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THRESHOLD WIND VELOCITY AS AN INDEX OF SOIL SUSCEPTIBILITY TO WIND EROSION UNDER VARIABLE CLIMATIC CONDITIONS

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ABSTRACT

Wind erosion starts when the threshold wind velocity (μ_t) is exceeded. We evaluated the sensitivity of μ_t to determine the wind erosion susceptibility of soils under variable climatic conditions. Three years field data were used to calculate μ_t by means of the equation $\mu_t = \bar{u} - \sigma\ \Phi^{-1}(\gamma)$, where $\bar{u}$ is the mean wind speed (m s^{-1}), σ the $\bar{u}$ standard deviation (m s^{-1}), γ the saltation activity and Φ the standard normal distribution function of γ. Saltation activity was measured with a piezoelectric sensor (Sensit). Results showed that $\bar{u}$ of the whole studied period (3·41 m s^{-1}) was lower than μ_t (7·53 m s^{-1}), therefore, wind erosion was produced mainly by wind gusts. The μ_t values ordered in the sequence: Winter (6·10 m s^{-1}) < Spring (8·22 m s^{-1}) = Summer (8·28 m s^{-1}) < Autumn (26·48 m s^{-1}). Higher μ_t values were related to higher air humidity and lower wind speeds and temperatures. The μ_t values did not agree with the erosion amounts of each season, which ordered as follows: Summer (12·88 t ha^{-1}) > Spring (3·11 t ha^{-1}) = Winter (0·17 t ha^{-1}) = Autumn (no erosion). Low μ_t and erosion amounts of Winter were produced by a scarce number of gusts during eroding storms. We concluded that μ_t is useful as an index of soil susceptibility to wind erosion of different climatic periods. The use of a unique μ_t value in wind erosion prediction models can lead to erroneous wind erosion calculations. Copyright © 2008 John Wiley & Sons, Ltd.

KEY WORDS: threshold wind velocity; wind erosion; saltation activity; climatic conditions; Argentina

INTRODUCTION

Wind erosion is one of the most relevant soil degradation processes of arid and semi-arid regions of the world (Dregne, 1986). This process starts when wind velocity reaches a value that initiates the movement of soil particles, the so-called threshold wind velocity (μ_t).

The threshold wind velocity is variable and can be affected by soil surface conditions (soil moisture, vegetal cover and roughness) as well as by climatic factors (precipitation, temperature, evapotranspiration and relative humidity) (Stout, 2003, 2004). Some authors found a larger influence of soil water contents and some atmospheric variables such as air humidity (Ravi *et al*., 2004, 2006) and air temperature on the threshold wind velocity (Gregory and Darwish, 1989; McKenna-Neuman, 2003).

In the past, wind tunnel tests have been used to establish the threshold wind velocity (Bagnold, 1941; Kawamura, 1951; Zingg, 1953; Iversen and Rasmussen, 1994). The wind tunnel provides a controlled environment that allows a careful and systematic study of the threshold conditions (Stout and Zobeck, 1996; Stout, 2004), but it does not reflect exactly the field conditions. Furthermore, wind tunnel experiments have been used to test numerous empirical and theoretical models that express threshold velocity as a function of soil moisture (Bagnold, 1941; McKenna-Neuman and Nickling, 1989; Fecan *et al*., 1999; Cornelis *et al*., 2004). On the other hand, the determination of μ_t under natural field conditions is more difficult than with wind tunnels due to the intermittency

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of the saltation process (Stout, 2004) and the difficulty in obtaining accurate measurements of atmospheric and soil variables.

The Sensit is an electronic device based on a sensible diode which counts impacts of particles, mostly larger than $200\,\mu m$. This device has been used by Stout and Zobeck (1996, 1997) and Stout (1998, 2003, 2004) in order to develop a method for calculating μ_t in the field. Its high precision is based on the accurate determination of saltation, which facilitates the calculation of μ_t under realistic wind and surface conditions.

The wind erosion prediction models use a unique annual μ_t value to differentiate periods with high speed winds, which can erode the soil, from calm periods. The Revised Wind Erosion Equation (RWEQ) assumes a μ_t value of $5\,m\,s^{-1}$ (Fryrear *et al*., 1998), whereas the Wind Erosion Prediction System (WEPS) uses a μ_t value of $8\,m\,s^{-1}$ (Wagner, 2004). No attempts were done to determine the possible variation of μ_t under different climatic conditions existing within a year, nor tested its utility as an index of soil susceptibility variations to suffer wind erosion. The objective of this study was to calculate the annual and seasonal variability of μ_t in a semi-arid environment in order to test its variations under different climatic conditions and its reliability to be used as an index of soil susceptibility to wind erosion.

MATERIALS AND METHODS

The study was carried out in 1-ha plot located in the Experimental Field of the Faculty of Agronomy of the National University of La Pampa (36°34′S and 64°16′W). The climate of the study region is semi-arid, with a mean annual rainfall of 760 mm, most of which falls during Spring and Summer months. Mean annual air temperature is 15·5°C (Vergara and Casagrande, 2002). The mean annual wind velocity varies between 10 and $15\,km\,h^{-1}$, Spring being the season in which the wind reaches the highest speeds (INTA *et al*., 1980). The soil of the study site was a sandy loam Entic Haplustoll with 10 per cent clay, 17 per cent silt, 73 per cent sand and 1·6 per cent organic matter contents, with a A-AC-C horizon sequence (INTA *et al*., 1980).

The study was conducted between January 2003 and December 2005. The sampling plot had conditions for the occurrence of maximum wind erosion amounts as it remained bare and flat. These conditions were achieved by ploughing the soil up 20 cm of depth, with a harrow disk and then with a spike toothed harrow, both few days before measurements start and each time either weeds or soil crusting appear on the soil surface. Wind velocities were measured using cup-anemometers mounted at 2 m height and registered with an automatic meteorological station. Particle saltation was measured with a Sensit piezoelectric device (Fig. 1). The Sensit is an instrument that counts the number of particles that impact a piezoelectric sensing element, the output data being a pulse signal

Figure 1. Overview of the meteorological station and the Sensit.

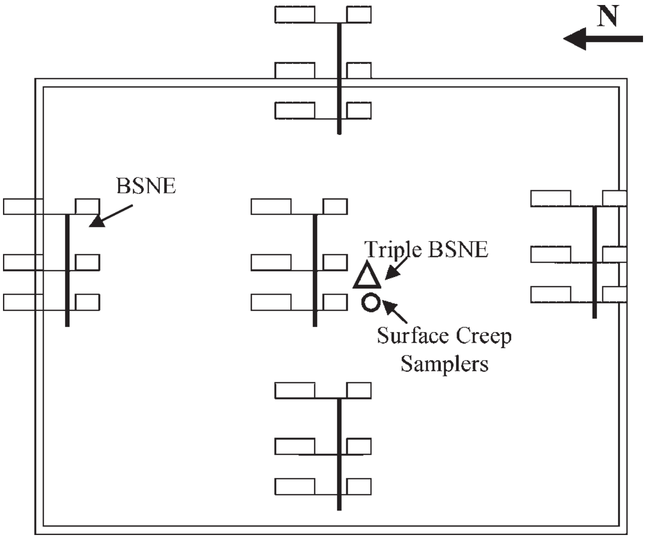

Figure 2. Location of dust samplers in the study site.

proportional to the number of particles impacts (Stockton and Gillette, 1990) allowing to calculate the duration of each erosive storm. The lower edge of the sensing element of the Sensit was at a height of 2 cm above the soil surface. The automatic meteorological station and the Sensit were located at the centre of the measurement plot and their data were recorded with 1 min frequency. Wind direction was obtained from tri-diurnal readings (9, 15 and 21 hr) collected by a meteorological tower located at INTA Anguil Experimental Station placed 20 km away from the experimental site.

Wind erosion in the sampling plot was measured using a combination of dust samplers: BSNE (Big Spring Number Eight), Triple BSNE and Surface Creep Samplers (Zobeck *et al.*, 2003), their space location is detailed in Figure 2. These combination of samplers allowed capture mass of sediment between 0·0015 and 1·5 m height above the soil surface. The sampling frequency was daily and when the erosive storm was insignificant the replacement of dust sampler was not made. The eroding material collected in each sampler was used to determine the horizontal flux using the equation of Stout and Zobeck (1996):

$$F_{(Z)} = f_{\mathrm{o}}(1 + (\mathrm{z}/\beta)^{-\delta} \tag{1}$$

where $F_{(z)}$ is the horizontal mass flux (kg m^{-1} s^{-1}) at height z, f_{o} the horizontal mass flux at the soil surface, β a scale height parameter and δ is a regression coefficient. The integration of the horizontal mass flux as a function of height allowed the calculation of the mass transport (kg m^{-1} s^{-1}). The difference between mass transport at leeward and windward sides of the sampling field allowed the calculation of the soil loss per square metre (Q). The multiplication of Q by the plot wide allowed the calculation of net soil loss from the plot expressed in t ha^{-1}.

One minute wind velocity observations averaged from 5 min periods were used to estimate μ_{t} (m s^{-1}) using the equation proposed by Stout (2004):

$$\mu_{\mathrm{t}} = \overline{u} - \sigma\Phi^{-1}(\gamma) \tag{2}$$

where $\bar{u}$ is the mean wind speed in m s^{-1}, σ the standard deviation of the mean wind speed, γ the saltation activity and Φ is the standard normal distribution function of γ. γ is a dimensionless ratio of the total number of minutes of saltation activity divided by the total number of minutes within the period of measurement, which was 5 min. The γ value always falls between 0 and 1, thus $\gamma = 1$ indicates continuous saltation activity and $\gamma = 0$ inactive saltation conditions. The function $\Phi^{-1}(\gamma)$ is undefined, thus threshold can be calculated only when the condition $0 < \gamma < 1$ is satisfied. Therefore, Eq. 2 can only be used when saltation activity is detected (Stout, 2004).

The mean wind velocity of the periods with saltation activity ($\bar{u}_{(\mu t)}$, m s^{-1}) was also calculated by averaging the wind velocity of the periods with Sensit pulses.

The total number of analysed storms during the sampling period (2003–2005) was 370, from which 70 had saltation activity.

All variables were defined by seasons: Summer (21st December to 20th March), Autumn (21st March to 20th June), Winter (21st June to 20th September) and Spring (21st September to 20th December).

The μ_t values were related to climatic factors which determine soil moisture conditions, such as precipitation, temperature and relative humidity. The quotient between mean precipitation and mean temperature was used to characterise the climate of each measurement period (UNESCO-FAO, 1963).

The μ_t data were compared between years and seasons by simple ANOVA and with the Fisher's least significant difference (LSD). The μ_t data registered in Autumn were excluded from this statistical analysis because only one storm, occurred in 2005, presented saltation activity.

RESULTS AND DISCUSSION

Figure 3 shows the environmental conditions of the measuring period. The mean monthly temperature had a recurrent behavior along the 3 years measurement period, being the averaged seasonal values higher in Summer (21·4°C) than in Spring (16·7°C), Autumn (13·1°C) and Winter (9·3°C). The averaged precipitation of the 3 years measurement period was higher in Spring (192·7 mm) and Summer (187·3 mm) than in Autumn (149·7 mm) and Winter (86 mm). The air relative humidity was higher in Autumn (70 per cent) than in Winter (67 per cent), Summer (61 per cent) and Spring (56 per cent).

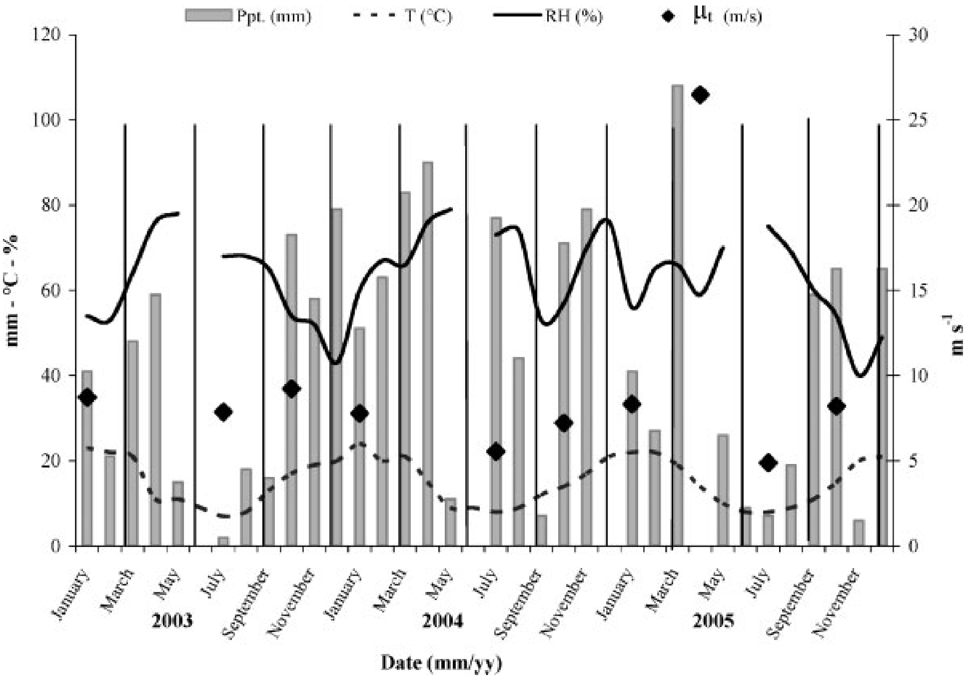

Figure 3. Environmental conditions during the period 2003–2005.

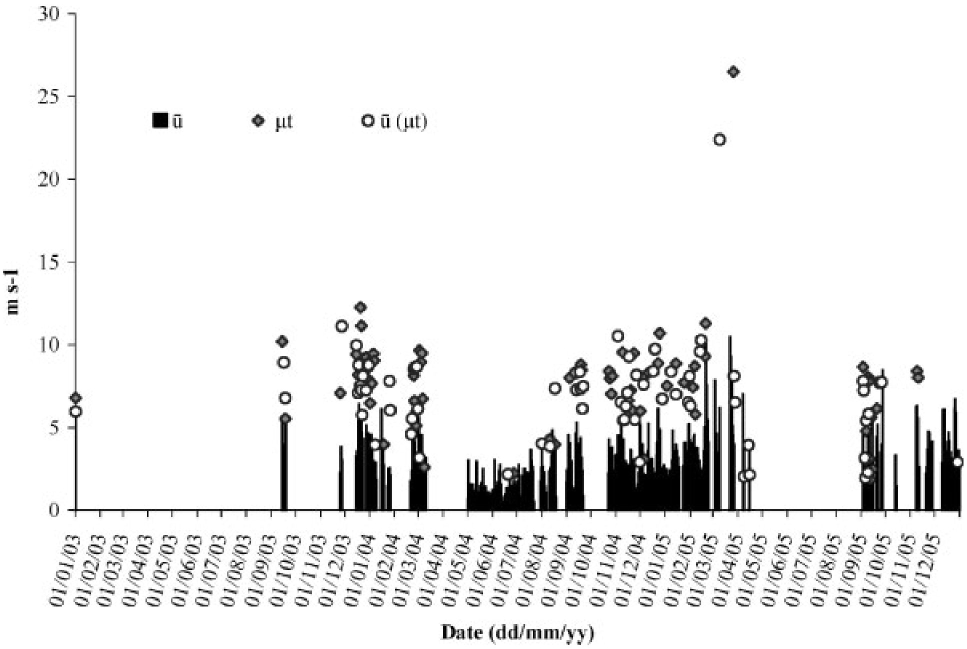

Figure 4. Mean wind velocity ($\bar{u}$), threshold wind velocity (μ_t) and mean wind velocity of the periods with saltation activity [$\bar{u}_{(\mu t)}$] recorded between 2003 and 2005.

The wind direction was mainly from North (30 per cent of the cases), followed by South (19 per cent), East (9 per cent) and calm (14 per cent). Considering only the storms with saltation activity ($n = 70$), the predominant wind direction was also North (46 per cent), followed by South (29 per cent) and East (21 per cent). This agrees with results of Casagrande and Vergara (1996), who found similar tendencies for 30 years climatic data record of the studied region. These results indicated that North is the wind direction with more erosive effects in this region.

The full record of the mean wind speed ($\bar{u}$), the wind velocity during the period with saltation activity [$\bar{u}_{(\mu t)}$] and the threshold wind velocity (μ_t) of the measuring period are presented in Figure 4. Seventy storms (19 per cent) of a total of 370 presented saltation activity. The measurement time of these 70 storms was 90 420 min, from which only 1239 min (1·4 per cent) presented saltation activity. Clearly, saltation activity occupied a small period of time of the total measuring period, in agreement with results of other authors (Stout and Zobeck, 1996, 1997, Stout, 2003). This indicated that the saltation activity showed high intermittency, due to the high variation of the climatic factors influencing soil surface conditions.

Table I shows that $\bar{u}$ varied between 1·24 and 4·75 m s^{-1}, with a mean of 3·41 m s^{-1} and a standard deviation of 1·07 m s^{-1}. The $\bar{u}_{(\mu t)}$ varied between 4·54 m s^{-1} and 8·20 m s^{-1} with a mean of 7·01 m s^{-1} and a standard deviation of 1·29 m s^{-1}. The μ_t values ranged from 4·89 m s^{-1} to 9·24 m s^{-1}, with a mean of 7·53 m s^{-1} and a standard deviation of 1·44 m s^{-1}. Both μ_t and $\bar{u}_{(\mu t)}$ data registered in Autumn were excluded from this analysis because they only correspond to one storm occurred in 2005.

The mean μ_t value of all measured storms (7·53 m s^{-1}) was greater than the μ_t value considered by the RWEQ (5 m s^{-1} at a 2 m height, Fryrear *et al*., 1998), and smaller than the μ_t value considered by WEPS (8 m s^{-1}, Wagner, 2004). The μ_t value found here was estimated at 1 min intervals, averaged over 5 min periods. It is known that μ_t decreases as long as the averaging time increases (Stout, 1998) which, therefore indicates that μ_t values could be somehow greater than 7.53 m s^{-1} if shorter periods of time were considered for its calculation.

Table I shows that the seasonal averaged μ_t value of the 3 years measurement period was lower in Winter (6·10 m s^{-1}) than in Spring and Summer (8·22 and 8·28 m s^{-1}, respectively). The yearly averaged μ_t was higher in

Table I. Threshold wind velocity (μ_t), mean wind velocity ($\bar{u}$), mean wind velocity of the periods with saltation activity [$\bar{u}_{(\mu t)}$] and averaged amount of eroded soil

		Summer	Autumn	Winter	Spring	Average yearly
μ_t (ms^{-1})	2003	8·72^{a} ($n = 5$)	—	7·87^{a} ($n = 2$)	9·24^{a} ($n = 4$)	8·6^{b} ($n = 11$)
	2004	7·78^{a} ($n = 17$)	nd	5·55^{b} ($n = 5$)	7·22^{a} ($n = 15$)	6·9^{a} ($n = 37$)
	2005	8·33^{a} ($n = 8$)	26·48 ($n = 1$)	4·89^{b} ($n = 10$)	8·21^{a} ($n = 3$)	7·1^{a} ($n = 21$)
	Average seasonal	8·28^{a}	26·48	6·10^{b}	8·22^{a}	7·53
$\bar{u}$ (μ_t) (ms^{-1})	2003	7·87^{a} ($n = 5$)	—	7·54^{a} ($n = 2$)	8·20^{a} ($n = 4$)	7·87^{b} ($n = 11$)
	2004	7·29^{a} ($n = 17$)	nd	5·13^{b} ($n = 5$)	6·94^{a} ($n = 15$)	6·45^{a} ($n = 37$)
	2005	7·86^{a} ($n = 8$)	22·38 ($n = 1$)	4·54^{b} ($n = 10$)	7·72^{a} ($n = 3$)	6·71^{a} ($n = 21$)
	Average seasonal	7·67^{a}	22·38	5·74^{b}	7·62^{a}	7·01
$\bar{u}$ (ms^{-1})	2003	4·75^{a} ($n = 7$)	—	4·17^{a} ($n = 6$)	3·87^{a} ($n = 9$)	4·26^{a} ($n = 22$)
	2004	3·14^{a} ($n = 46$)	1·24^{d} ($n = 51$)	2·20^{c} ($n = 67$)	2·67^{b} ($n = 60$)	2·31^{b} ($n = 224$)
	2005	3·44^{ab} ($n = 68$)	4·72^{a} ($n = 12$)	3·20^{b} ($n = 13$)	4·00^{ab} ($n = 31$)	3·84^{a} ($n = 124$)
	Average seasonal	3·77^{a}	2·98^{c}	3·19^{bc}	3·51^{ab}	3·41
Amount of eroded solid (t ha^{-1})	2003	32·936	—	0	1·807	11·581^{a} ($n = 5$)
	2004	3·893	0	0·021	2·473	1·597^{b} ($n = 7$)
	2005	1·809	0	0·476	5·039	1·831^{b} ($n = 7$)
	Average seasonal	12·879^{a}	0^{b}	0·166^{b}	3·106^{b}	5·003

Values followed by the same letter are not statistically different ($p < 0{\cdot}05$).

[nd] Data not available.

[n] Number of storms.

— Not measured.

2003 (8·6 m s^{-1}) than in both 2004 (6·9 m s^{-1}) and 2005 (7·1 m s^{-1}). These results indicated that conditions for the occurrence of soil erosion were not the same along the sampling period.

The 3 years averaged $\bar{u}_{(\mu t)}$ values varied significantly between seasons of the year ($p < 0{\cdot}05$, Table I), being higher in Summer (7·67 m s^{-1}) and Spring (7·62 m s^{-1}) than in Winter (5·74 m s^{-1}).

Autumn μ_t (26·48 m s^{-1}) and $\bar{u}_{(\mu t)}$ values (22·38 m s^{-1}) were not considered for the comparison of these values between seasons, as they correspond to only one storm occurred in 2005, data that were defined by the deleted studentised residual analysis as outlier ($p < 0{\cdot}001$).

The $\bar{u}$ values were different ($p < 0{\cdot}05$) between years and seasons of the year (Table I). Year 2003 and 2005 had higher $\bar{u}$ (4·26 and 3·84 m s^{-1}, respectively) than 2004 (2·31 m s^{-1}). Summer (3·77 m s^{-1}) and Spring (3·51 m s^{-1}) showed similar $\bar{u}$ values. Winter (3·19 m s^{-1}) and Spring were also not different amongst them but Winter and Autumn had lower $\bar{u}$ values than Summer. Autumn (2·98 m s^{-1}) showed the lowest $\bar{u}$ values than most of the seasons. These results were not in agreement with μ_t values, indicating that the threshold wind velocity appears to be independent of wind speed. Nevertheless, the seasonal μ_t values correlated well with $\bar{u}_{(\mu t)}$ ($y = 0{,}8145x + 0{,}877$, $R^2 = 0{,}9981$, $p < 0{\cdot}001$) and with lower significance with $\bar{u}$ ($y = 1{,}2493\mathrm{Ln}(x) + 0{,}957$, $R^2 = 0{,}4487$, $p < 0{\cdot}05$), indicating a logical dependence of μ_t from these independent variables.

The climatic conditions were not much different between Autumn and Winter than between Autumn and both Summer and Spring, but μ_t values were quite different between Autumn and Winter. Autumn had higher precipitations (122 mm in 2003, 184 mm in 2004 and 143 mm in 2005) than Winter (36 mm in 2003, 128 mm in 2004 and 94 mm in 2005), higher air relative humidity in most of the years (in average, 70 per cent in Autumn and 67 per cent in Winter) but similar mean wind speeds (2·98 m s^{-1} in Autumn and 3·19 m s^{-1} in Winter). The quotient between mean precipitation and mean temperature (UNESCO-FAO, 1963) was, in average of the three studied years, 2·9 in Autumn and 2·3 in Winter, indicating more moist conditions in Autumn than in Winter. These tendencies were the same along the three studied years and indicate that Autumn presented worst environmental conditions for the occurrence of wind erosion than the other seasons of the year, due to higher air humidity or lower wind speeds. This agrees with results of Ravi *et al.* (2004, 2006), who found that soil moisture contents (determined mainly by the relative air humidity) explained μ_t variations in wind tunnel studies.

The average amount of eroded soil was higher in Summer (12·88 t ha^{-1}) than in Spring (3·11 t ha^{-1}), Winter (0·17 t ha^{-1}) or Autumn, where no erosion was recorded. These results indicated that wind erosion amounts were not in agreement with μ_t values, which were higher in Spring and Summer than in Winter and Autumn. This speaks for a lack of correlation between the conditions for the occurrence of wind erosion and the amount of soil which is effectively eroded.

The disagreement between wind erosion amounts and μ_t values is particularly evident in Winter, where μ_t values and wind erosion amounts are low: high wind erosion amounts should be related to low μ_t. Such apparent contradiction can be explained either by the occurrence of very short lasting and less erosive storms or by low wind speeds and the lack of gusts during the storms. Winter presented longer lasting storms (570 min.) than Summer (408 min.) and Spring (225 min.), but storms with wind speeds higher than 7·53 m s^{-1} (the averaged μ_t value), lasted less (73 min) than in Summer (309 min) and Spring (143 min). The mean wind speed of the eroding storms, $\bar{u}_{(\mu t)}$, was lower ($p < 0{\cdot}05$) in Winter (5·74 m s^{-1}) than in Summer and Spring (7·67 and 7·62 m s^{-1}). These results indicated that the low wind speeds and lower amount of wind gusts during the erosion events explained the occurrence of low erosion amounts in Winter though the low μ_t values of this season.

CONCLUSIONS

The mean wind velocity for the whole studied period (3·41 m s^{-1}) was lower than the corresponding μ_t value (7·53 m s^{-1}) which indicates that wind erosion was produced mainly by wind gusts.

North was the prevailing wind direction of most eroding storms (46 per cent of the cases).

The μ_t value was higher than that considered by the RWEQ (5 m s^{-1} at a 2 m height), and lower than the μ_t value considered by WEPS (8 m s^{-1}).

Winter presented a lower μ_t value (6·10 m s^{-1}) than both Spring (8·22 m s^{-1}) and Summer (8·28 m s^{-1}) and Autumn (26·48 m s^{-1}). Higher μ_t values were mostly related to higher air humidity, wind speeds and temperature.

The μ_t values were not in agreement with the erosion amounts of each season, as Summer (12·88 t ha^{-1}) had higher erosion than Spring (3·11 t ha^{-1}), Winter (0·17 t ha^{-1}) and Autumn (no erosion) This indicates that the conditions for the occurrence of wind erosion expressed by μ_t values not necessarily agree with the amount of soil effectively eroded. Winter was a typical case of this, as it had both low μ_t (6·10 m s^{-1}) and erosion amounts. This divergence was explained mainly by the scarce number of gusts during eroding storms in this season.

We deduced that the equation proposed by Stout (2004) allows a rapid determination of the threshold wind speed under field conditions, an index of soil susceptibility to wind erosion. Nevertheless, μ_t is variable amongst seasons of the year and the use of a unique yearly μ_t value in wind erosion prediction models can lead to erroneous wind erosion calculations. More detailed climatic information must be further analysed, particularly wind gusts and the duration of eroding storms, to determine adequate μ_t values to be used in wind erosion models.

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