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Degradation of the soil surface roughness by rainfall in two loess soils

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ABSTRACT

The soil surface roughness is one of the main factors affecting wind erosion. Little is known about the influence of rains on the degradation rate of the soil surface roughness in different tillage systems and soil types. The purpose of this paper was to evaluate the dynamics of the oriented (Kr) and the random (Crr) soil surface roughness as affected by three tillage tools: a disk tandem (DT), a lister-bedder (LB) and a drill-hoe (DH), and two rain amounts (7 and 28 mm), in two soil types (an Entic Haplustoll and a Typic Ustipsamment). Measured Kr and Crr decay rates were compared with the predicted data, according to the equations provided by the Revised Wind Erosion Equation (RWEQ). Results indicated that initial Kr values were different in each tillage tool in both soils (LB>DH>DT, $p<0.05$), while Crr values were mostly similar. The degradation rate of Kr (ORR) was in general higher in the Ustipsamment than in the Haplustoll and in DT than in DH and LB, in both soils. The degradation rate of Crr (RRR) was affected by the soil type (mostly higher in the Ustipsamment than in the Haplustoll) but not by tillage. Increasing rains degraded Kr and Crr at higher rates in both soils, but Kr degraded relatively less when its initial values were higher (LB<DH<DT). RWEQ equations underestimated the soil surface roughness decay in both studied soils, between 60 and 72% for RRR and between 90 and 97% for ORR. The accumulated rain amounts (CUMR) and rain energy (CUMEI) allowed a good prediction of the relative degradation of the oriented roughness. The relative Kr variation as a function of the initial Kr value varied potential negatively and were different for each soil and rain amounts. These equations may allow the calculation of the degradation rate of the oriented roughness as affected by certain rain amounts and the initial Kr. In view of these results it must be further investigated if a unique equation can be developed for predicting soil surface degradation for different soils and rain amounts.

1. Introduction

Wind erosion is an important soil degradation process in semiarid regions, which can be substantially reduced by the soil surface roughness (Jester and Klik, 2005). The soil surface roughness modifies the wind profile, increasing the height of the wind shear velocity near the soil surface, decreasing its erosion (Stout and Zobeck, 1996). This makes the surface roughness act as a shelter, protecting the soil surface against the impact of saltating grains (Zobeck and Popham, 2001).

Soil surface roughness can also affect several physical soil properties such as infiltration, solar radiation and reflection, soil temperature, and trafficability (Zobeck and Onstad, 1987). More recent studies consider that soil surface roughness acts at small scales as an erodibility factor determining the resistance or vulnerability of the soil to erosion. At higher scales roughness becomes an erosivity factor, structurally mediating erosive energy of wind and water (Merrill et al., 2001).

The soil surface roughness is a parameter of the SOIL subroutines of most existing wind erosion prediction models, for example the Wind Erosion Equation (WEQ, Woodruff and Siddoway, 1965), the Revised Wind Erosion Equation (RWEQ, Fryrear et al., 1998) and the Wind Erosion Prediction System (WEPS, Hagen, 1991). These models consider precipitation as the most important factor for soil roughness degradation.

RWEQ has been demonstrated to be a reliable model for predicting wind erosion in many parts of the world (Fryrear et al., 1998; Van Pelt et al., 2004; Zobeck et al., 2001) including the semiarid Pampas of Argentina (Buschiazzo and Zobeck, 2008). This model calculates the degradation rate of both, the oriented and the random roughness on the basis of the accumulated rains, the rainfall energy index and a decay factor which depends on soil texture and organic matter contents (Potter, 1990; Saleh, 1997). The degradation rate of both roughness is calculated on the basis of the quotient between their initial and final values after a rain event. This calculation may underestimate K′, the factor that unifies Crr and Kr, and that is used in the model to predict wind erosion amounts. This is because the consideration of a relative Kr value at the start of each successive wind

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erosion period can be much smaller and not related to the initial Kr value. It is known that the height of the ridges is the main factor driving wind erosion (Lyles and Tatarko, 1987; Zobeck and Popham, 2001), therefore we assume that the consideration of the initial Kr value for calculating K′ in successive erosion events can improve the performance of the model for predicting the soil surface roughness decay rate as a function of rains.

Many authors analyzed the effect of rains on the random roughness (Crr), for example Burwell and Larson (1969), Dexter (1977), Johnson et al. (1979) Onstad et al. (1984) and Steichen (1984) found larger Crr changes as a function of increasing rainfall kinetic energies and Onstad et al. (1984), Römkens and Wang (1985) and Potter (1990) as a function of increasing accumulated rainfall. Zobeck and Popham (2001) found that the rate of degradation of the random roughness by rains of the same energies depends on its initial values. In general, this change increases with larger initial roughness values. Zobeck and Popham, 2001 demonstrated that the rate of change in random roughness also depended on the initial roughness value.

The degradation of the oriented roughness (Kr) as a function of rains has been less studied than that of the random roughness (Crr). Lyles and Tatarko (1987) found that the decay of ridge height was better explained by two- and three variable regression equations, where the cumulative precipitation, the sand to silt ratio and the organic matter contents were included. Other studies indicated that the decay of soil ridges is much slower than that of soil aggregates, ridges being more stable and effective for controlling wind erosion when the wind direction was perpendicular to the ridges (Saleh and Fryrear, 1997). Lyles and Tatarko (1987) indicated that the ridge height ratio (the quotient between the final and the initial ridge height) decreases with increasing precipitation, depending on its initial height, which is defined by tillage type and soil conditions at the time of operation. These authors also found that cumulative rains were the primary factors influencing changes in ridge height, while soil properties were secondary factors. Saleh (1997) concluded that soil ridge decay is influenced by the initial roughness value.

The calculation of soil surface degradation rates by RWEQ includes a soil factor which depends on clay and organic matter contents. This factor reflects the stability of soil aggregates against the degradation effects of rains. López et al. (2007) demonstrated that the equation considered by RWEQ for calculating the amount of erodible fraction (aggregates finer than 0.84 mm, directly related to the potential erosivity of the soil), does not predict this fraction adequately for soils of the semiarid Pampas of Argentina. These authors concluded that properties regulating the aggregate stability of soils of this region are different from those considered by RWEQ.

Another issue to be considered in relation to the calculation of the degradation rate of the soil roughness by wind erosion prediction models is use of both the accumulated rainfall amounts (CUMR) and the storm energy (CUMEI). Some authors suggest that CUMR can be used without considering CUMEI (Cogo et al., 1984; Mannering et al., 1966; Potter, 1990; Zobeck and Onstad, 1987). If this is true the SOIL ROUGHNESS subroutines of the RWEQ can be simplified as the calculation of CUMR is much simpler than that of CUMEI.

Based on former results, the objective of this study was to evaluate the dynamics of soil roughness decay (oriented and non-oriented) as a function of rains, in different tillage systems in two different textured soils. The purpose of this analysis was to evaluate if equations of RWEQ can be used in their present state for calculating the degradation of both, the oriented and the random roughness of soils of the semiarid Pampas of Argentina.

2. Material and methods

Two different textured soils of the semiarid Pampas of Argentina were used for this study: a loamy-sand Entic Haplustoll and a sandy Typic Ustipsamment (INTA et al., 1980). The Haplustoll was placed within the Experimental Field of the Faculty of Agronomy of La Pampa National University (36°34′ S and 64°16′ W), and the Ustipsamment within the Experimental Field of the Anguil Experimental Station of INTA (36°52′ S and 64°02′ W).

The Entic Haplustoll had a horizon sequence A–AC–C–C_k (INTA et al., 1980). It content was 11% of clay, 19% of silt, 70% of sand, 1.6% of organic matter and its field capacity was 13.6%. The initial aggregate size distribution for this soil was: >19.2 mm (54.2%), 19.2–6.4 mm (17.1%), 6.4–2.0 mm (7.2%), 2.0–0.84 mm (3.1%), 0.84–0.42 mm (2.4%) and<0.42 mm (16.1%). The Typic Ustipsamment had a horizon sequence A–AC–C (INTA et al., 1980), 7% of clay, 10% of silt, 83% of sand, 2.2% organic matter, 7.8% field capacity and its initial aggregate size distribution was: >19.2 mm (46%), 19.2–6.4 mm (14.6%), 6.4–2.0 mm (6%), 2.0–0.84 mm (2.9%), 0.84–0.42 mm (4.4%) and<0.42 mm (26.1%).

The following treatments were carried out in order to simulate contrasting soil surface conditions produced by different tillage tools: lister-bedder (LB), drill-hoe (DH) and disk tandem (DT). An overview of the soil surface roughness produced by each tillage tool is illustrated in Fig. 1 and their characteristics are listed in Table 1. The random and the oriented roughness data produced by each tillage tool are presented in Table 2. Ridges had approximately 1:1 side slopes in this study, differing from the 1:3 sized slopes provided by RWEQ.

The effect of rains on the degradation rate of the soil surface roughness was performed with a rain simulator. This device consisted of a square frame supported by four expandable foots that allowed its leveling. The square frame supported a tube connected to a nozzle and a manometer. A Miscela CM 46, 1.75 HP motor was used to pump the water from a 2000 L tank. The nozzle was a 460.968.30 CG model, developed by Lechler GmbH, Fellbach, Germany. The nozzle was placed at 3.4 m height above the soil surface and covered a diameter wetting area of 4 m. The experiment design is presented in Fig. 2.

Rain simulations were carried out at a constant water pressure of 1 kg cm^{-2}, corresponding to a water flow of 42 mm h^{-1}. Two simulations times were used: 10 and 40 min, which represent 1.83 and 7.30 Mj ha^{-1} and total rains amounts of 7 and 28 mm, respectively.

The rain energy at each simulation time was calculated with the following equation (Foster et al., 1981):

$$e = 0.119 + 0.0873 * \log i \quad (1)$$

where e is the rain energy in Mj ha^{-1} and i is the rain intensity in mm h^{-1}, when $i \leq 76$ mm h^{-1}.

Determinations of random and oriented soil surface roughness were carried out before and after rain simulations by quintuplicate in all cases. The readings were averaged in order to obtain a unique Crr and Kr value.

The oriented roughness (Kr) was measured on the basis of the height and the wide of the ridges, by means of the following equation (Zingg and Woodruff, 1951):

$$Kr = 4\left[(RH)^2 / (RS)\right] \quad (2)$$

where Kr is the soil oriented roughness in cm; RH is the ridge height in cm and RS the ridge spacing in cm. The initial Kr values of each treatment in both soils are presented in Table 2.

The random roughness (Crr) was measured parallel to the ridges by means of the chain method (Saleh, 1993) and calculated with the following equation:

$$Crr = (1 - L_2 / L_1) * 100 \quad (3)$$

where Crr is non-oriented roughness; L_1 is the full length of the chain and L_2 is the horizontal distance between chain ends when placed on the soil surface. Crr was measured on ridge crests. The chain was 1 m

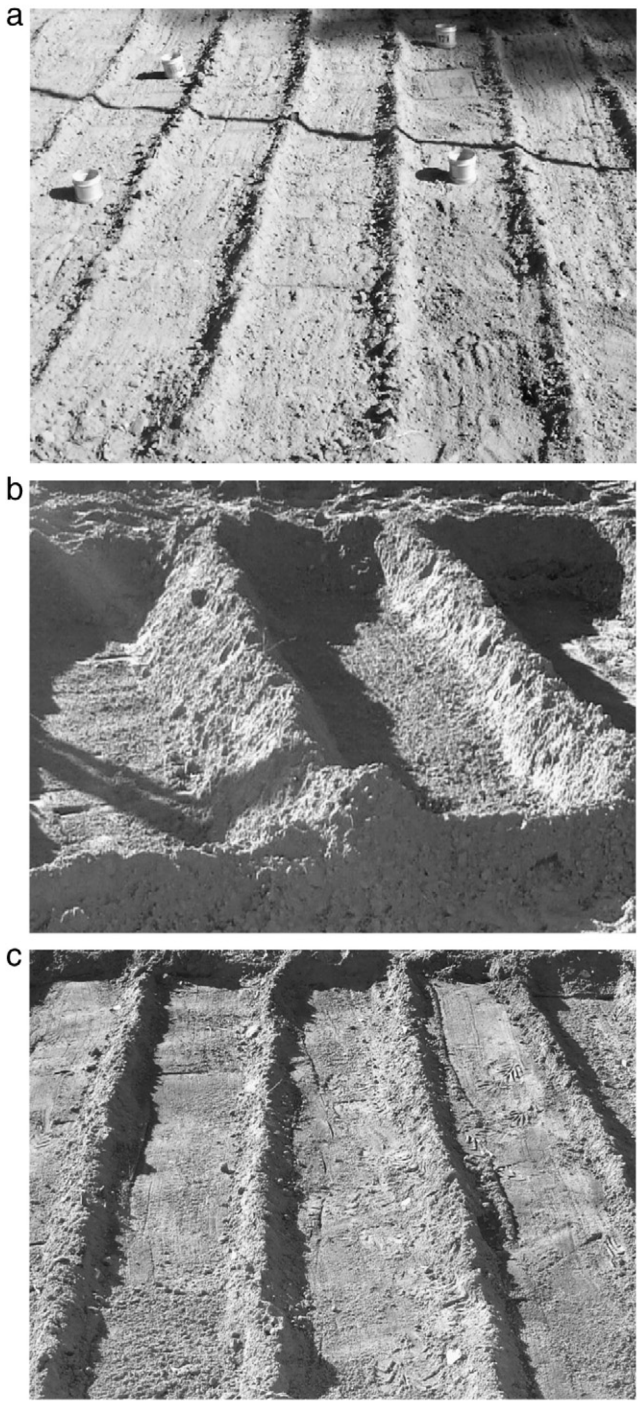

Fig. 1. View of the soil surface after the simulation of a) a disk tandem (DT), b) a lister-bedder (LB) and c) a drill-hoe (DH).

long and each chain-link had 1.25 cm. The initial Crr values of each treatment in both soils are presented in Table 2.

Measured degradation rates of Crr (RRR) and Kr (ORR), those produced by rain simulations, were calculated with Eqs. (4) and (5):

$$RRR = Crr_f \,/\, Crr_i \tag{4}$$

where Crr_f is the Crr measured after and Crr_i is the Crr measured before a rain event.

$$ORR = Kr_f \,/\, Kr_i \tag{5}$$

Table 1
Ridge spacing and height produced by different tillage tools.

Tillage tools	Ridge spacing[a] (cm)	Ridge height[a] (cm)	Flat furrow width between ridges[b] (cm)
DT	30.5	2.54	22.6
DH	35.6	5.10	27.6
LB	101.6	25.4	70.7

[a] According to RWEQ (Fryrear et al., 1998).
[b] Used in this study.

where Kr_f is the Kr measured after and Kr_i the Kr measured before a rain event.

RRR was also calculated with Eq. (6) (Fryrear et al., 1998):

$$RRRc = e^{(DF(-0.0009CUMEI-0.0007CUMR))} \tag{6}$$

where RRRc is the calculated Crr change rate, DF is a soil parameter based on its clay (Cl) and organic matter contents (OM), which define the stability and the amount of aggregates (Eq. (7)), CUMEI is the accumulated storm erosivity expressed in Mj-mm $(\text{ha-hr})^{-1}$, and CUMR the accumulated rainfall amount expressed in mm.

$$DF = e^{\left(0.943-0.07Cl\,+\,0.0011\left(Cl^2\right)-0.674OM\,+\,0.12\left(OM^2\right)\right)} \tag{7}$$

Kr degradation rate was calculated with Eq. (8):

$$ORRc = e^{\left(DF\left(-0.025(CUMEI\hat{}0.31)-0.0085\left(CUMR^0.567\right)\right)\right)} \tag{8}$$

where ORRc is the calculated Kr change rate after a rain simulation.

The relative degradation rate of both Kr and Crr was calculated on relative basis by means of the following equation:

$$D = 100-(SR_f \,/\, SR_i)*100 \tag{9}$$

where D is the relative degradation rate of Kr or Crr, SR_f is Kr or Crr measured after a rain event, and SR_i is Kr or Crr measured before a rain event.

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

3. Results and discussion

Table 2 shows that Crr was affected by tillage tools in a different way in each soil ($p<0.05$), as it was higher in LB (1.05) than in both DH (0.55) and DT (0.53) in the Ustipsamment, and higher in DT (1.21) than in DH (0.83) in the Haplustoll. LB (0.92) was not different from the other two tillage tools in the Haplustoll.

High Crr values of LB in the Ustipsamment can be produced by the translocation of clods from the moister subsoil to the soil surface by

Table 2
Random (Crr) and oriented soil surface roughness (Kr) of two soils produced by different tillage tools.

Soil type	Tillage tool	Crr	Kr (cm)
Typic Ustipsamment	LB	1.05[bc]	25.40[a]
	DH	0.55[a]	2.92[b]
	DT	0.53[a]	0.85[c]
Entic Haplustoll	LB	0.92[bc]	25.40[a]
	DH	0.83[ab]	2.92[b]
	DT	1.21[c]	0.85[c]

Different letters indicated that data are significantly different (Tukey, $p<0.05$) between tillage tools and soil types.

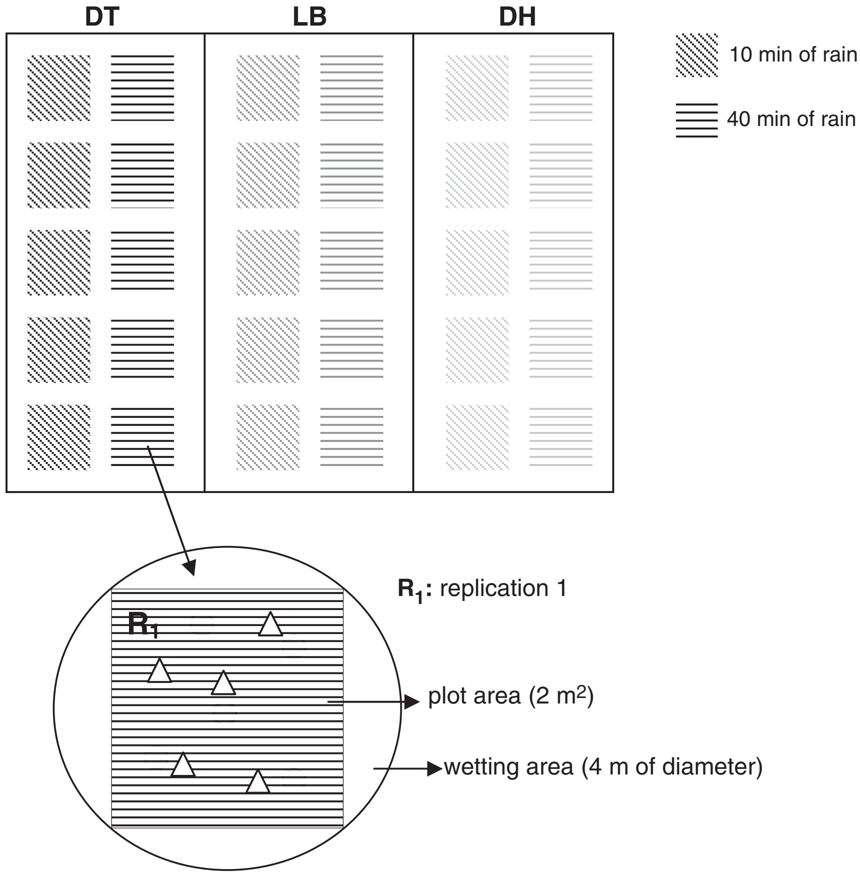

Fig. 2. Experiment design. DT = a disk tandem, LB = a lister-bedder, DH = a drill-hoe.

tillage, since LB plowed deepest in the soil (25.4 cm) than DT and DH, which plowed only up to 5.1 cm depth. The formation of clods by tilling of moist subsoils has been described by Quiroga et al. (1999), particularly in soils with low OC contents, and by Mendez and Buschiazzo (2008) in soils of the Semiarid Pampas Region (RSPC). Powers and Skidmore (1984) showed that clods are formed by a compression effect of tillage, which forces the particles into closer proximity and creates a compact clod unit.

In the Haplustoll, the largest natural aggregation and the shallow ploughing that generated DT (up to 2.5 cm depth) produced high Crr. The other two tillage systems ploughed deepest and probably translocated part of the less structured subsoil to the soil surface producing lower Crr.

The initial Crr values were not different among soils ($p<0.05$), excepting in DT, as the Ustipsamment showed lower values (0.53) than the Haplustoll (1.21, Table 2). Based on the results of Zobeck and Onstad (1987) and García Moreno et al. (2008), we expected lower Crr values in the weaker aggregated Ustipsamment than in the best developed Haplustoll. Probably, the lack of differences between soils can be attributed to the methodology used for simulating tillage operations, as the manual creation of ridges may have destroyed natural aggregates and formed clods. Some variability in the initial moisture contents of the soils at experiment start may have also affected the soil surface roughness. Similar inconveniences are found in Zobeck and Onstad (1987).

Table 3 shows the effect of rain simulation and tillage tools on Crr (RRR) and Kr (ORR). It can be seen that ORR was different between tillage systems in the Haplustoll ($p<0.05$), being lower in LB than in DH and DT after both simulation times.

In the Ustipsamment, ORR of LB was lower than the other two tillage tools ($p<0.05$) after both rain simulation times: 0.87 after 10 min and 0.72 after 40 min. Such tendencies are in agreement with highest initial Kr values of LB (25.4) than of the other tillage tools (2.92 and 0.85). These results indicated that ORR is affected by the initial value of Kr. Lyles and Tatarko (1987) showed that the initial height of the ridges was the variable that better correlated with the roughness decay by rain.

In the Haplustoll, only DT presented lower ORR values after both rain application times (0.65 after 10 min and 0.41 after min) than the

Table 3
Degradation rate of the oriented (ORR) and the random soil surface roughness (RRR) of two soils in three tillage systems, after two rain simulation times.

		ORR		RRR	
Rain simulation time (min)	Tillage tool	Entic Haplustoll	Typic Ustipsamment	Entic Haplustoll	Typic Ustipsamment
10	LB	0.98^{a}	0.87^{ab}	0.66^{ab}	0.63^{abc}
	DH	0.84^{bc}	0.72^{de}	0.71^{a}	0.52^{cd}
	DT	0.65^{de}	0.63^{e}	0.55^{bcd}	0.53^{bcd}
40	LB	0.93^{ab}	0.72^{de}	0.55^{bcd}	0.27^{g}
	DH	0.74^{cd}	0.49^{f}	0.43^{def}	0.37^{efg}
	DT	0.41^{f}	0.43^{f}	0.47^{de}	0.31^{fg}

Different letters indicate significant differences (Tukey, $p<0.05$) between tillage tools and soil types for each soil surface roughness. Each value is the average of five replicates.

other two tillage systems. Apparently, the better aggregation of this soil made the relative Kr decay to be a function of the initial height of the ridge. Thus, the same amount of rain affected relatively more ridge height when their initial values were lower.

In the Ustipsamment, the oriented roughness behaved similarly in all tillage systems, showing higher degradation after 40 min, than after 10 min rain ($p<0.05$). In this weakly aggregated soil, ridge persistence depended mainly on clods resistance, which, indeed, brokedown more with higher duration and amounts of rains, in agreement with results of Bennet et al. (1951). According to Lyles et al. (1969) clods persistence depended on soil texture, while their size and density was defined mainly by tillage tools.

The decay rate of Kr (ORR) was higher in the Ustipsamment than in the Haplustoll in LB and DH ($p<0.05$) for a 40 min lasting rain, and only in DH for a 10 min lasting rain. These differences can be attributed to the lower aggregation of the Ustipsamment, in agreement with its higher sand- and lower clay contents. Such results agree with those of Steichen (1984) and Zobeck and Onstad (1987), who demonstrated that soil surface roughness decay rate is lower in more developed and better structured soils.

Former results indicated that ORR was not only affected by tillage tools but also by soil type, rain amounts and their interactions. Similar conclusions were presented by Lyles and Tatarko (1987) and Zobeck and Popham (2001), who found significant differences in ridge height between soils and tillage tools with rain amounts. Zobeck and Popham (2001) concluded that best model included some information on the initial roughness after tillage, being the independent variables the initial roughness value (e.g. ridge height) and the cumulative amount of rainfall.

The Crr decay rate (RRR) was not different between tillage tools ($p<0.05$) after both rain simulation times, in both soils. The exception to this trend was DT (0.55) in which RRR had a higher change than in DH (0.71) after 10 min rain simulation (Table 3). This suggests that RRR does not depend only on tillage tools but on intrinsic soil properties. These results do not agree with those of Zobeck and Onstad (1987) and Zobeck and Popham (2001) who considered that tillage tools and soil type had significant effects on the random roughness decay. This contradiction can be explained, as mentioned earlier, on the basis of the formation of clods in the soil surface when the moister subsoil is mobilized during tillage operations to the soil surface. The use of a less sensible methodological device for measuring Crr may have affected these results too, as is known that the chain method is less precise than other devices like, for example, the profile meter (Römkens et al., 1986), laser scanning (Huang, 1998) and stereophotography (Wagner, 1995).

Crr degraded more after 40 min than after 10 min rain in all tillage systems in the Ustipsamment ($p<0.05$, Table 3). This did not happen in the Haplustoll, in which only DH was more degraded after the longer (0.41) than after the shorter simulation time (0.73). The other tillage systems presented similar RRR values in this soil. This indicated that the longer lasting rain (40 min) had a greater degrading effect on the Ustipsamment than in the Haplustoll, confirming the importance of soil aggregation and rain amounts on Crr decay rates. These results agree with those of Johnson et al. (1979), Steichen (1984), Zobeck and Onstad (1987) who indicated that different soils produced different rates of Crr decay due to variable soil textures, which conditioned the aggregation rate and stability of aggregates.

RRR was higher in the Ustipsamment than in the Haplustoll ($p<0.05$) in LB and DT after 40 min rain and only in DH after 10 min rain. These results were probably affected by the methodology used for simulating tillage tools, as the manual formation of ridges may have destroyed natural aggregates, modifying the original relationship between soil texture and soil aggregation. García Moreno et al. (2008) described the importance of tillage and soil type interactions on RRR, as they concluded that a sandy soil had higher RRR changes in all tillage tools than a finer textured soil.

Fig. 3 shows the relationships between measured and with Eqs. (6) and (8) calculated degradation rates of the oriented (ORRc) and the random roughness (RRRc). Calculated degradation rates of both roughnesses were lower than those measured in the field, in both soils. The underestimation of both roughnesses was lower for the Ustipsamment than for the Haplustoll, being 60% and 72% for RRR, respectively and 90% and 97% for ORR, respectively. The lower underestimation of RRR than of ORR can be related with the prediction of the degradation of both soil roughnesses on the basis of soil properties. This calculation way is better applicable to simulate RRR than ORR, as soil properties only reflect the stability of aggregates but not of the ridges. As a matter of fact, Saleh (1998) indicated that a lack of information on ridge decay rates in RWEQ is given. This author explained that the equations used by this model simulate only the decay of the random roughness but not of the oriented roughness. Furthermore, such prediction was obtained on the basis of only 16 studied soils.

Another factor that may have contributed to the underestimation of the model is the different shape of the ridges considered in this study and by RWEQ. As a matter of fact, our simulated ridges had 1:1 slopes in all tillage tools, while those provided by RWEQ are 1:3 sloped. This difference of about 3 times on the soil volume may have affected the rate of ridge degradation, as 1:1 sloped ridges may have degraded faster than 1:3 sloped ones.

The general underestimation of RRR by the model was probably produced by the different effect of soil properties on soil aggregation in the soils considered by RWEQ and the soils studied here. López et al. (2007) found that the amount of the wind erodible fraction (aggregates finer than 0.84 mm) predicted with RWEQ did not agree with results of field measurements in similar soils than analyzed here. Such differences can also occur with the DF factor. Potter (1990) found that differences in the DF factor resulted in under- or overestimations of the roughness decay, mainly due to different organic matter- and clay contents of the soils studied.

Each tillage tool presented specific relationships between ORR and ORRc in both soils. This did not occur for RRR, where no differences between tillage tools were detected. Such results were apparently produced by the consideration of different initial heights of the ridges by ORR, and the low effect of tillage on RRR. It can be deduced that initial heights of the ridges should be considered in the models in order to predict adequately their degradation rates, particularly in better developed soils. Zobeck and Onstad (1987), Lyles and Tatarko (1987) and Zobeck and Popham (2001) suggested that a factor related with tillage operations, which defines the initial soil roughness, should be included in the models for predicting the degradation of soil surface roughness.

ORR of tillage tools producing higher ridges (LB) were better predicted by RWEQ than for the other tillage tools (DH and DT). This seems to be related with the lower relative degradation rate of higher ridges, which minimize the error of the model.

Former results indicated that RWEQ does not predict the decay rates of the random and, mainly, of the oriented roughness in the studied soils. Because of that other alternatives were analyzed in order to obtain reliable and simpler degradation models, based on accumulated rains (CUMR) and the rain energy (CUMEI).

Table 4 shows that the best relation between the degradation rate of both soil surface roughnesses (ORR and RRR) and accumulated rain amounts (CUMR) was linear negative. Increasing CUMR produced higher degradation rates of Kr and Crr created by all tillage tools, in both soils. Some authors proposed the use of only the rain amount or rain energy as a single parameter (Van Donk and Skidmore, 2003; Zobeck and Onstad, 1987) to evaluate both soil roughness decay using exponential negative relations (Onstad et al., 1984; Potter et al., 1990; Römkens and Wang, 1985; Saleh, 1998).

Table 4 also shows that ORR was different between tillage tools and soils, while RRR was similar in all tillage tools and only varied between soils ($p<0.05$). In the Haplustoll, Kr degradation rates were

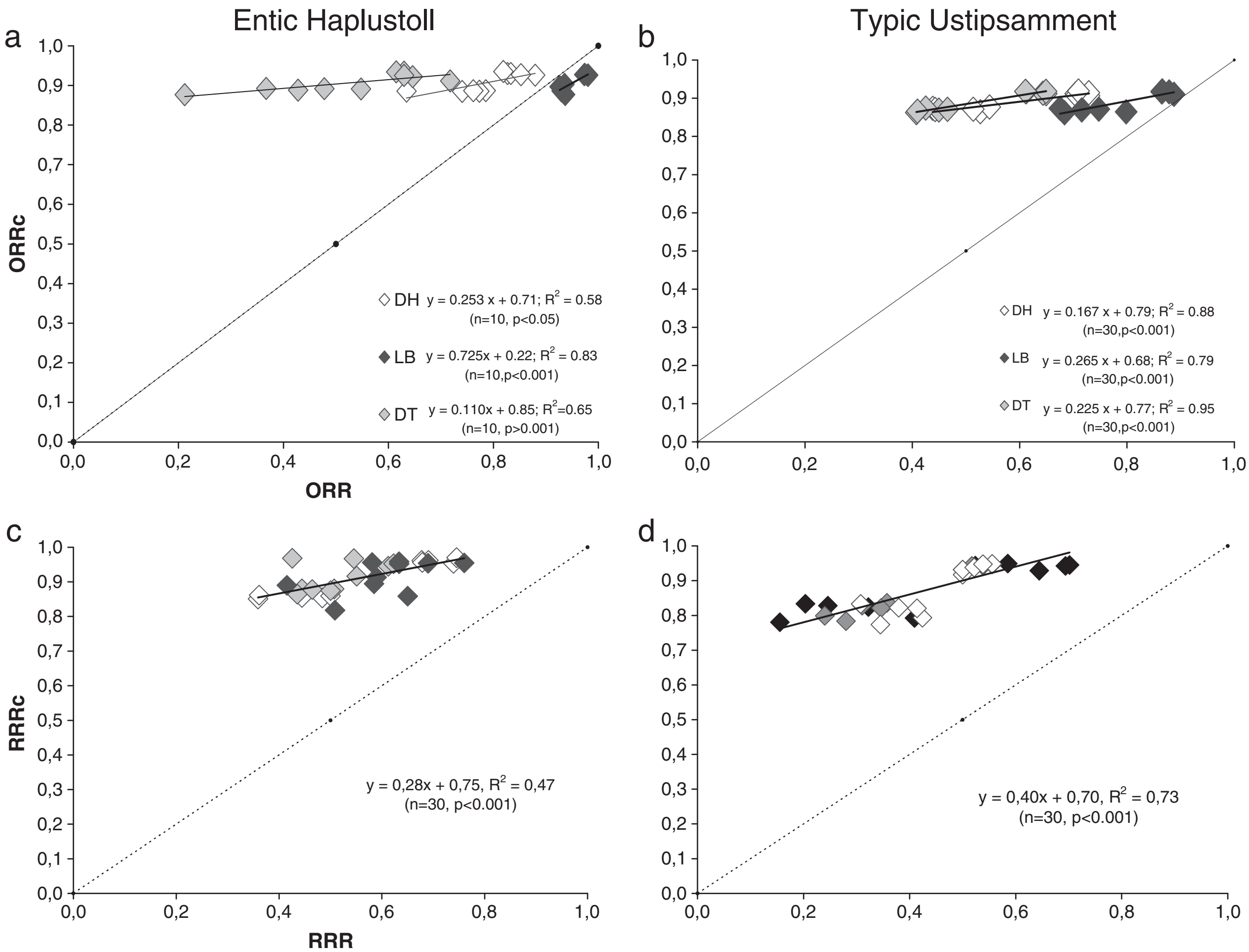

Fig. 3. Relationships between a) the calculated with RWEQ degradation of the oriented roughness (ORRc) and the degradation of the measured oriented roughness (ORR) in the Entic Haplustoll, b) ORRc and ORR in the Typic Ustipsamment, c) the calculated with RWEQ degradation of the random roughness (RRRc) and the degradation of the measured random roughness (RRR) in the Entic Haplustoll, and d) RRRc and RRR in the Typic Ustipsamment, in all cases in three tillage tools (DT = a disk tandem, LB = a lister-bedder, DH = a drill-hoe).

higher for DT (regression slope = −0.014) than for DH (regression slope = −0.005) and LB (linear regression slope = −0.002), indicating that Kr was relatively less degraded in LB and DH than in DT, demonstrating that higher ridges were more resistant against degradation by rains. These results are consistent with those of Lyles and Tatarko (1987) who showed that the effects of CUMR on ridge persistence depends on their initial height. Zobeck and Popham (2001) also related the ridge decay rate with its initial height.

In the Ustipsamment the slopes of the regression equations between ORR and CUMR (Table 4) were slightly higher in DT (−0.010) and DH (−0.012) than in LB (−0.007), indicating lower Kr decay rates in LB than in DH and DT. Similar results were found for the Haplustoll, with the exception of DH which presented lower ORR than in the Ustipsamment. This may be related with the intrinsic properties of both soils, i.e. the better structure of the Haplustoll than of the sandy Ustipsamment.

In general terms, the degradation rate of Kr was higher in the Ustipsamment than in the Haplustoll, indicating that ridges were more degradable by rainfall in the sandy than in the sandy-loam soil. Soil texture, through its effects on soil aggregation, was an important factor affecting ridge persistence and clods formation in agreement with results of Lyles and Tatarko (1987).

Table 4
Parameters of the equations that fit the negative linear regressions between the degradation rate of the oriented (ORR) and the random roughness (RRR) with the simulated rain amounts (CUMR) and the rain energy (CUMEI), in two soils.

		CUMR				CUMEI				
		a	b	R^2	p	a	b	R^2	p	n
Typic Ustipsamment	ORR (DT)	−0.010	0.707	0.964	<0.001	−0.0009	0.710	0.942	<0.001	10
	ORR (LB)	−0.007	0.923	0.804	<0.001	−0.0006	0.920	0.748	<0.01	10
	ORR (DH)	−0.012	0.809	0.905	<0.001	−0.0010	0.826	0.838	<0.001	10
	$RRR_{(DT\text{-}LB\text{-}DH)}$	−0.012	0.650	0.746	<0.001	−0.0010	0.650	0.717	<0.001	30
Entic Haplustoll	ORR (DT)	−0.014	0.741	0.607	<0.01	−0.0014	0.741	0.466	<0.05	10
	ORR (LB)	−0.002	0.993	0.868	<0.001	−0.0002	0.986	0.634	<0.01	10
	ORR (DH)	−0.005	0.877	0.602	<0.01	−0.0005	0.877	0.593	<0.01	10
	$RRR_{(DT\text{-}LB\text{-}DH)}$	−0.009	0.701	0.492	<0.001	−0.0009	0.701	0.467	<0.001	30

a and b are constants of the equations of the linear regression.

Table 4 shows that the best adjustment between RRR and CUMR was linear and negative, and that no differences between tillage tools existed, therefore RRR variations as a function of rain amounts was independent from tillage tools in both soils but dependent from physical soil factors. This may be due to the fact that the persistence of clods and aggregates to breakdown by rainfall should be more affected by soil texture and the size and density of clods than by tillage tools. These results agree with those of Lyles et al. (1969), but not with those of Zobeck and Onstad (1987) and Zobeck and Popham (2001). These last authors suggest that Crr decay is affected by both tillage and CUMR. Saleh (1998) found that finer aggregates degraded more than coarse aggregates. The difference with our results may be caused in the different soils analyzed in both studies: most of the soils presented by Saleh (1998) were clayey-silt and silty-loam, mainly with higher organic matter contents than soils of our study.

The slopes of the regression equations that fit the relationships between RRR and CUMR were higher for the Ustipsamment (−0.012) than for the Haplustoll (−0.009), indicating that aggregates decay was higher in the sandy than in the sandy-loam soil. Such results agree with those of Potter et al. (1990), Zobeck and Onstad (1987), Saleh (1998) and Zobeck and Popham (2001) who demonstrated the positive effect of finer textures on the stability of the soil against the degrading effect of rains.

Table 4 shows ORR and RRR values as a function of rain energy (CUMEI). The best fitting was linear and negative for all treatments, demonstrating higher degradation rates of soil roughness with increasing rain energies. These results agree with those of Zobeck and Onstad (1987), Bertuzzi et al. (1990), Borselli (1999), and Martínez-Mena et al. (2001) who proposed the rain energy to be the best variable for estimating the soil roughness decay. However, the fitting of the regression proposed by RWEQ is exponential (Saleh, 1998) and in some other cases it has been found to be quadratic (Eltz and Norton, 1997), in both cases negative. Differences with our results can be related to the lower rain energy simulated in our case than in these studies and in the coarser textures of the two soils tested here than in these studies.

The ORR values as a function of rain energy were affected by tillage tools and soil type while RRR only varied with soil type. Changes in both roughness values under variable CUMEI and CUMR values were similar. In the Haplustoll, ORR had lower degradation rates in LB (slope = −0.0002) than in DH (−0.0005) and DT (−0.0014). Again, higher ridges were relatively more stable, which agrees with results of Lyles and Tatarko (1987). In the Ustipsamment, ORR had higher degradation rates in DT and DH (regression slope = −0.0009 and −0.0010, respectively) than in LB (regression slope = −0.0006), being higher ridges relatively more stable.

Lower ORR changes in the Haplustoll than in the Ustipsamment must be attributed to their different textures and aggregation rates, in agreement with results of Dexter (1977) and Lyles and Tatarko (1987).

RRR was not affected by tillage tools as reflected by the similar slopes of the regression equations between RRR and CUMEI. Probably, this was caused by the larger dependence of the random roughness from soil properties rather than on tillage tools (Dexter, 1977; Zobeck and Onstad, 1987).

The slope of the regression of the relationship between RRR and CUMEI was slightly higher in the Ustipsamment (−0.0011) than in the Haplustoll (−0.0009), indicating larger changes of Crr in the sandier soil. Authors such Dexter (1977), Lyles and Tatarko (1987) and Zobeck and Onstad (1987) found similar results.

In general, we observed that the equations that fit the relationship between both RRR and ORR with CUMR and CUMEI had a higher determination coefficients (R^2) for the Ustipsamment that for the Haplustoll. This indicates that the Ustipsamment was more sensitive to small changes in the energy and amounts of rainfall than the Haplustoll, in agreement with its more labile aggregates.

The equations that fit the relationships between both RRR and ORR with CUMR had higher R^2 than those with CUMEI. These results agree with those of Cogo et al. (1984), Lyles and Tatarko (1987), Zobeck and Onstad (1987) and Zobeck and Popham (2001), who concluded that rain amounts is a better parameter to be used in the models to estimate the degradation rate of Kr and Crr than rain energy. Moreover, the calculation of CUMR is much easier than of CUMEI.

Based on these results and in agreement with those of Lyles and Tatarko (1987) and Zobeck and Popham (2001), we analyzed the relative variation of Kr decay (D) as a function of the initial Kr value. This calculation differed from the proposed by RWEQ because the model does not estimate Kr changes in relation to its initial value, and only considers a quotient between both values, losing the effect of the initial ridge height.

Fig. 4 shows that D varied potential and negatively with Kr, the adjustment was significant at 1% level in all cases. In general the variation of D with Kr was higher for the Haplustoll, but the final D values were higher for the Ustipsamment. This indicates that the degradation of the oriented soil roughness was higher for the Ustipsamment than for the Haplustoll in both simulated rain amounts. Again, the soil with lower natural aggregation and cloddiness was more affected by rains than the better aggregated soil. Fig. 4 also shows that variations of D were higher with lower rain amounts, indicating lower degradation rates of Kr.

Equations of Fig. 4 may allow the calculation of the degradation rate of the oriented roughness as affected by certain rain amounts and

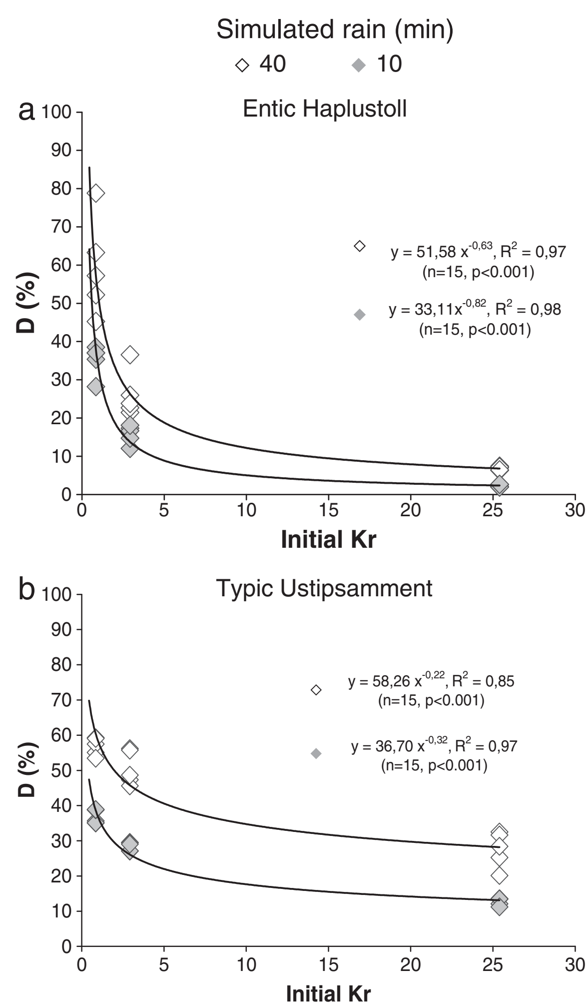

Fig. 4. Relative Kr variations (D) after rain simulations as a function of the initial Kr in a) an Entic Haplustoll and b) a Typic Ustipsamment.

the initial Kr. In view of these results it must be further investigated if a unique equation can be developed where more rain conditions are considered.

Relative changes of Crr were not related with the initial Crr values in both soils and simulated rain amounts. These tendencies were due to the fact that tillage tools mostly did not affect the random roughness. These results do not agree with those of Zobeck and Popham (2001) who indicated that the rate of change of the natural roughness depended on its initial value and in general increased with increasing initial roughness.

4. Conclusions

The degradation of the oriented roughness (ORR) differed between tillage tools, soil type and rainfall ($p<0.001$). In general ORR was higher in the Ustipsamment than in the Haplustoll and in DT than in DH and LB, in both soils. The degradation of the random roughness (Crr) was mostly not affected by tillage tools.

The formation of clods, mainly in tillage systems that plow deeper, mobilizing the moister subsoil, can reduce the degradation rate of Crr.

Calculated degradation rates of both roughnesses were lower than those measured in the field, in both soils. This underestimation was lower for the Ustipsamment than for the Haplustoll. Underestimations may be produced by the low accuracy of RWEQ for predicting the decay rates of the oriented roughness.

Accumulated rain amounts (CUMR) and rain energy (CUMEI) allowed a good prediction of the relative degradation of the oriented roughness. Nevertheless, CUMR explained better such variations. Therefore, CUMR can be used instead of CUMEI for predicting ORR for the studied soils.

The relative variation of Kr as a function of the initial Kr values varied potential and negatively, and were different for each soil and rain amounts. These equations may allow the calculation of the degradation rate of the oriented roughness as affected by certain rain amounts and the initial Kr. In view of these results it must be further investigated if a unique equation can be developed for predicting soil surface roughness degradation.

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References

Bennet, H.H., Bell, F.G., Robinson, B.D., 1951. Raindrops and erosion. USDA. Circ. N° 895.

Bertuzzi, P., Raws, G., Couralt, D., 1990. Testing roughness indices to estimate soil surface changes due to simulated rainfall. Soil Tillage Res. 17, 87–99.

Borselli, L., 1999. Segmentation of soil roughness profiles. Earth Surf. Process. Landf. 24, 71–90.

Burwell, R.E., Larson, W.E., 1969. Infiltration as influenced by tillage-induced random roughness and pore space. Soil Sci. Soc. Am. Proc. 33 (3), 449–452.

Buschiazzo, D.E., Zobeck, T.M., 2008. Validation of WEQ, RWEQ and WEPS wind erosion for different arable land management systems in the Argentinean Pampas. Earth Surf. Process. Landf. 33, 1839-1850.

Cogo, N.P., Moldenhauer, W.C., Foster, G.R., 1984. Soil loss reductions from conservation tillage practices. Soil Sci. Soc. Am. J. 48, 368–373.

Dexter, A.R., 1977. Effect of rainfall on the surface microrelief of tilled soil. J. Terramech. 14, 11–22.

Eltz, F.L.F., Norton, L.D., 1997. Surface roughness changes as effected by rainfall erosivity, tillage and canopy cover. Soil Sci. Soc. Am. J. 61 (6), 1746–1755.

Foster, G.R., McCool, D.K., Renard, K.G., Moldenhauer, W.C., 1981. Conversion of the universal soil loss equation to SI metric units. J. Soil Water Conserv. 36, 355–359.

Fryrear, D.W., Ali Saleh, J.D., Bilbro, H.M., Schomberg, J.E., Zobeck, T.M., 1998. Revised Wind Erosion Equation (RWEQ). Wind Erosion and Water Conservation Research Unit, USDA-ARS, Southern Plains Area Cropping Systems Research Laboratory: Technical Bulletin, 1.

García Moreno, R., Díaz Alvarez, M.C., Tarquis Alonso, A., Barrington, S., Saa Requejo, A., 2008. Tillage and soil type effects on soil surface roughness at semiarid climatic conditions. Soil Tillage Res. 98, 35–44.

Hagen, L.J., 1991. A wind erosion prediction system to meet users needs. J. Soil Water Conserv. 46, 106–111.

Huang, C.H., 1998. Quantification of soil microtopography and surface roughness. In: Baveye, P., Parlange, J.Y., Stewart, B.A. (Eds.), Fractals in soil science: Advances in Soil Science.

INTA, Gob. de La Pampa, UNLPam., 1980. Inventario Integrado de los Recursos Naturales de la Provincia de La Pampa. INTA, Buenos Aires. 487 pp.

Jester, W., Klik, A., 2005. Soil surface roughness measurement — methods, applicability and surface representation. Catena 64, 174–192.

Johnson, C.B., Mannering, J.V., Moldonhauer, W.C., 1979. Influence of surface roughness and clod size and stability on soil and water losses. Soil Sci. Soc. Am. J. 43 (4), 772–777.

López, M.V., de Dios Herrero, J.M., Hevia, G.G., Gracia, R., Buschiazzo, D.E., 2007. Determination of the wind-erodible fraction of soils using different methodologies. Geoderma 139 (3–4), 407–411.

Lyles, L., Tatarko, J., 1987. Precipitation effects on ridges created by a grain drill. J. Soil Water Conserv. 42 (4), 269–271.

Lyles, L., Disrud, L.A., Woodruff, N.P., 1969. Effects of soil physical properties, rainfall characteristics and wind velocity on clod disintegration by simulated rainfall. Soil Sci. Soc. Am. Proc. 33 (2), 302–306.

Mannering, J.V., Meyer, L.D., Johnson, C.B., 1966. Infiltration and erosion as effected by minimum tillage for corn. Soil Sci. Soc. Am. Proc. 30, 101–105.

Martínez-Mena, M., Abadia, R., Castillo, V., Albaladejo, J., 2001. Diseño experimental mediante lluvia simulada para el estudio de los cambios en la erosión del suelo durante la tormenta. Rev. C & G. 15 (1–2), 31–43.

Mendez, M., Buschiazzo, D.E., 2008. Canopy and residue cover effects on wind erosion of an Haplustoll in a semiarid environment of Argentina. Soil Sci. 173, 468–479.

Merrill, S.D., Huang, C., Zobeck, T.M., Tanaka, D.L., 2001. Use of the chain set for scale-sensitive and erosion-relevant measurement of soil surface roughness. In: Stott, D.E., Mohtar, R.H., Steinhardt, G.C. (Eds.), Sustaining the Global Farm, pp. 594–600.

Onstad, C.A., Wolfe, M.L., Larson, C.L., Slack, D.C., 1984. Tilled soil subsidence during repeated wetting. Trans. Am. Soc. Agric. Eng. 27, 733–736.

Potter, K.N., 1990. Soil properties effect on random roughness decay by rain. Trans. Am. Soc. Agric. Eng. 33 (6), 1889–1892.

Potter, K.N., Zobeck, T.M., Hagen, L.J., 1990. A microrelief index to estimate soil erodibility by wind. Trans. Am. Soc. Agric. Eng. 33, 151–155.

Powers, D.H., Skidmore, E.L., 1984. Soil structure as influenced by simulated tillage. Soil Sci. Soc. Am. J. 48, 879–884.

Quiroga, A.R., Buschiazzo, D.E., Peinemann, N., 1999. Soil compaction is related to management practices in the semi-arid Argentine Pampas. Soil Tillage Res. 52, 21–28.

Römkens, R.J.M., Wang, J.Y., 1985. Soil translocation by rainfall. J. Miss. Acad. Sci. 30, 9–21.

Römkens, R.J.M., Singarayar, S., Gantzer, C.J., 1986. An automated non contact surface profile meter. Soil Tillage Res. 6, 193–202.

Saleh, A., 1993. Soil roughness measurement: chain method. J. Soil Water Conserv. 48 (6), 527–529.

Saleh, A., 1997. Soil surface roughness measurement: a comparison study. Agronomy Abstracts, p. 271.

Saleh, A., 1998. Soil surface roughness decay by rainfall amount and erosivity index (EI). In: Fryrear, D.W., Saleh, A., Bilbro, J.D., Schomberg, H.M., Stout, J.E., Zobeck, T.M. (Eds.), Revised Wind Erosion Equation (RWEQ). : Technical Bulletin, 1. Southern Plains Area Cropping Systems Research Laboratory, Wind Erosion and Water Conserv. Res. Unit, USDA-ARS.

Saleh, A., Fryrear, D.W., 1997. Soil roughness wind erosion equation (RWEQ). In: Fryrear, et al. (Ed.), 1998.

Steichen, J.M., 1984. Infiltration and random roughness of a tilled and untilled clay pan soil. Soil Tillage Res. 4 (3), 251–262.

Stout, J.E., Zobeck, T.M., 1996. The Wolfforth field experiment: a wind erosion study. Soil Sci. 161 (9), 616–632.

Van Donk, S.J., Skidmore, E.L., 2003. Measurement and simulation of wind erosion, roughness degradation and residue decomposition on and agricultural field. Earth Surfaces Processes Landforms. 28, 1243–1258.

Van Pelt, R.S., Zobeck, T.M., Potter, K.N., Stout, J.E., Popham, T.W., 2004. Validation of the wind erosion stochastic simulator (WESS) and the revised wind erosion equation (RWEQ) for a single event. Environmental Modelling and Software. 19, 191–198.

Wagner, W.S., 1995. Mapping a three-dimensional soil surface with handheld 35 mm photography. Soil Tillage Res. 34, 187–197.

Woodruff, N.P., Siddoway, F.H., 1965. A wind erosion equation. Soil Sci. Am. Proc. 29 (5), 602–608.

Zingg, A.W., Woodruff, N.P., 1951. Calibration of a portable tunnel for simple determination of roughness and drag on field surfaces. Agron. J. 43 (4), 191–193.

Zobeck, T.M., Onstad, C.A., 1987. Tillage and rainfall effects on random roughness: a review. Soil Tillage. Res. 9, 1–20.

Zobeck, T.M., Popham, T.W., 2001. Cropping and tillage effects on soil roughness indexes. Trans. Am. Soc. Agric. Eng. 44 (6), 1527–1536.

Zobeck, T.M., Van Pelt, R.S., Stout, J.E., Popham, T.W., 2001. Validation of the revised wind erosion equation (RWEQ) for single events and discrete periods. Proceeding of the International Symposium on Soil Erosion Research for the 21 the Century, 3–5 January, Honolulu, pp. 471–474.