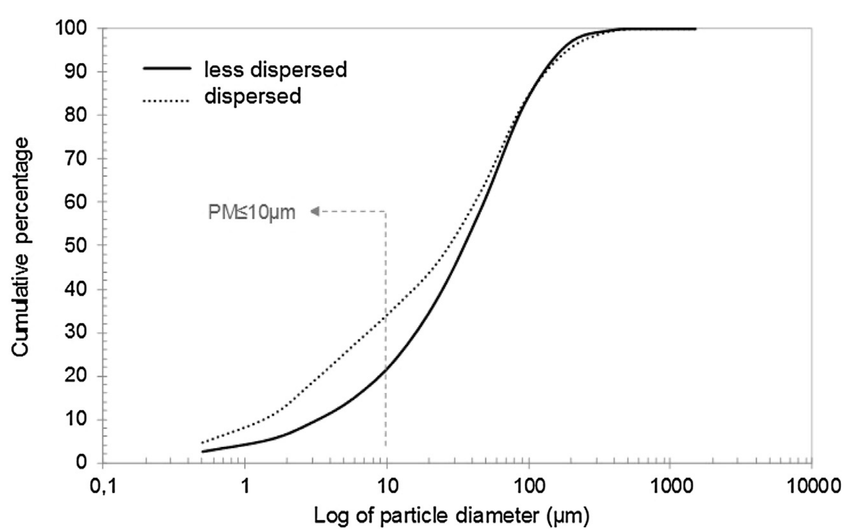

Fig. 3. Grain size distribution (µm) of the soil, after dispersed and less dispersed treatments.

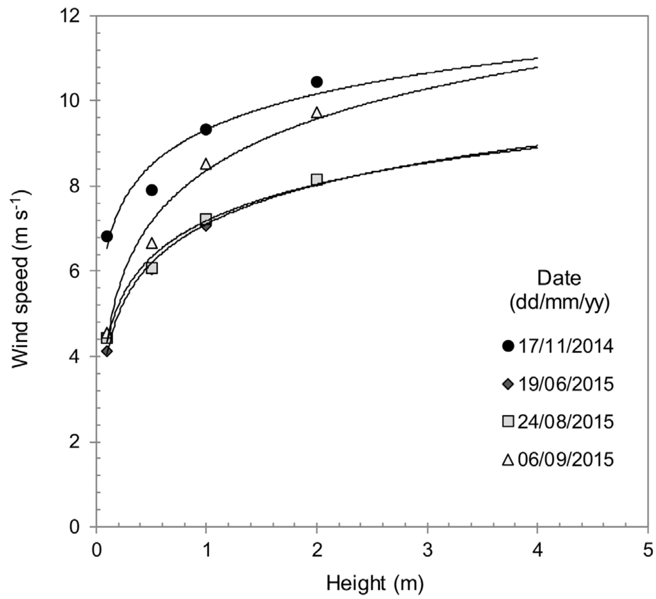

Fig. 4. Average wind profiles during four high-wind events.

values, a linear regression was performed between the average wind speed at 2 m height and the friction velocity obtained from the hourly profiles. Using this regression ($u_*pred = 0.054Wa + 0.1132$; R^2: 0.5 (r: 0.71); $p < 0.001$; n: 137), the value of u_*pred was obtained for every measured wind speed, and used in Eq. (4).

Multiple regression and correlation analyses were made between the PM_{10} concentration and the meteorological variables. To make these analyses the INFOSTAT software (Di Rienzo et al., 2002; FCA-UNC, Córdoba, Argentina) was used, with a 1% significance level ($p < 0.01$).

3. Results and discussion

3.1. Mass transport and PM_{10} emission

The mass transport (Q, calculated up to 1 m above the soil surface) values were highly variable. The maximum value was 20 kg m^{-1} and the minimum value was 0.01 kg m^{-1}. The average value of Q was 1.75 kg m^{-1} with mean wind speeds ranging between 4 and 10 m s^{-1}, corresponding friction velocities ranged between 0.3 and 0.8 m s^{-1} (Table 2).

Comparing all the recorded events, the average PM_{10} concentration values were between 0.006 and 0.09 mg m^{-3} at 1.8 m height and between 0.002 and 0.048 mg m^{-3} at 3.5 m height. The maximum concentration was 1.15 mg m^{-3} at 1.8 m height and 0.67 mg m^{-3} at 3.5 m height.

The average F_VPM_{10} value was 6.32E–03 mg m^{-2} s^{-1} (6.11E-03-mg m^{-2} s^{-1} for the spring − summer period and 6.65E–03 mg-m^{-2} s^{-1} for the autumn − winter period). The maximum value was 14.4E–03 mg m^{-2} s^{-1} (17/11/2014, Table 2). For comparison, F_VPM_{10} values from agricultural soils of the Columbia Plateau (silt loam textured soils under conventional tillage practices such as disking), ranged between 1.0E-02 and 2.55E–01 mg m^{-2} s^{-1} (Kjelgaard et al., 2004; Sharratt et al., 2007). Agricultural soils of Spain (silt loam texture soil under mouldboard ploughing and a pass of a clod-breaking roller) and Niger (bare, loose, sandy soil), produced PM_{20} emission values that exceeded the 3.0E–01 mg m^{-2} s^{-1} (Sabre et al., 1997; Gomes et al., 2003). Also, PM_{10} emissions of 2.35E–01 mg m^{-2} s^{-1} were measured at Owens (dry) Lake (a saline playa surface, classified as a loam soil) (Gillette et al., 1997). The lower values of F_VPM_{10} found in this study with relation to those found in the literature, were probably due to structural and textural differences between the studied surfaces, differences in measurement methodologies, fetch distances, and weather conditions. Moreover, different tillage implements produce variable conditions concerning the condition of the surface, making it difficult to compare the F_VPM_{10} values from different studies under field conditions. However, taking into account the small area where the study was made, the contribution of dust particles to the atmosphere from the agricultural soils of this region of Argentina can be considerable, especially during spring. A large proportion of the SCRA soils evolved on loessical sediments (Zárate, 2003), a material that is extremely susceptible to being re-transported by the wind from Argentina, even up to the Antarctic continent (Gaiero, 2007).

In general, higher PM_{10} concentrations were measured together with high values of Q, (Fig. 5). However, we could not find a significant correlation ($p > 0.05$) between Q and PM_{10} emission, despite the known theoretical dependence between these processes. We believe this was due to the complex relation between the variability of the soil surface conditions and the variability of the weather. This lack of correlation was also mentioned by other authors (Goossens and Gross, 2002; Houser and Nickling, 2001; Sharratt et al., 2007; Hagen et al., 2010).

3.2. PM_{10} concentration gradient

A significant linear correlation was found ($p < 0.001$) between PM_{10} concentration at different heights (Fig. 6). PM_{10} concentrations measured at 1.8 m exceeded, on average, five times the concentrations measured at 3.5 m. A higher PM_{10} concentration (at 1.8 m) indicates the formation of a more developed dust plume, and therefore a greater PM_{10} emission to the atmosphere.

Fig. 6 shows two series of data that produced different regression lines. These datasets are from events recorded during different periods of the year. The PM_{10} concentration for the autumn − winter period (events: 19/06/2015; 17/07/2015; 26/07/2015; 21/08/2015) at 3.5 m, varied from 0.003 to 0.006 mg m^{-3}, with maximum values that ranged from 0.008 to 0.025 mg m^{-3} (Table 2). At 1.8 m height the average values ranged between 0.015 and 0.040 mg m^{-3}, with maximum values between 0.074 and 0.144 mg m^{-3}. As stated by Clausnitzer and Singer (2000), as the air temperature close to the soil surface rises during the day, the conditions of the layer immediately over the soil become more unstable, and the dust particles can rise and disperse more easily due to thermal turbulence. During the coldest months, when the temperatures are significantly lower, the decrease in the thermal turbulence can also decrease the vertical ascent rate of dust particles, hence limiting the development of the dust plume along the fetch distance. During the events which occurred in the autumn-winter period, the maximum speeds reached the 15 m s^{-1}. However, it is likely that the low temperatures in this period caused that the PM_{10} released from the surface was less than in the spring-summer period (Fig. 6). Moreover, in general the humidity of the air is higher during the coldest months, causing low emissions of PM_{10}. Assuming that the smaller particles can reach higher heights, the lower slope of the profile also implies a lower probability of entrainment of fine material above the boundary layer during the autumn − winter period, also reducing the possibility of transporting particles at longer distances from the source.

The results show differences in the PM_{10} emissions according to the period of the year. However, the correlation between the PM_{10} concentrations at different heights was high. Therefore efficient measurements could be made using a single measurement height, at least during spring − summer.

3.3. Meteorological conditions during PM_{10} emission

Fig. 7 shows the relationship between each of the meteorological variables and the PM_{10} emission (F_VPM_{10}). According to Eq. (4), an increase of the PM_{10} concentration gradient results in higher values of F_VPM_{10}, hence when F_VPM_{10} exceeded 5.0E–03 mg m^{-3} s^{-1} the PM_{10}

Table 2
Variables measured during the erosive events.

Date (dd/mm/yy)	Duration (minutes)	Wind speed ($m\ s^{-1}$)				Air temperature (°C)		Air humidity (%)		Soil moisture (%)	Soil temperature (°C)		Vegetation cover (%)	PM_{10} concentration ($\mu g\ m^{-3}$)				Background	$F_V PM_{10}$ ($mg\ m^{-2}\ s^{-1}$) 10^{-3}	Q ($kg\ m^{-1}$)	Crust occurrence
		Average	Maxim	μ[a]	Direction	Average	Rank (mín-max)	Average	Rank (mín-max)		Average	Rank (mín-max)		1,8 m		3,5 m					
														Average	Maxim	Average	Maxim				
24/09/2014	269	6.6	14	0.4	NE	22	18–24	33	27–39	3.3	16.4	14–19	0	13	918	7	38	3.2	2.02	0.05	No
27/09/2014	495	8.3	14	0.4	N	19	12–24	37	25–53	2.4	14.5	12–18	0	15	576	9	28	2.8	2.21	0.08	No
21/10/2014	190	5.4	11	0.3	N	33	31–34	36	32–43	5.4	24.8	21–28	0	13	47	9	24	nd*	0.89	0.02	No
17/11/2014	430	10.1	17	0.5	N	36	29–38	21	12–39	2.7	26.9	24–30	0	90	1150	48	670	11	14.4	19.7	Yes
14/06/2015	290	7.4	15	0.6	S	13	12–14	35	31–40	7	9.7	8–11	0	6	126	5	33	nd*	0.55	0.18	No
15/06/2015	324	6.2	13	0.4	SW	18	12–21	26	21–37	4.7	8.4	7–11	0	6	47	4	13	1.9	0.74	0.05	No
19/06/2015	388	8.1	14	0.5	N	11	7–14	46	40–55	4.6	6.6	5–8	0	36	99	6	25	7.2	11.4	0.23	No
24/06/2015	390	6.6	12	0.5	N	12	5–15	57	45–86	4.3	5.7	4–8	0	15	83	2	9	5.7	5.02	0.09	No
17/07/2015	420	6.9	13	0.5	N	15	5–20	52	37–84	7.6	7	5–10	0	24	106	2	12	7.1	8.26	0.06	Yes
26/07/2015	440	7.2	15	0.5	N	16	12–19	76	64–97	5.3	11.3	10–13	5	40	144	4	19	10	13.9	0.1	Yes
21/08/2015	395	7.5	15	0.6	N	20	14–22	65	54–92	4.8	13	11–16	25	35	74	3	8	9.9	13.1	0.07	Yes
24/08/2015	395	7.5	14	0.5	N	16	10–20	61	42–87	4.9	11.8	10–14	27	6	34	5	23	0.1	0.46	0.14	Yes
25/08/2015	400	6.5	12	0.6	N	17	12–20	60	50–79	3.7	12.8	12–15	27	21	43	11	22	0.7	3.96	0.01	Yes
31/08/2015	395	9.3	15	0.8	S	18	17–19	43	36–55	3.7	16.4	13–20	0	21	101	10	35	5.7	5.74	1.3	No
06/09/2015	445	8.6	16	0.7	N	22	17–25	37	31–52	2.8	15.9	14–18	0	54	200	29	108	3.7	12.2	4.1	No

[a] There were problems in the operation of the dust monitor Kanomax.

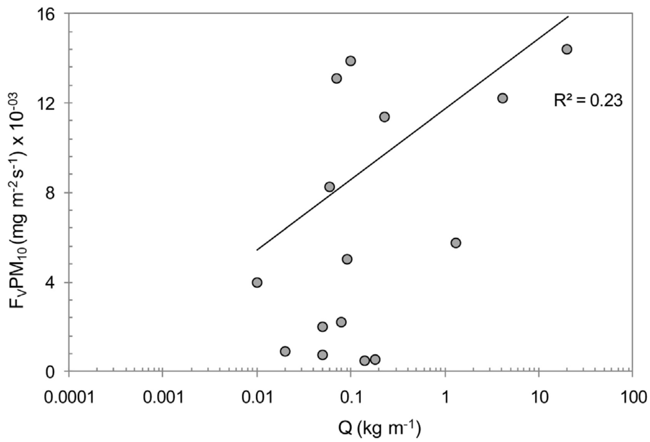

Fig. 5. Relationship between Q and F_VPM_{10}.

concentrations at 1.8 m were higher than 0.05 mg m^{-3} (50 µg m^{-3}) (10 min data, not shown in the present work). This value is the maximum allowed by the World Health Organization (WHO) for a 24 h period (50 µg m^{-3}). For these reasons, we established this concentration value at 1.8 m as a limit. When this limit was reached or surpassed we assumed that a "threshold" for a certain meteorological condition was overrun. During 30% of the events (Table 2), the average PM_{10} concentrations at 1.8 m height reached or exceeded 0.05 mg m^{-3}. During these events the maximum concentration values (at 1.8 m height) were very high, even exceeding 1 mg m^{-3} (1000 µg m^{-3}).

PM_{10} emissions increased drastically when air humidity (RH) dropped below 20%, reaching up to 2.11E–02 mg m^{-2} s^{-1} at 12.5% (Fig. 7a). Csavina et al. (2014) showed that the air humidity plays a very important role on the wind erosion in semiarid environments. In agreement with the results of this study, Stovern et al. (2015) found an inverse relationship between the concentration of dust and the relative humidity of the air. These authors noted that the highest values of dust concentration occurred at 25% air humidity, and that from this value on, the dust concentration decreased until the humidity reached 75%. Over 75%, the dust concentration was zero.

When the air temperature (T_air) exceeded 30 °C (Fig. 7b), the PM_{10} emissions increased exponentially. At temperatures below 30 °C the effect of the air temperature was not so evident. Clausnitzer and Singer (2000) found, also on a loamy soil, that the changes of air temperature during the day were significantly correlated with the changes of PM_{10} emission, and that the soil temperature did not have a significant influence in the emission process. Previous studies also found that the water content in the soil and the air temperature (Hussein and Karppinen, 2006) are the main factors that determine the dust emission from agricultural soils (Clausnitzer and Singer, 1997; Fécan et al., 1999).

Regarding the wind speed (Fig. 7c and d), above 8 m s^{-1} the PM_{10} emission was greater than at lower wind speeds. De Oro and Buschiazzo (2009) found for similar soils as these, that the mean threshold wind speed (minimum speed needed for wind erosion to begin on a bare soil) ranges between 6 and 8 m s^{-1}, according to the season of the year. In coincidence with the results obtained in the present study, Panebianco and Buschiazzo (2008) found that the wind erosion was produced mainly by the maximum wind speeds (wind gusts) indicating that the variable Wm (maximum wind speed) is more decisive than Wa (average wind speed). Gledzer et al. (2010) stated that at low wind speeds, the dust emission (2 m height) is determined principally by the pulsations of the wind (Wm) that produce the movement of the particles of the soil, and by the convection of the air. Kjelgaard et al. (2004a) also found, on soils located at Oregon and Washington (USA), that the threshold speed needed to produce major PM_{10} emissions is 8 m s^{-1}. On the other hand, Abulaiti et al. (2014) found that both the flux of saltating particles and the dust concentration in the air increased significantly when the wind speed reached 10–15 m s^{-1}, but this depended on the conditions of the soil surface.

Fig. 7e shows the observed relationship between the soil temperature (T_soil), and the PM_{10} emission. Above 25 °C there was a marked increase in the emission. Reginato et al. (1976) found, on a loam soil, an inverse relationship between surface soil temperature and gravimetric soil water content, greater soil temperatures produce higher evaporation rates. In the absence of water, the cohesion between the soil particles decreases (Fecan et al., 1999), facilitating the release of dust during the wind erosion process.

3.3.1. Multiple regression analysis

A multiple regression analysis was performed to determine the set of meteorological variables that conditioned most significantly the PM_{10} emission.

In the first exploratory analysis, it was found that the correlation between the variables Wa-F_VPM_{10} and T_soil-F_VPM_{10} were not signifi-

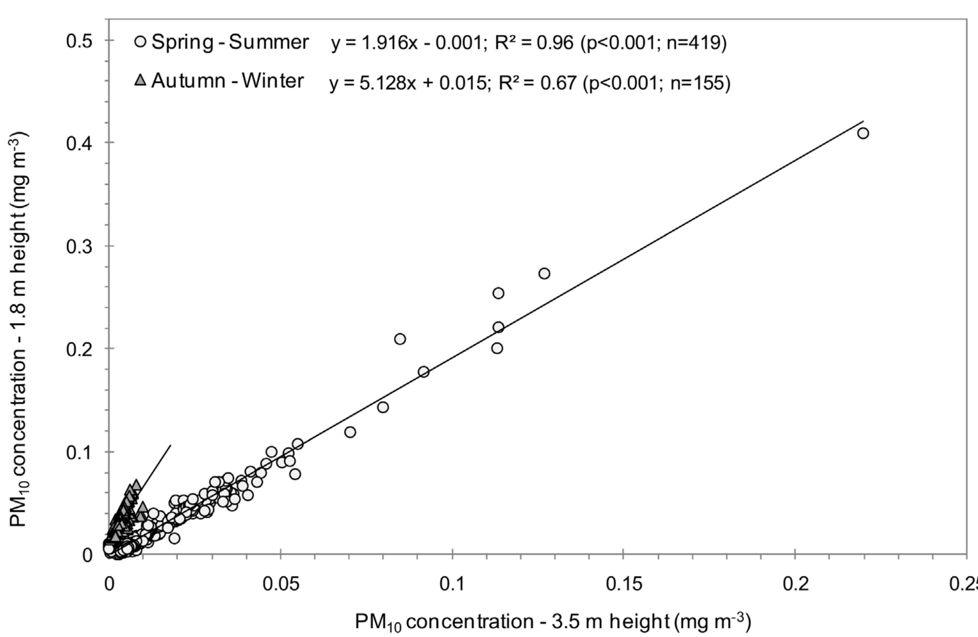

Fig. 6. Correlation between PM_{10} concentrations measured at 1.8 and 3.5 m.

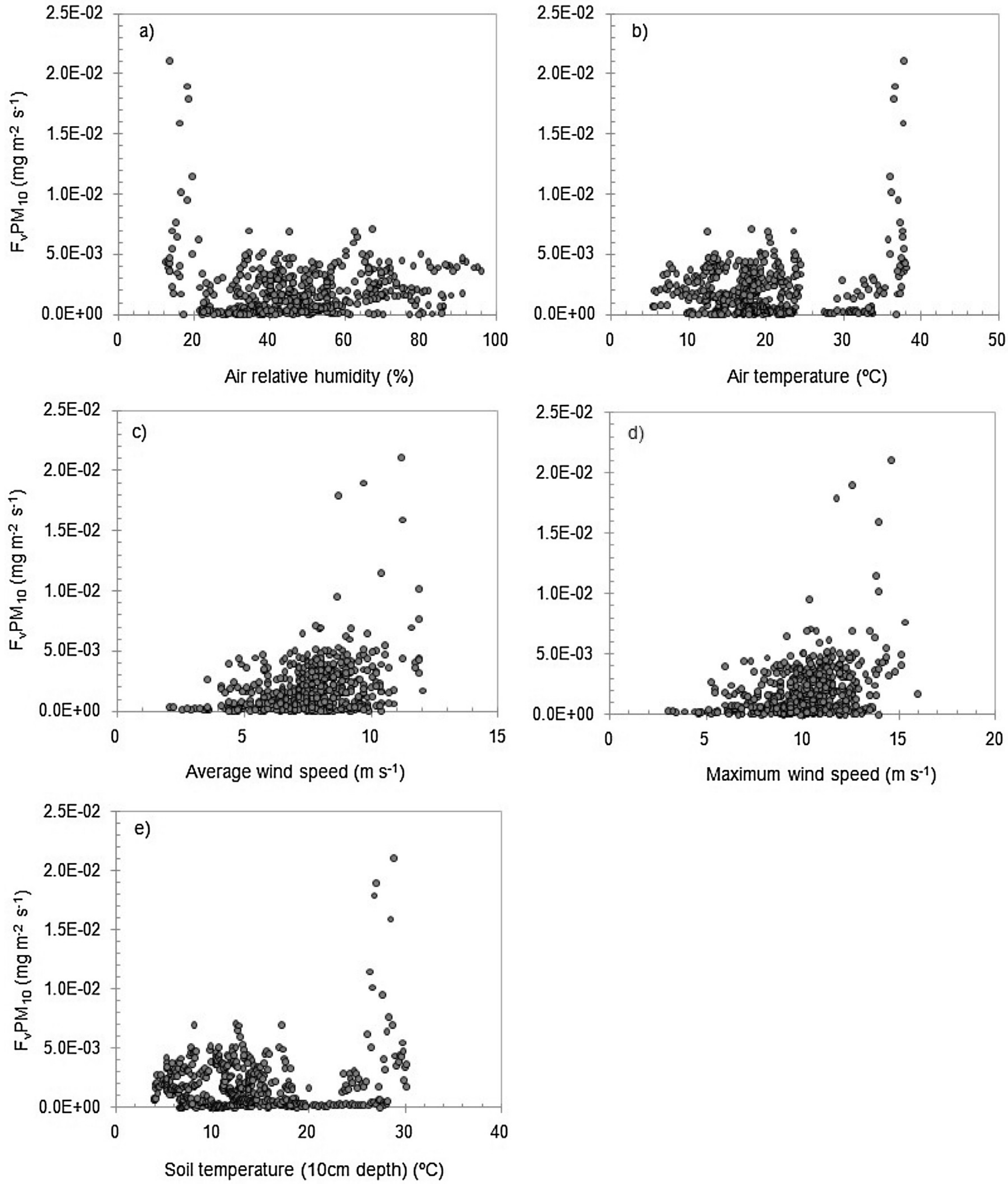

Fig. 7. F_VPM_{10} ($mg\,m^{-2}\,s^{-1}$) according to different meteorological variables (n = 574).

cant at $p > 0.01$. A new analysis was carried out using the variables RH, T_air and Wm as predictors of F_VPM_{10} (Table 3). An apparent lack of homocedasticity was corrected by transforming F_VPM_{10} using square roots. In this case the regression was highly significant ($p < 0.001$), and the model explained 32% of the variability (R^2_{adjusted}).

The analysis of individual interrelation was made between the dependent variable (F_VPM_{10} transformed) and the regressor variables (RH, T_air, Wm). For all the relations there was a high degree of association ($p < 0.001$; n = 516). A positive association was found for the variables Wm and T_air, and a negative association for RH. The resulting equation was:

$$F_VPM_{10} = (-0.06 - 0.00062*RH + 0.00073*T\_air + 0.01*Wm)^2 \quad (4)$$

(R^2_{adjusted}: 0.32; $p < 0.001$)

Table 3
Analysis of variance (CS type III). RH: relative humidity; Wm: maximum wind speed; T_air: air temperature.

F.V.	SS	Df	MC	F	p-value
Model	0.06	3	0.02	80.54	< 0.0001
RH	0.03	1	0.03	131.97	< 0.0001
Wm	0.05	1	0.05	189.88	< 0.0001
T_air	0.01	1	0.01	31.21	< 0.0001
Error	0.14	513	0.00026		
Total	0.20	516			

The variables RH, T_air and Wm showed a significant correlation ($p < 0.01$) with the PM_{10} emission. However, Wm and RH determined to a greater extent the PM_{10} emission from the soil surface (Table 3).

There was no correlation between the air and the soil temperature (T_air and T_soil) and the PM_{10} emission. Although in the regression model the At correlated significantly with F_VPM_{10} (Table 3), the F value showed that this variable had a lower relative weight in the regression.

The influence of the wind speed and the relative air humidity as synergistic variables in the dust-emission process has been already discussed (Clausnitzer and Singer, 2000; Csavina et al., 2014; Stovern et al., 2015). Csavina et al. (2014) demonstrated that the PM_{10} concentrations are not correlated with the wind speed or the relative air humidity independently. However, in presence of winds of higher speed (> 4 m s^{-1}), a correlation between the dust concentration and the relative humidity was observed.

At the study site, the increase of the air temperature and the occurrence of strong winds is a characteristic of the spring − summer period (Fig. 2), hence it is difficult to totally separate the effect of both variables. However, the relative humidity fluctuates within this period, influencing the PM_{10} emission rate.

In this region, where summer crops predominate (soybean, corn, sunflower), tillage operations are carried out during months with high wind speed and low moisture (September-November; Fig. 2).The low coverage rates combined with the weather produce a higher wind-erosion and PM_{10} emission risk (Buschiazzo et al., 2007; Mendez and Buschiazzo, 2010). Avoiding tillage and other operations during periods of high wind speed and temperature and low humidity could reduce PM_{10} emissions, reducing the risk of affecting the health of people close to the emission source and the loss of soil nutrients associated with the finer particles (Zobeck et al., 1989; Buschiazzo et al., 2007).

3.4. The interaction between weather and surface conditions

3.4.1. Aggregate size distribution

Fig. 8 shows the aggregate size distribution of the topsoil (5 cm) during the events. There was a high variability of the aggregate size distribution. Probably this variability is related to the soil moisture at tillage (Tisdall and Adem, 1986; Barzegar et al., 1995; Mendez and Buschiazzo, 2010). Mendez et al. (2015) found, in a sandy loam texture soil and under laboratory conditions, that the PM_{10} emissions decrease with the increase of the size of the aggregates. These authors demonstrated that the aggregates < 0.42 mm showed high potential for PM_{10} emission, representing more than 50% of the total emissions from the soil and more than 90% of the emissions of the erodible fraction (aggregates < 0.84 mm). On the other hand, Halleaux and Rennó (2014) suggested that the formation of aggregates helped by the soil moisture can increase dust emission. Herein, a correlation between the aggregate size distribution and the PM_{10} emission was not found due to the presence of many other variables affecting the wind erosion process at the field level.

3.4.2. Vegetation cover

During most of the study, the soil surface remained uncovered. However, during four of the events the soil had a vegetation cover between 5 and 27% (Table 2). The magnitudes of Q and F_VPM_{10} were not influenced by this cover values, due in part to the fact that the vegetation cover was mainly due to small seedlings that did not affect the surface movement of soil particles. Moreover, in coincidence with the presence of vegetation cover, there were superficial crusts due to precipitation that occurred previous to the events, so this was another variable to be considered.

3.4.3. Variability of environmental conditions and crusting

In general, it has been considered that crusted soils are less prone to wind erosion and consequently, they produce lower dust emission than loose soils. However, some studies have shown that the direct emission of PM_{10} from crusted surfaces may be important in certain environments (Kjelgaard et al., 2004b). In this study, we found that the highest values of F_VPM_{10} were measured when the surface was crusted. In addition, during 70% of the events with a crusted surface, the maximum concentration of PM_{10} exceeded the established threshold value of 0.05 mg m^{-3}. The F_VPM_{10} average during the events that had a weak physical crust was of 7.94E–03 mg m^{-2} s^{-1}, duplicating the value of F_VPM_{10} average for the events were the soil was not crusted (4.53E–03 mg m^{-2} s^{-1}). Interestingly, the average value of Q measured when the soil was crusted was nine times less (0.08 kg m^{-1}) than the average Q for the events without a crust (0.68 kg m^{-1}).

As an example of the combination between the variability of the surface and the meteorological conditions that can be found in agricultural areas, we present the data of four events (Fig. 9). During the event that occurred on 17/11/2014 (Fig. 9a) the soil surface was crusted due to a rain (10 mm in 24 h) precipitated 10 days before. The soil surface was very crusted (Fig. 10a), with a crust formed mainly by fine material, and accumulation of sand in the micro depressions caused by surface runoff, called by some authors as "loose erodable material" or "layer of loose sand grains" or "saltation hotspots" (Zobeck, 1989; Potter, 1990; Rajot et al., 2003). Despite the crusting of the soil surface (soil moisture: 2.7%), F_VPM_{10} reached relatively high values (2.19E–02 mg m^{-2} s^{-1}), due to the release of the fine material when the crust was broken by the saltating sand grains.

In the event on 15/06/2015 (Fig. 9b), the soil surface was dry (soil

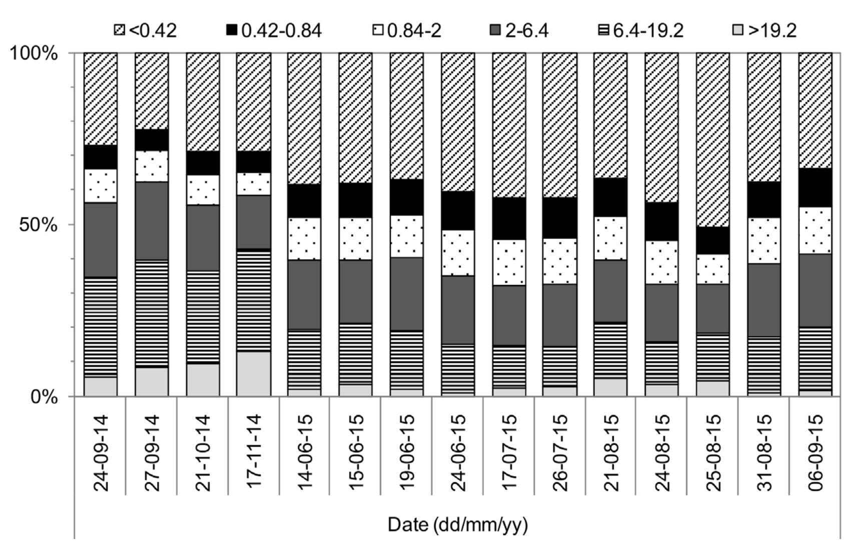

Fig. 8. Aggregate size distribution (mm) of the topsoil before the events.

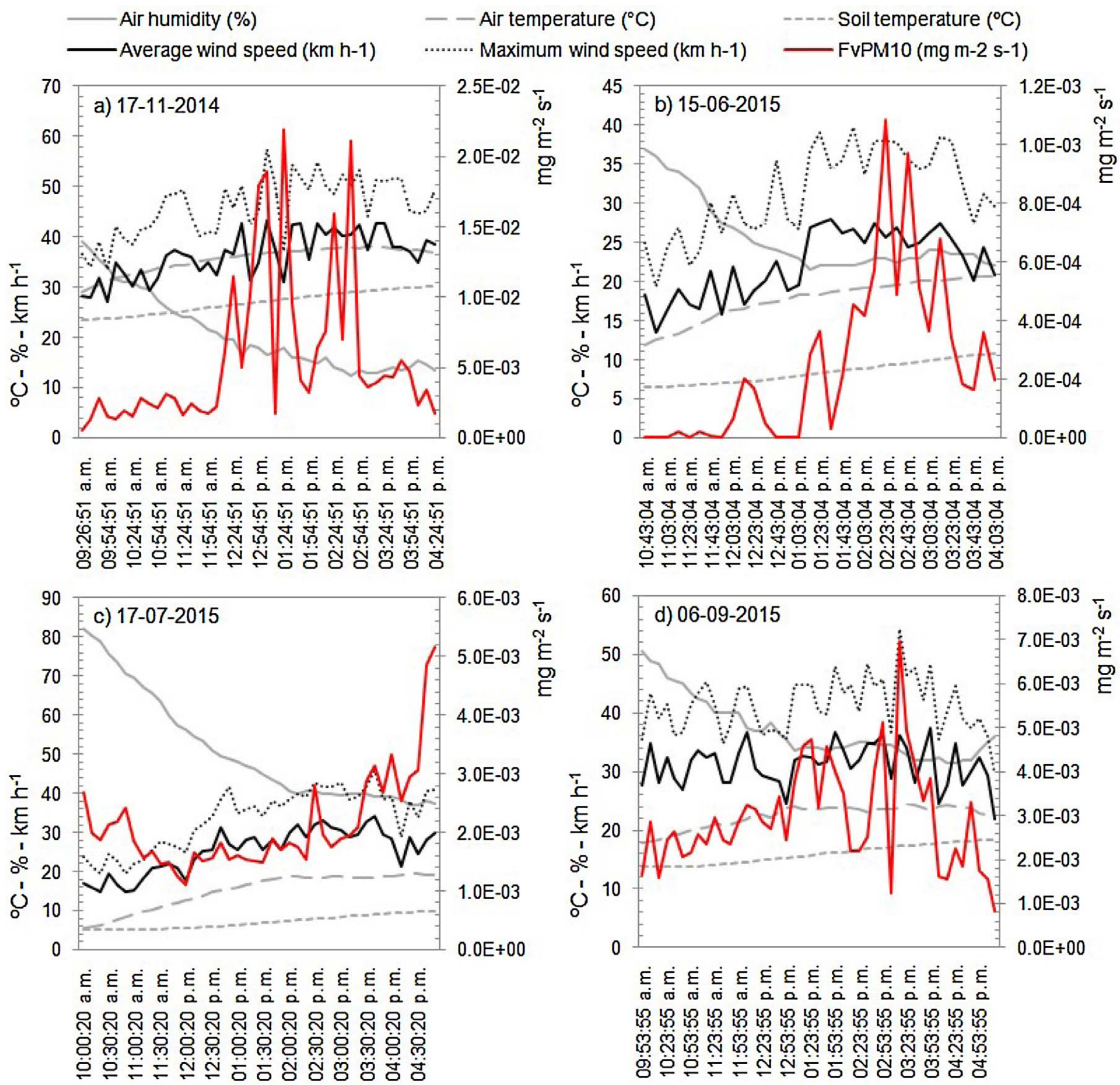

Fig. 9. Relationships between the meteorological variables and F_VPM_{10} for different events.

moisture < 5%) and loose, and with presence of aggregates of small size (Fig. 10b), due to the tillage made five days prior to the event. In spite of this, the maximum value of F_VPM_{10} was 1.09E–03 mg m^{-2} s^{-1}, 95% less than the maximum value of F_VPM_{10} of the event of 17/11/2014. However, in this event (15/06/2015) the wind speed was lower (Wm = 13 m s^{-1}) than the one registered during the event (17/11/2014) described above (Wm = 17 m s^{-1}).

On the other hand, during the event on 17/07/2015 (Fig. 9c) soil had a degree of crusting less than in the event of 17/11/2014, due to the occurrence of a low-intensity rain (3 mm accumulated in 24hs) three days before the wind erosion event (Fig. 10c). As a result, the surface soil moisture was relatively high (7.6%). The maximum PM_{10} emission was 5.17E–03 mg m^{-2} s^{-1}, with a Wa of 6.9 m s^{-1} and a Wm of 13 m s^{-1}. Halleaux and Rennó (2014) and Reynolds et al. (2007) observed higher dust flows with an increase of the surface soil moisture, indicating that the increase of the soil moisture leads to the formation of aggregates that improve the saltation and the dust production. Brungard et al. (2015) found that erosion in certain types of soils with weak physical crusts can reach similar magnitudes or even overcome the erosion produced on the same soil without a crust, suggesting that soils with weak physical crusting are very susceptible to wind erosion, particularly sandy soils (Rajot et al., 2003).

During the event on 06/09/2015 (Fig. 9d), the surface was dry (soil moisture < 3%) and disaggregated due to recent tillage (Fig. 10d). No rainfall was registered during the 30 days prior to the date of the event. In this case the average wind speed was of 8.6 m s^{-1} with maximum speeds that reached 16 m s^{-1}, causing a high value of erosion (4.1 kg m^{-1}) and consequent high PM_{10} emission (1.22E–03 mg m^{-2} s^{-1} on average) (Table 2) compared to the rest of the events.

4. Conclusions

The main objective of this study was to evaluate the combined effect of the key meteorological variables on the PM_{10} emission amount from loam soil in the central region of Argentina, under field conditions.

The maximum wind speed (Wm), relative air humidity (RH) and air temperature (T_air) were better correlated with the PM_{10} emission (F_VPM_{10}) than other meteorological variables. According to multiple regression analysis, the variables Wm and RH conditioned the F_VPM_{10} in a synergistic way. In the Semiarid Central Region of Argentina summer crops (soybean, maize, sunflower) are usual. The tillage operations are made during months with low air humidity and high wind speeds (September − November).

For estimating the threshold meteorological conditions for PM_{10} emission, a benchmark was established when the PM_{10} average concentration values at 1.8 m high overcame the value allowed by

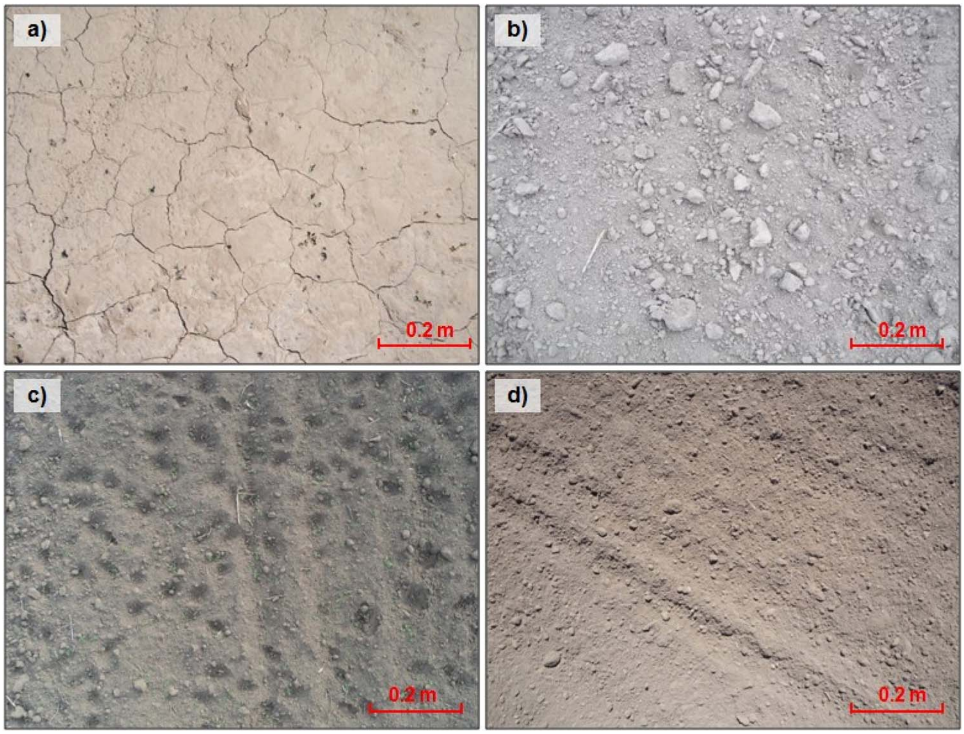

Fig. 10. View of the soil surface: a) (17/11/2014) and c) (17/07/2015) crusted; b) (15/06/2015) and d) (06/09/2015) uncrusted.

the World Health Organization. Generally, this value was overrun when the air humidity was below 20%, the air temperature above 30 °C and the mean wind speed surpassed 8 m s^{-1} (gusts above 10 m s^{-1}) at 2 m height. During these events the maximum concentration values were very high, even exceeding 1 mg m^{-3} (1000 µg m^{-3}). Besides the effect on people and ecosystems near to the emitting soil, considering the extent of this region, the dust emitted could be have an effect on ecosystems located far away.

The slope of the PM_{10} concentration gradient was steeper during the spring − summer period than during the autumn − winter period, showing the influence of convection on the vertical movement of dust particles over agricultural soils.

The relationship between crusting of the soil and the dust-emission process is still a controversial issue. Herein, the average amount of eroded material (Q) when the soil was not crusted was nine times greater than the value of Q when the soil was crusted. On the contrary, the PM_{10} emission was doubled when the soil was crusted.

Although the surface aggregate size distribution and the surface soil moisture should also have influence on the process of PM_{10} emission, we were not able to quantify their effect.

We found that PM_{10} emission can even occur with 27% vegetation cover; hence it is necessary to emphasize the importance of soil management using conservation practices, as well as the maintenance of the surface with vegetation cover after the harvest of summer crops. Avoiding agricultural operations during high wind speed and low air humidity condition is recommended in order to reduce dust emissions.

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