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RWEQ – Wind erosion predictions for variable soil roughness conditions

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ABSTRACT

The soil surface roughness is a main factor in all wind erosion prediction models, including the Revised Wind Erosion Equation (RWEQ). The objective of this study was to test the erodibility of two typical soils of the semiarid Argentinean Pampas under three different tillage conditions (compared to a flat surface) at three wind velocities using a wind tunnel and to evaluate the performance of the RWEQ model. Results showed that all rough surfaces were less eroded by wind than a flat surface (FS) in both soils and all wind velocities. An exception was LB (lister-bedder) in the Haplustoll that showed similar erosion than FS. Wind erosion increased rapidly above 16.5 m s^{-1} wind velocity in all tillage conditions. The relative wind erosion (RE) calculated with the RWEQ (K' factor) fitted well with measured RE, except for $K' < 0.1$ (rougher surface) where the measured RE were much higher than the predicted. More than 70% of RE variability was explained by the oriented roughness (Kr) in both soils. The aforementioned indicates that Kr can be used instead of K' (a value that contains both, Kr and the random roughness – Crr factors) to predict wind erosion with RWEQ in the studied soils. Absolute wind erosion amounts predicted with RWEQ fitted well with measured data only for DT, mainly at low wind velocity. For the other tillage tools, the model did not apply well as it underestimated the erosion for the rougher soil surface condition (LB) and overestimated it for the less rough surface (DH).

1. Introduction

Wind erosion is an important soil degradation process that takes place in arid and semiarid environments (Lal, 2001), including the semiarid Argentinean Pampas (SAP) (Buschiazzo et al., 1999). Ridge tillage is an alternative practice to control wind erosion in rain-fed croplands of semiarid regions, where crops usually do not produce enough residues and soils remain bare during long periods of time (Bielders et al., 2000; Liu et al., 2006). Ridge tillage that produces appropriate ridge height and which is performed perpendicularly to prevailing winds decreases wind erosion amounts in 85–90% in relation to a smooth surface (Fryrear, 1984).

Few studies have analyzed the relationship between ridge tillage and wind erosion. Armbrust et al. (1964), under laboratory and wind tunnel conditions, found that the efficiency in trapping soil particles and the decrease of wind velocity depend on ridge height. This effect also depends on soil cloddiness (Fryrear, 1984) and on the ridge height–spacing ratio (Kardous et al., 2005). Liu et al. (2006) found that when tillage ridges had the same height, wind erosion rates were proportional to the spacing between ridges. They also found that the effectiveness of ridge tillage to control wind erosion depends on wind velocity, which increases above a certain wind velocity. These previous studies showed the importance of ridge geometric characteristics, wind speeds and soil cloddiness on wind erosion control by ridge tillage, but these factors were studied independently among them. In addition, some of the previously mentioned reports were performed under laboratory conditions with artificial ridges made of quartz grains or wood that did not represent the interaction of the abovementioned factors in natural conditions.

Wind erosion can be estimated using wind erosion prediction models. The Revised Wind Erosion Equation (RWEQ) is a model that can be used in a wide variety of conditions, including regions with scarce climatic information like the semiarid Pampas (Buschiazzo and Zobeck, 2008) and other semiarid regions of the world (Guo et al., 2013; Visser et al., 2004). RWEQ includes a soil roughness factor (K') that represents the combined effects of both the oriented and the random roughness (Kr and Crr, respectively)

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on wind erosion. The previously mentioned factor was developed empirically using the ratios between soil losses of rough and flat surfaces and only one wind speed was used (Fryrear, 1984; Saleh and Fryrear, 1998). The relation between wind erosion and K' would probably be variable under different wind speeds and, furthermore, soil types. Therefore, in order to validate this model it is important to test it under variable wind speed and soil roughness conditions.

The interactions among soil cloddiness, ridge characteristics and wind speed have an important effect on wind erosion control. Little is known about these interactions. The dominance of some of these parameters could affect K' factor and, as a consequence, the performance of the RWEQ model. Therefore, the objectives of this study were: (a) to determine wind erosion amounts of two soils under three tillage tools and three wind velocities, (b) to validate the K' and Kr factors of RWEQ and (c) to test RWEQ for different wind speeds and soil roughness surfaces under wind tunnel conditions.

2. Materials and methods

Two different textured soils of the semiarid Argentinean Pampas (SAP) were used for this study: a sandy–loam Entic Haplustoll and a loamy–sand Typic Ustipsamment. These are representative of most soils of the SAP.

The Haplustoll was placed within the Experimental Field of the Faculty of Agronomy of National University of La Pampa (36°34′ S and 64°16′ W), and the Ustipsamment within the Experimental Field of Anguil Experimental Station of INTA (36°52′ S and 64°02′ W).

One to 2 kg of undisturbed soil samples were taken by triplicate from the 2.5 cm topsoil. Sampling was randomly done on 10 m^2 areas of soils submitted to continuous cropping since more than 50 years. Soil samples were air-dried, gently fragmented and then sieved with a rotary sieve. This device is essentially a rotating nest of concentric cylindrical sieves having 0.42, 0.84, 2, 6.4 and 19.2 mm^2 openings (Chepil, 1962). In addition, we took a composite sample of the first 20 cm to characterize soil texture and organic carbon content (Table 1).

The experiments were carried out with a portable wind tunnel, which is composed of three sections: (a) a trailer, (b) a flow-straightening section and (c) a working section. The trailer is the platform for a push type fan, the flow-straightening section homogenizes and orients the flow by means of a honeycomb and flaps, and the working section is 4 m long, 0.5 m wide and 1 m high. More details of this device can be found in Mendez et al. (2011). The tunnel was calibrated to obtain a logarithmic wind speed profile expected over a smooth and flat surface. The boundary layer thickness was 0.6 m and the threshold friction velocity 0.74 $m\,s^{-1}$ under natural roughness and bare soil, in field conditions.

Wind velocities were controlled at the end of the test section of the wind tunnel with a pitot static anemometer at 50 cm high from the soil surface and at the center of the wind tunnel. The eroded material was collected with a vertical slot sampler installed at the central point of the wind tunnel end. This sampler had a 3 mm wide and 1 m high inlet (Zobeck et al., 2003; van Pelt et al., 2010). The bottom of the lowest opening of the sampler was set flush with the tunnel floor.

The following tillage treatments were carried out in order to simulate contrasting soil surface conditions produced by different tillage tools: disk tandem (DT), drill-hoe (DH) and lister-bedder (LB). A flat surface (FS) was established by removing the plants residues and smoothing the surface with a garden rake. A view of treatments is shown in Fig. 1 and their main characteristics in Table 2. Tillage ridges were built manually with tools like hoes within the wind tunnel section, the bottom of ridges were set level with the tunnel floor and oriented perpendicularly to the wind direction. Although these tillage tools are used in the SAP, the data of height and spacing of ridges to build it were extracted from Revised Wind Erosion Equation Manual (RWEQ Manual) (Fryrear et al., 1998).

The oriented roughness (Kr) was estimated before each simulated event in all treatments by means of the following equation (Zingg and Woodruff, 1951):

$$\mathrm{Kr} = 4\frac{\mathrm{RH}^2}{\mathrm{RS}} \tag{1}$$

where Kr is the soil oriented roughness in cm; RH is the ridge height and RS the ridge spacing both in cm. RH and RS were measured with a tape-measure (Fig. 2). The Kr values of each treatment in both soils are presented in Table 2.

The random roughness, Crr [adimentional], was measured in FS in all simulations at different wind speeds while for the rest of roughness conditions (DT, DH and LB) it was measured at the start of performance, where nine readings were averaged to characterize natural roughness in each tillage treatment (Table 3). Crr was measured by means of the chain method (Saleh, 1993) and calculated with the following equation:

$$\mathrm{Crr} = 1 - \frac{L_2}{L_1} \times 100 \tag{2}$$

where Crr is the random roughness; L_1 [cm] is the full length of the chain and L_2 [cm] is the horizontal distance between chain ends when placed on the soil surface. The chain was 1 m long and each chain-link had 1.25 cm.

Wind erosion simulations were performed for each treatment (Table 2) in quadruplicate during three minutes and at three different wind velocities: 9.5, 16.5 and 22.5 $m\,s^{-1}$. The experiment involved 12 different sets of simulated ridges for each tillage implement (DT, DH and LB). These wind velocities were selected considering that these are the most common during the months of highest wind speeds (late winter and spring) (Casagrande and Vergara, 1996).

The RWEQ model estimates soil erosion and transport by wind between the soil surfaces and a height of 2 m for certain times of the year (Fryrear et al., 1998). The wind acts as trigger in this model, so any surface can erode more than the capacity of maximum wind transport (Fryrear et al., 1998). RWEQ utilizes monthly weather data, soil and field data, and management inputs. This model incorporated residue decomposition, soil roughness decay based on rainfall characteristics and clay content and the soil

Table 1
Main physical and chemical properties of the upper 20 cm of the studied soils.

	AS (mm) D (%)						Texture (%)			OC (%)
	>19.2	19.2–6.4	6.4–2	2–0.84	0.84–0.42	<0.42	Clay	Silt	Sand	
Entic Haplustoll	54.2 (5.1)	17.1 (2.2)	7.2 (0.8)	3.1 (0.1)	2.4 (0.2)	16.1 (0.1)	11	19	70	0.9
Typyc Ustipsamment	46 (6.2)	14.6 (2.1)	6 (0.3)	2.9 (0.1)	4.4 (0.3)	26.1 (0.3)	7	10	83	1.3

ASD = aggregate size distribution, OC = organic carbon contents. ASD was determined with a rotary sieve (Chepil, 1962). Each value is the average of 3 soils samples data.

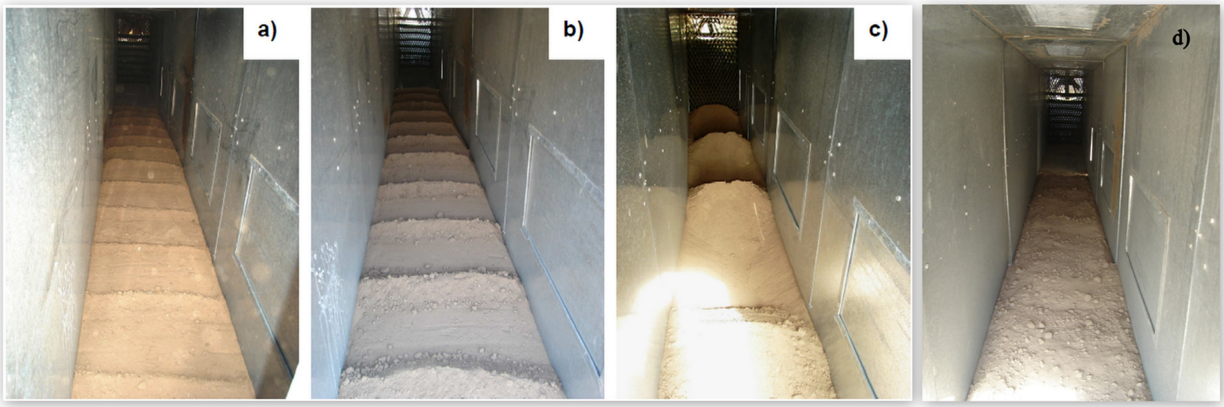

Fig. 1. View of the soil surface conditions produced by different tillage tools: (a) disk tandem (DT), (b) drill-hoe (DH), (c) lister-bedder (LB) and (d) flat surface (FS).

Table 2
Ridge spacing and height produced by different tillage tools. DT = disk tandem; DH = drill-hoe; LB = lister-bedder. Kr (oriented roughness).

Tillage tool	Ridge height* (cm)	Ridge spacing* (cm)	Kr	Height/ spacing
DT	2.54	30.50	0.85	1:12
DH	5.10	35.60	2.92	1:7
LB	25.40	101.60	25.40	1:4

* According to RWEQ (Fryrear et al., 1998).

roughness factor (K') that include, both random (clods) and oriented (ridges) roughness, the most important factors that reduce wind velocity at the surface, controlling wind erosion.

In each case, Crr and Kr values were used in order to calculate the soil roughness factor (K'). This factor is a single soil roughness value used by the RWEQ model to express the integrated effect of Crr and Kr and is expressed on relative wind erosion basis (Fryrear et al., 1998) using the following equation (Fryrear, 1984):

$$K' = e^{(1.86\ \mathrm{Kr} - 2.41\ \mathrm{Kr}^{0.934} - 0.124\ \mathrm{Crr})} \tag{3}$$

Absolute wind erosion amounts were expressed by means of the mass transport, Q (g m^{-2} min^{-1}). This parameter was calculated according to Eq. (4), where Ps (g) is the weight of the sediments collected in the wind tunnel sampler, S (m^2) is the eroded area and T (min) is the simulation time:

$$Q = \frac{Ps}{S \times T} \tag{4}$$

Measured wind erosion was calculated on relative basis (RE) with the following equation (Hagen, 2001):

$$\mathrm{RE} = \frac{Q_i}{Q_{\mathrm{FS}}} \tag{5}$$

where Q_i is the mass transport of the i treatment (DT, DH or LB) and Q_{FS} is the amount of eroded soil from the flat surface (FS). The wind erosion control efficiency (EC) of each tillage type was calculated with Eq. (6):

$$\mathrm{EC} = 100 - (\mathrm{RE} * 100) \tag{6}$$

RWEQ (Revised Wind Erosion Equation) model simulations were made using the simplified version “Stand alone” (Buschiazzo and Zobeck, 2008), which is used for discrete, short period simulations. The simulations were run using K' data obtained in this study, and data already presented by de Oro and Buschiazzo (2011) who used the same soils, wind velocities and tillage tools as here, which allowed the analysis of a larger amount of soil surface roughness data.

An ANOVA analysis with three fixed factors (soil type, tillage tool and wind velocity) and a randomized complete design was used to compare the effects of each treatment (tillage tool, soil type and wind velocity) on wind erosion amounts. When the variance indicated a significant effect of the treatment on each measured parameter, the Tukey test was used to compare their means.

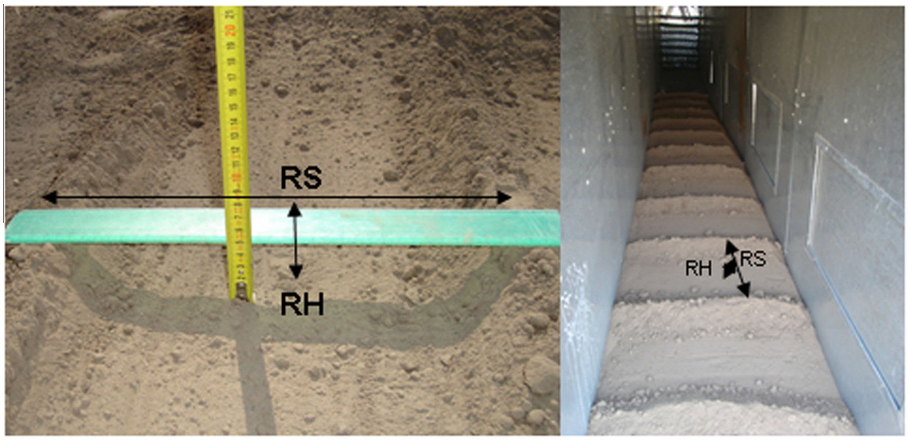

Fig. 2. Ridge spacing (RS) and ridge heights (RH).

Table 3
Random roughness (Crr) measured in each roughness conditions in both soils. DT = disk tandem; DH = drill-hoe; LB = lister-bedder and FS = flat surface.

Treatments	Crr	
	Haplustoll	Ustipsamment
FS	1.07 (0.05)	0.38 (0.07)
DT	1.21 (0.20)	0.53 (0.07)
DH	0.83 (0.22)	0.54 (0.08)
LB	0.92 (0.23)	0.55 (0.16)

Standard deviations are in parentheses.

A logarithmic function was used to transform the data and to achieve normality and homoscedasticity of data. The relationships between RE and soil surface roughness parameters (K', Kr and Crr) were analyzed by means of simple regression analysis. Tests were performed at a 0.05 probability level using INFOSTAT software (Di Rienzo et al., 2011).

3. Results

3.1. Effects of tillage treatments, soil types and wind velocities on wind erosion

Table 4 shows that the mass transport (**Q**) of both soils was lower in most rough treatments compared to the flat surface (FS) at all wind velocities ($p < 0.05$). An exception to this general trend was LB in the Haplustoll, where **Q** was not statistically different to that of FS ($p > 0.05$) at 16.5 and 22.5 m s^{-1} wind speeds.

In the Haplustoll, at a wind speed of 9.5 m s^{-1} **Q** was 11.1 g m^{-2} min^{-1} in FS, being the erosion higher than DT (1.1 g m^{-2} min^{-1}), DH (3.3 g m^{-2} min^{-1}) and LB (6.7 g m^{-2} min^{-1}) and under ridges treatments **Q** was low in DT, follow then by DH and finally by LB. At wind speeds of 16.5 and 22.5 m s^{-1} **Q** in FS was 70.0 and 233.3 g m^{-2} min^{-1}, respectively; being the erosion only higher than DT (23.3 and 90.0 g m^{-2} min^{-1} respectively) and DH (21.1 and 96.7 g m^{-2} min^{-1}, respectively) and similar to LB (55.5 and 171.1 g m^{-2} min^{-1}). Compare only ridges treatments DT and DH produced less erosion than LB at both wind velocities (16.5 and 22.5 m s^{-1}).

In the Ustipsamment, at a wind speed of 9.5 m s^{-1}, **Q** was higher in FS (27.8 g m^{-2} min^{-1}) than in the ridges treatments (DT, DH and LB). On the other hand, **Q** was lower in DT and DH (2.2 g m^{-2} min^{-1} as average of both treatments) than in LB (4.4 g m^{-2} min^{-1}). At the higher wind velocities (16.5 and 22.5 m s^{-1}) **Q** was also higher in FS than in the ridges treatments. On the other hand, **Q** was higher in DT than in the other tillage treatments (DH and LB). **Q** in DT was 24.4 and 174.4 g m^{-2} min^{-1} at 16.5 and 22.5 m s^{-1}, respectively while in DH (16.7 and 131.1 g m^{-2} min^{-1}, respectively) and LB (15.6 and 118.9 g m^{-2} min^{-1}, respectively).

In FS, **Q** was higher in the Ustipsamment than in the Haplustoll only at 9.5 m s^{-1}. In DT (smallest ridges) **Q** also was higher in the Ustipsamment than in the Haplustoll but only at 9.5 and 22.5 m s^{-1} wind speeds ($p < 0.05$). In DH (medium ridges), **Q** at the lowest wind velocities (9.5 m s^{-1}) was higher in the Haplustoll than in the Ustipsamment soil but at the highest speeds (22.5 m s^{-1}) **Q** was higher in the Ustipsamment than in the other soil. Finally was not difference between soils at 16.5 m s^{-1} ($p < 0.05$). In LB (high ridges) **Q** was higher in the better aggregated soil (Haplustoll) than in the Ustipsamment, being the differences significant at the highest wind velocities ($p < 0.05$).

Q was positive related to wind velocity in both soils. Above 16.5 m s^{-1}, **Q** increased sharply, in all tillage tools, especially in the Ustipsamment. In the Haplustoll soil, an increase from 9.5 to 16.5 m s^{-1} represent an increment of 58.9 g m^{-2} min^{-1} in FS, of 22.2 g m^{-2} min^{-1} in DT, of 17.8 g m^{-2} min^{-1} in DH and of 48.8 g m^{-2} min^{-1} in LB. This increment was the double when we compared the increase from 16.5 to 22.5 m s^{-1}: 163.3 g m^{-2} min^{-1} (FS), 66.7 g m^{-2} min^{-1} (DT), 75.6 g m^{-2} min^{-1} (DH) and 115.6 g m^{-2} min^{-1} (LB). In the Ustipsamment soil, for the first range of speed, the absolutes increases of **Q** were for FS 57.8 g m^{-2} min^{-1}, for DT 22.2 g m^{-2} min^{-1}, for DH 14.5 g m^{-2} min^{-1} and for LB 11.2 g m^{-2} min^{-1}. In the second range of speed (16.5–22.5 m s^{-1}) the increases were at least 6 times higher than that in the low speed range, the exception was FS (only 3.5 times): 201.1 g m^{-2} min^{-1} (FS), 150.0 g m^{-2} min^{-1} (DT), 114.4 g m^{-2} min^{-1} (DH) and 103.3 g m^{-2} min^{-1} (LB). It can observed that in the first range of wind speed (9.5–16.5 m s^{-1}) the **Q** increments were very similar in both soils but in the range of the highest speeds the increments was more greater in the Ustipsamment than in the Haplustoll.

3.2. Relative wind erosion as a function soil roughness

The relative wind erosion (RE) varied from 8% to 61% in the Ustipsamment and 10–79% in the Haplustoll. RE is used by several wind erosion prediction models, for example RWEQ (Fryrear et al., 1998), instead of the absolute wind erosion amounts. This allows the comparison of wind erosion as a function of the surface roughness between soils (Eq. (6)). For a better interpretation of the tillage effectiveness in reducing wind erosion we used the efficiency of control (EC, Eq. (6)). In the Ustipsamment, at a wind velocity of 9.5 m s^{-1}, the mean EC of all tillage treatments was 89% (ranging from 84% to 92%) while at higher wind velocities it decreased to 51% (varying between 34% and 59%).

In the Haplustoll, EC also decreased when the wind velocity increased but with a greater variation between tillage treatments than in the Ustipsamment. At a wind velocity of 9.5 m s^{-1}, the mean EC was 67% (ranging from 39% to 90%) and at 22.5 m s^{-1} EC decreased to 49% (ranging from 26% to 61%). The RWEQ model used K' factor to express relative wind erosion on the basis of random and oriented soil roughness effect (Fryrear et al., 1998).

Fig. 3 shows the relationship between RE and K' for both soils. A lineal model fitted adequately to both data for K' values higher than 0.1 in both soils and tillage tools ($p < 0.01$). The RWEQ model estimated better the data obtained from the tillage (DT and DH) in the Ustipsamment (more sandy soils) due to the fact that the model was developed on sandy soils. But when data from

Table 4
Mass transport (**Q**) in g m^{-2} min^{-1} at three wind velocities (m s^{-1}) on two soils under different tillage tools.

	Typic Ustipsamment				Entic Haplustoll			
Wind velocity (m s^{-1})	FS	DT	DH	LB	FS	DT	DH	LB
9.5	27.8^{a}	2.2^{e}	2.2^{e}	4.4^{c}	11.1^{b}	1.1^{f}	3.3^{d}	6.7^{c}
16.5	85.6^{a}	24.4^{c}	16.7^{de}	15.6^{e}	70.0^{ab}	23.3^{c}	21.1^{cd}	55.5^{b}
22.5	286.7^{a}	174.4^{b}	131.1^{cd}	118.9^{de}	233.3^{ab}	90.0^{f}	96.7^{ef}	171.1^{bc}

Different letters indicate that data are significantly different between tillage tools and soil types for each wind velocity (Tukey, $p < 0.05$). Each value is the average of four replicates. FS = flat surface; DT = disk tandem; LB = lister-bedder; DH = drill-hoe.

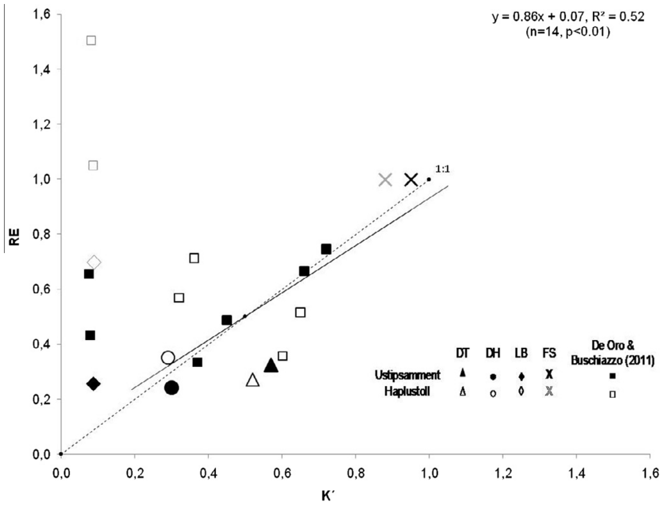

Fig. 3. Relationship between the measured (RE) and the RWEQ – calculated relative wind erosion (K' factor). DT (disk tandem), DH (drill-hoe), LB (lister-bedder) and FS (flat surface). Fitted function correspond to $K' > 0.1$ ($n = 14$, $p < 0.05$). Data from de Oro and Buschiazzo (2011) are illustrated by square icons black and white depending the soil.

Haplustoll was observed (more aggregated soil with high % of clay), the model tends to underestimate RE in DH (medium height ridges) and to overestimate it in DT (low height ridges).

For K' data lower than 0.1, which corresponds to LB (highest ridges), the fitting between RE and K' was not good ($p > 0.05$). In fact, RE data were much higher than K' data. This indicates RWEQ underestimated RE. These differences were higher in the Haplustoll.

RE was weakly correlated with random roughness (Crr) in both soils in a linear way ($p > 0.05$). This indicates that Crr has a low effect on wind erosion on both soils. Crr values of the flat surface (FS) were higher for the Haplustoll (1.07) than for the Ustipsamment (0.38) consistent with the better soil aggregation that the first soil presented from the second one (Table 1). Considering all tillage treatment, Crr controlled a 12% of the wind erosion in the Haplustoll and a 5% in the Ustipsamment.

In both soils, more than 70% of RE variability was explained by Kr (Fig. 4). In the Ustipsamment, the relationship between RE and Kr was power and negative for high wind velocities (22.5 and 16.5 m s^{-1}), while for 9.5 m s^{-1} the relationship was positive ($p < 0.01$), exhibiting little variation above a Kr value of 5 in all cases. In the Haplustoll, a power and positive relationship existed between RE and Kr for all wind velocities ($p < 0.01$). For a same value of Kr the effective to control wind erosion decreases as wind velocity increased. This also occurred in Ustipsamment soil.

Linear regression analysis showed that the RWEQ-estimated and the observed absolute wind erosion amounts were highly correlated ($p < 0.05$) for all roughness and soils (Fig. 5). RWEQ predicted between 53% and 95% of the observed erosion under all tillage conditions. Nevertheless, all regressions showed different slopes than the 1:1 relationship between variables.

In DT (Fig. 5a) the slop of the regression in both soils represents ¼ the model slope (1:1). However, at lower wind speed the model estimated better the observed erosion but then at high wind velocities (22.5 m s^{-1}) the model underestimated the observed erosion four times more, also in both soils.

For the other two tillage conditions, the RWEQ model largely overestimates the observed erosion in DH (Fig. 5b) and underestimates in LB (Fig. 5c). In the case of DH the slope was ten times higher than 1:1 model slope in the Ustipsamment and six times in the Haplustoll. In LB the slope of the model was largely higher than the slope of the observed erosion, 200 times for the Ustipsamment and 500 times for the Haplustoll soil. As well as for DT, the greater over and underestimation occurred at highest wind speeds.

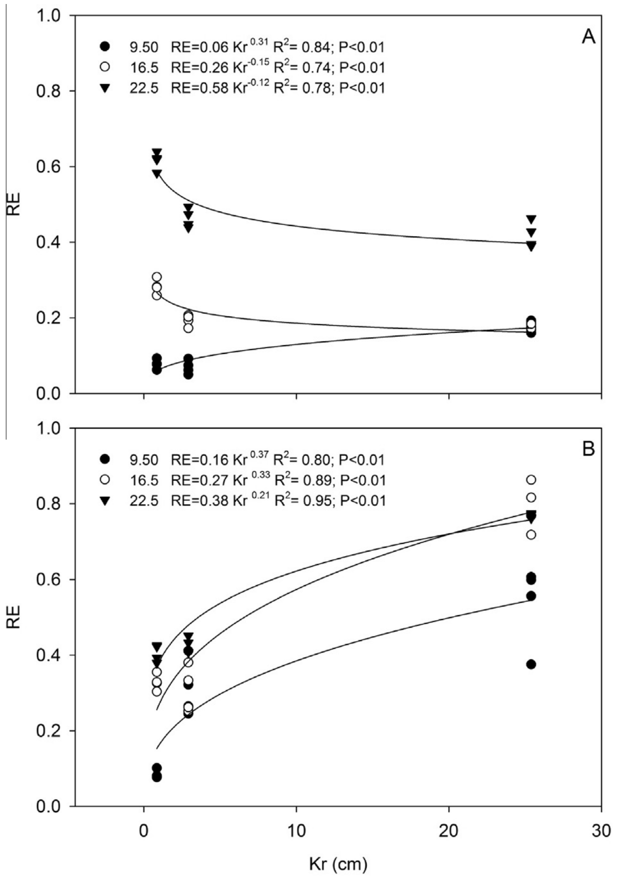

Fig. 4. Relationships between the relative wind erosion (RE) and the oriented soil surface roughness (Kr) at three different wind velocities in two soils: (A) Ustipsamment and (B) Haplustoll.

4. Discussion

Wind erosion under the flat surface (FS) was higher than under different kind of ridges tillage (DT, DH and LB) in both soils and wind velocities. Ridges were very efficient in reducing wind erosion at all wind velocities in both soil types. These results can be attributed to the shelter effect of ridges that trap soil particles in the furrow between ridges and reduce wind velocity near the soil surface (Fryrear, 1984; Marlatt and Hyder, 1970).

An exception to this general trend was LB in the Haplustoll at the highest wind speed. This may be due to the high wind velocity and more turbulent airflow on the upper position of the ridges which made the soil to be eroded easily. The higher exposure and the effect of turbulence on ridges crest may have been more pronounced in the soil with better aggregation (Table 1) and therefore more stable ridges (Haplustoll). Such results agree with findings of other authors, who attributed the relative high wind erosion of very rough surfaces to the turbulence of the airflow on the crest of the ridges, particularly at high wind velocities (Armbrust et al., 1964; Marlatt and Hyder, 1970; Zhang et al., 2004).

In the Haplustoll, the mass transport (**Q**) increased as ridges height increased from 2.54 to 25.40 cm under all wind velocities. These results partially agree with those of Armbrust et al. (1964)

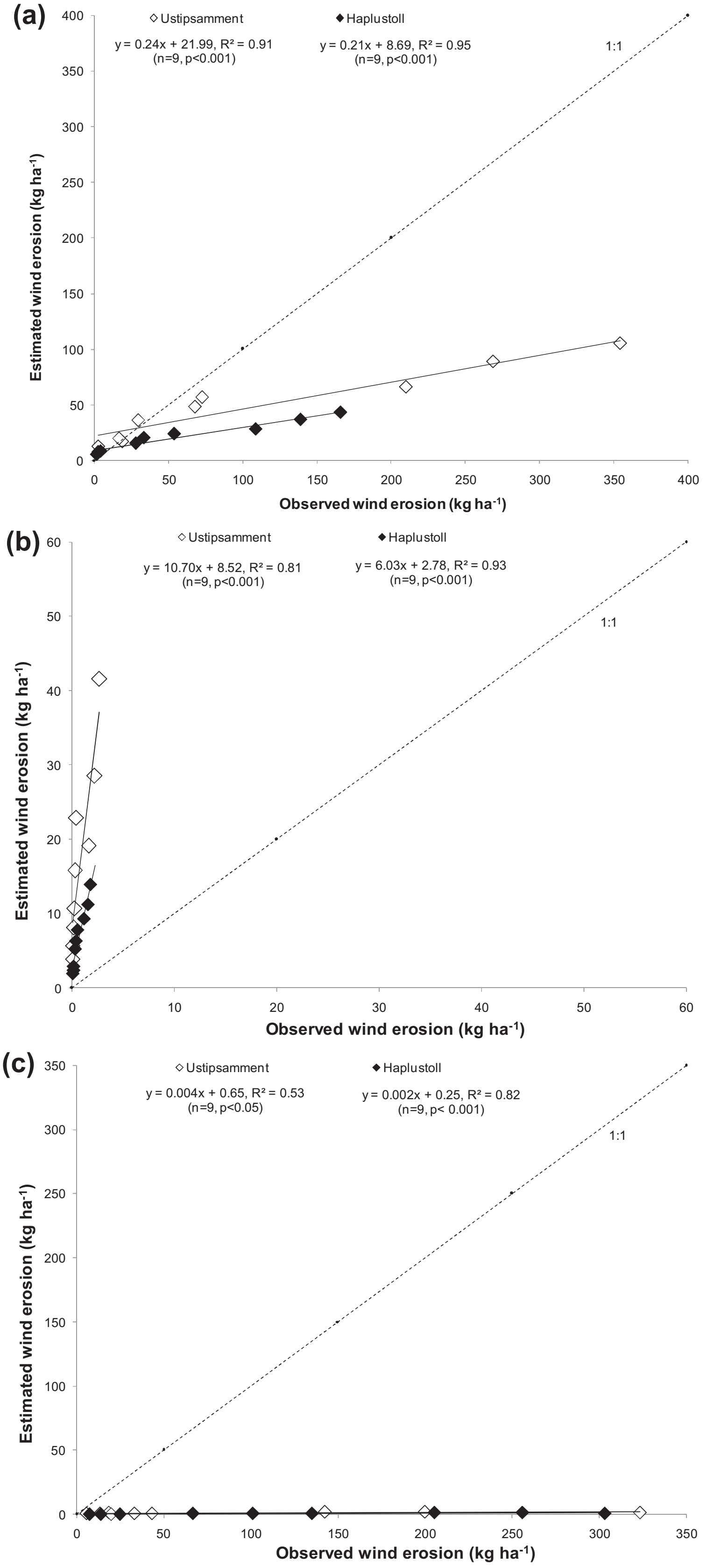

Fig. 5. Relationships between the observed and the RWEQ-estimated wind erosion amounts for three tillage tools: (a) DT (disk tandem), (b) DH (drill-hoe) and (c) LB (lister-bedder).

who showed an increase in soil erosion as ridges height increased from 10 to 20 cm. However, for ridges lower than 5 cm height, Armbrust et al. (1964) found that these were flattened before soil erosion ceased, and therefore were not effective in trapping soil particles. Probably the difference with our results may because in our study ridges were constructed with soils which maintained their natural aggregation and therefore more stable than artificial ridges built by Armbrust et al. (1964) study.

In the Ustipsamment, DH and LB were more effective in reducing **Q** than DT at the two highest wind velocities, meanwhile at the lowest wind velocity (9.5 m s^{-1}) it was the opposite. Probably, in this soil (Ustipsamment), which presents low aggregation and especially under high wind velocities, DT produced low height ridges which are susceptible to be flattened becoming not efficient in trapping soil particles and controlling wind erosion Armbrust et al. (1964). This confirms that the erodibility of the ridge changes according to the wind velocity and soil type.

Results showed that the wind erosion control efficiency of ridges and the ridges erodibility depend on the interaction between ridge–clods relationship and wind velocity. Fryrear (1984) showed that the benefits of soil cloddiness and soil ridges are additive to control wind erosion. However, Armbrust et al. (1964) reported that these factors appear to be dominant in some ridges heights depending on the wind velocity. Also, Kardous et al. (2005) showed that the trapping efficiency decreased with increasing wind velocity generating more erosion.

A wind speed of 16.5 m s^{-1} was considered a critical velocity from which wind erosion increased rapidly in all tillage tools. These results agree with those of He et al. (2004) and Liu et al. (2006) who found that ridge tillage was more effective beyond a critical wind velocity (15 m s^{-1}).

The relative wind erosion calculated with RWEQ (K' factor) overestimated the measured relative erosion (RE) (Fig. 3) in the less rough surface (DT) in the Haplustoll but not in the Ustipsamment. This can be due to the higher efficiency of the Haplustoll ridges in controlling wind erosion than those of the Ustipsamment (sandier soil), as they were not destroyed by abrasion during simulations. The better fitting between the predicted and the measured RE found in the Ustipsamment can be due to the fact that RWEQ model was developing using soils with high san content similar to the Ustipsamment (Fryrear et al., 1998). In medium ridges (DH), RWEQ underestimated RE in the Haplustoll but not in the Ustipsamment. This can be due to the additive effect of soils cloddiness and height ridge may have increased wind velocity in the ridge crest producing more erosion than the estimated by model, in the Haplustoll. The better fitting in the Ustipsamment as it was explained to DT. In highest ridges (LB) RWEQ underestimated RE in both soils as a consequence of the more turbulent movement of the airflow in ridges crests, a not considered effect by RWEQ, mainly, in the better aggregated soil.

Crr was not as effective as Kr in controlling erosion in both studied soils, in agreement with results of Fryrear (1984) who indicated that ridges are more effective in controlling erosion than the random roughness (Crr). Considering that Kr explained much of wind erosion variations, which is in agreement with results of other authors (Armbrust et al., 1964; Lyles and Tatarko, 1986; Bielders et al., 2000; Liu et al., 2006), it can be concluded that Kr can be used, instead of K', as a simple tool for calculating the relationship between wind erosion and the soil surface roughness, when ridges are perpendicular to the wind direction, in relatively low aggregated soils of semiarid regions.

The power and negative relationship between RE and Kr in a coarse-textured soil and less aggregated soil (Ustipsamment) (Fig. 4A) shows that ridges with lower height (mainly 2.5 cm high) were flattened by abrasion under increasing wind velocity, being less effective in controlling erosion, in agreement with Fryrear (1984), and of Armbrust et al. (1964) results, who showed that ridges with 1.3–2.5 cm height were less effective in controlling wind erosion. On the other hand, these authors also showed that in high aggregated soils, ridges lower than 5 cm height were more effective in controlling erosion, even at high wind velocities, which agrees with the results found for the Haplustoll.

In the Haplustoll RE and Kr correlated in a power and positive way for all wind velocities (Fig. 4B). In this soil, with more stable ridges than in the Ustipsamment, as wind velocity increase RE increase due the high wind eddying and turbulent on ridges crest. These results agree with those of Armbrust et al. (1964).

So we can observe that the effect of the ridges to control wind erosion depends on the interaction of soil cloddiness, wind velocity and ridges characteristics.

The large underestimation of wind erosion by RWEQ in LB is consistent with data presented in Fig. 3, which also indicates that the soil roughness subroutine of RWEQ, expressed by the K' factor, largely underestimates the relative erosion when the soil surface is very rough. This underestimation can be produced by the flowed prediction model of the wind movement in the presence of high ridges and the difficulty of RWEQ to predict wind erosion under highly variable surfaces of tilled fields. Wind erosion underestimations of RWEQ in DT and overestimations in DH are also related to results of Fig. 2, in which similar tendencies of K' and RE can be observed.

Differences between estimated and observed absolute wind erosion amounts can originate the different magnitudes of wind erosion occurring in a wind tunnel and at a field – scale. Van Pelt et al. (2004) concluded that RWEQ tended to overestimate wind erosion in low magnitude events and underestimate wind erosion for large magnitude events and highlights the difficulty of the model to predict the temporal and spatial variability of soil surface characteristics, the random nature of turbulence, and the temporal and spatial variability of wind-induced soil movement.

In the end, it seems RWEQ model does not apply well here in general when considering highly variable surface of tilled fields and higher wind velocities. But it seems to work best when surface roughness was small and the wind velocity was lower. It can be concluded that RWEQ can be used for estimating wind erosion in tillage systems with ridges presenting similar heights and spacing like DT (small roughness), but not useful for high ridges like DH and LB.

5. Conclusions

Rough surfaces considered here, created by three different tillage tools, produced less wind erosion than a flat surface (FS) in both soils and all wind velocities. An exception was high ridges (LB) in the Haplustoll where the highest wind velocities produced similar wind erosion than the flat surface.

Low and medium rough surfaces (DT and DH) were the most efficient in reducing wind erosion in the better aggregated Haplustoll, at all wind velocities. In the less aggregated Ustipsamment only the medium rough surface (DH) effectively controlled wind erosion at all wind velocities.

The wind erosion control efficiency of tillage types (EC) decreased when the wind velocity increased but with a greater variation between tillage treatments in the Haplustoll than in the Ustipsamment soil. EC in the Ustipsamment ranged from 89% to 51% while in the Haplustoll from 67% to 49%. Above 16.5 m s^{-1} wind erosion increased sharply, in all tillage tools, especially in the Ustipsamment.

In all tillage treatments Crr controlled less than 15% of the erosion in both soils. More than 70% of RE variability was explained by the oriented soil surface roughness produced by tillage (Kr) in both soils. Therefore, Kr can be used, instead of K', for calculating the effect of soil surface roughness on wind erosion in less structured soils of semiarid regions.

RWEQ adequately predicted RE for K' values higher than 0.1, but tended to underestimate it in DH (medium height ridges) and to overestimate it in DT (low height ridges). For K' data lower than 0.1, which corresponds to LB (highest ridges) the fitting with RE was not good, which indicates that the effect of roughness on the relative erosion amounts was underestimated by the soil roughness subroutine of RWEQ.

In general, under our study conditions, the RWEQ model does not apply well for highly and medium rough surfaces, but it seems to work fine for small rough surfaces, mainly at low wind velocities.

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