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Soil coverage evolution and wind erosion risk on summer crops under contrasting tillage systems

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ABSTRACT

The effectiveness of wind erosion control by soil surface conditions and crop and weed canopy has been well studied in wind tunnel experiments. The aim of this study is to assess the combined effects of these variables under field conditions. Soil surface conditions, crop and weed coverage, plant residue, and non-erodible aggregates (NEA) were measured in the field between the fallow start and the growth period of sunflower (*Helianthus annuus*) and corn (*Zea mays*). Both crops were planted on a sandy-loam Entic Haplustoll with conventional-(CT), vertical-(VT) and no-till (NT) tillage systems. Wind erosion was estimated by means of the spreadsheet version the Revised Wind Erosion Equation and the soil coverage was measured each 15 days. Results indicated that wind erosion was mostly negligible in NT, exceeding the tolerable levels (estimated between 300 and 1400 kg ha^{-1} year^{-1} by Verheijen et al. (2009)) only in an year with high climatic erosivity. Wind erosion exceeded the tolerable levels in most cases in CT and VT, reaching values of 17,400 kg ha^{-1}. Wind erosion was 2–10 times higher after planting of both crops than during fallows. During the fallows, the soil was mostly well covered with plant residues and NEA in CT and VT and with residues and weeds in NT. High wind erosion amounts occurring 30 days after planting in all tillage systems were produced by the destruction of coarse aggregates and the burying of plant residues during planting operations and rains. Differences in soil protection after planting were given by residues of previous crops and growing weeds. The growth of weeds 2–4 weeks after crop planting contributed to reduce wind erosion without impacting in crops yields. An accurate weeds management in semiarid lands can contribute significantly to control wind erosion. More field studies are needed in order to develop management strategies to reduce wind erosion.

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1. Introduction

Wind erosion of arid and semiarid regions of the world, including the semiarid Pampas of Argentina, is an important soil degradation process (Peterson et al., 2006; Buschiazzo et al., 1999). In addition, this process produces particulate matter smaller than 10 μm (PM10) which have negative effects on human health and affect some physical and chemical processes in the atmosphere like the formation of clouds and the radiation budget (Pope et al., 1995; Seinfeld and Pandis, 1997). Wind erosion of cultivated soil depends on the surface soil coverage with plant canopy and residues as well as the soil surface roughness produced by tillage practices. The effectiveness of these parameters in controlling wind erosion has been mostly quantified, under controlled wind tunnel conditions (Fryrear, 1984; Bilbro and Fryrear, 1994; Armbrust and Bilbro, 1997). However, little is known about the combined effect of all these cover types on wind erosion of summer crops under field conditions. The main advantage of agricultural field studies is that they provide information about the interactions that affect the success of the system and as such may better represent true farming systems (Nokes et al., 1997). The major disadvantage is the difficulty in understanding specific causal relationships because of the variability introduced by different farming practices (Temple et al., 1994). The influence of each soil cover component in real production systems changes with time depending on tillage operations, crop growth habits, fallow length, weed growth and, above all, climatic conditions. Under field conditions, weeds develop during the fallow and crop growth. However, previous wind erosion studies have not taken into account the soil protection given by weeds together with other types of soil cover like non-erodible

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aggregates, residues and crop canopy. For this reason, it is necessary to measure the soil protection given by weeds in order to assess their contribution to wind erosion control in different tillage systems.

The determination of the relative effect of each kind of cover on wind erosion as a function of time can be useful to decide management systems that minimize soil degradation and to develop additional functions in the currently available wind erosion prediction models. Most of existing studies of soil protection against wind erosion by crops were carried out for two small grain crops: spring wheat (*Triticum aestivum*) and barley (*Hordeum vulgare*) (Merrill et al., 1999; López et al., 2003; Mendez and Buschiazzo, 2010), but less information is available for large grain crops like corn (*Zea mays*) or sunflower (*Helianthus annuus*). In the central semiarid pampas of Argentina the more important large grains crops are cropped in between the Spring and the Summer. In the central semiarid pampas of Argentina, the climatic erosivity is higher during the spring when winter crops are in advanced vegetative stages and summer crops are planted (Panebianco and Buschiazzo, 2008). Because of that, we expect that wind erosion of large grain summer crops will be higher than for winter crops (Mendez and Buschiazzo, 2010).

The objective of this study was to assess the temporal variation of wind erosion as a function of the soil cover on summer crops under contrasting tillage systems.

2. Materials and methods

The study was conducted on the long term experimental plots of the Faculty of Agronomy of the University of La Pampa, Argentina (S36° 46′; W64° 16′; 210 m a.s.l.) where different tillage systems are compared (Fig. 1). The Faculty of Agronomy of the University of La Pampa is located in the center of Argentina, inside of the central semiarid pampas. This region represents the frontier between cultivated areas (eastward) and grassland areas (westward). This semiarid region has a mean annual precipitation of 764 mm and the mean annual temperature is 15.5 °C for the period 1971–2001. Prevailing winds blow from the north and the south, with higher speeds and gusts up to 60 km h^{-1} during the spring and the summer (Casagrande and Vergara, 1996).

Soil losses by wind erosion were estimated with the spreadsheet version of RWEQ in order to reach the aims of the paper.

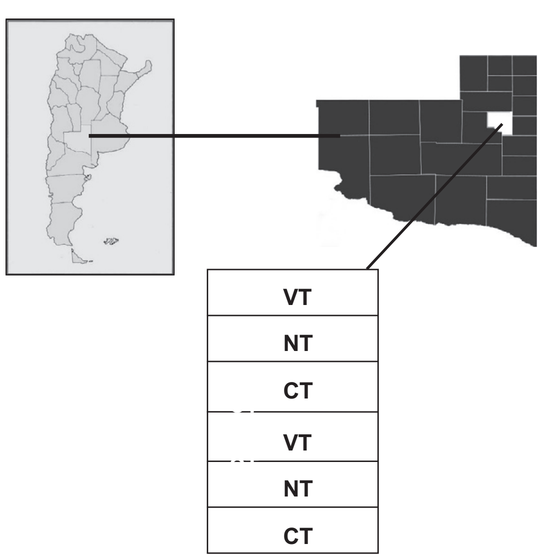

Fig. 1. Location of the study site and layout of the experimental plots. CT, conventional tillage; NT, no-tillage; and VT, vertical tillage.

2.1. RWEQ model description

RWEQ is an empirical model used to estimate long-term soil loss due to wind erosion (Fryrear et al., 1998). Soil movement is presented by a steady state equation that assumes the existence of a wind transport capacity. Soil transported by the wind is estimated with the following equation (Fryrear and Saleh, 1996).

$$Q(x) = Q_{max}\{1 - \exp[-(x/s)^2]\} \quad (1)$$

where $Q(x)$ is the amount of soil transported by the wind past a point x, Q_{max} is the maximum amount of soil that can be transported downwind and s is critical field length at which the transported load is 63.2% of Q_{max}.

The parameter Q_{max} and s are determinate by equation:

$$Q_{max} = 109.8\, x\, (\mathrm{WF} \times \mathrm{EF} \times \mathrm{SCF} \times \mathrm{K} \times \mathrm{COG}) \quad (2)$$

$$s = 150.71\, x\, (\mathrm{WF} \times \mathrm{EF} \times \mathrm{SCF} \times \mathrm{K} \times \mathrm{COG})^{-0.3711} \quad (3)$$

Where WF is the weather factor, EF is the erodible fraction (aggregates <0.84 mm), SCF is the soil crust factor, K is the soil roughness factor and COG is the combined residues-plant materials factor.

The factor WF, SCF, K and COG are expressed as soil loss ratio (SLR) which is the quotient between the soil loss with the factor and without the factor. The SRL values are between 0 and 1. The weather factor (WF) is the product of a wind-erosivity factor and two wind-erodibility factors, one for soil water content and the other for snow cover. The weather factor is estimated with the follow equation:

$$\mathrm{WF} = \mathrm{Wf}\frac{\rho}{g}(\mathrm{SW})\mathrm{SD} \quad (4)$$

Where WF Weather Factor kg m^{-1}, Wf wind factor (m s^{-1})^3, air density kg m^{-3}, g acceleration due to gravity m s^{-1} s^{-1}, SW soil wetness dimensionless and SD snow cover factor.

In the spreadsheet version of RWEQ the wind factor is equal to wind value (W) that is calculated with the following equation:

$$W = \sum_{i=1}^{N} U_2(U_2 - U_t)^2 \quad (5)$$

Where W wind value (m s^{-1})^3, U_2 wind speed at 2 m meters height, U_t threshold wind speed at 2 m (assumed 5 m s^{-1}) and N number of wind speed observations (i) in a time period of 1–15 days.

The snow cover factor was 1 (no snow limitation) in all cases because snow does not falls in the study region. The soil wetness factor was 1 (no wetness limitation) in all cases and no erosion was calculated during the first three days after a rain event. The equation to calculate snow cover factor and soil wetness factor can be consulted in the RWEQ user manual.

The erodible fraction (EF) is represented by the aggregates <0.84 m which can be transported by the wind (Chepil, 1942). The erodible fraction was estimated by the RWEQ model by the following equation:

$$\mathrm{EF} = (29.09 + 0.31\mathrm{Sa} + 0.17\mathrm{Si} + 0.33\mathrm{Sa/Cl} - 2.59\mathrm{OM} - 0.95\mathrm{CaCO_3})/100 \quad (6)$$

where Sa sand content (%), Si silt content (%), Sa/Cl sand to clay ratio, OM organic matter and $CaCO_3$ calcium carbonate.

Soil crust factor (SCF) was calculated with the following equation:

$$\mathrm{SCF} = 1/(1 + 0.0066(\mathrm{CL})^2 + 0.021(\mathrm{OM})^2) \quad (7)$$

Where CL is percent clay and OM is percent organic matter.

The soil roughness factor (K) is the product of the random roughness and oriented roughness. The random roughness is caused by clods or non-erodibles aggregates over soil surface and the oriented roughness by the ridges after tillage. Clods or non-erodibles aggregates over soil surface were treated like soil cover with flat residues and oriented roughness was considered 1 (no oriented roughness limitation) in all cases. Because of that the equations for this parameter were not presented here.

The combined residues-plant materials factor (COG) was calculated with the fallowing equation:

$$COG = SLR_F \times SLR_S \times SLR_c \quad (8)$$

where SLR_F soil loss ratio for flat residues, SLR_S soil loss ratio for standing residues and SLR_C soil loss ratio for crop canopy.

The soil loss ratio for flat, standing and crop canopy were calculated with the follows equations:

$$SLR_F = e^{(-0.0605 \times SC)} \quad (9)$$

where SLR_F is the soil loss ratio for flat residues and SC the percent soil coverage with flat residues. This equation was developed by Mendez and Buschiazzo (2008) for the conditions of the semiarid Pampas.

$$SLR_S = e^{\left(-0.0344 \times SA^{0.6413}\right)} \quad (10)$$

where SLR_S is the soil loss ratio for standing residues and SA silhouette area of residue per unit of ground area ($cm^2\ m^{-2}$).

$$SLR_C = e^{\left(-5.614 \times CC^{0.7366}\right)} \quad (11)$$

where SLR_C is the soil loss ratio for crop canopy and CC fraction of the soil covered by crop canopy.

A more complete description of the RWEQ model can be find in the RWEQ user manual and Merrill et al. (1999).

2.2. Field measurement and wind erosion estimation

Sunflower (*H. annuus*) and corn (*Z. mays*) were planted in the years 2005 and 2006 under conventional tillage (CT), vertical tillage (VT), and no-tillage (NT) in 10 ha plots. Soil samples of each tillage systems were taken and the mains characteristics of the A horizon are shown in Table 1. The soil at the study site classified as a fine sandy loam (Entic Haplustoll), with an A-AC-C-Ck horizon sequence.

In each treatment, soil coverage with plant residues (including stubble mulch and weed residues), sunflower and corn canopy, living weeds and clod or non-erodible aggregates (coarser than 10 mm in diameter) were measured approximately every 4 weeks during fallow and every 1 week after planting in triplicate. The soil coverage was measured using digital photographs of the soil surface. Photos were randomly taken, perpendicularly to the soil surface from a height of 1.5 m (covering approximately 1 m^2). Each digital photograph was divided into a 40 × 40 mm grid in the PC screen by means of the Paint program (Microsoft Corporation, 2009), producing a total of 126 crossing points. The percentage of soil cover was then determined as the quotient between the number of crossing points where flat residues, non-erodible aggregates, weeds or crops canopy cover were detected and the total amount of crossing points of the grid multiplied by 100.

The fallow period started when the first tillage operation was made in order to prepare the soil for corn or sunflower planting and it ended when the crop was planted. The crop period started after planting and it ended when the crop canopy cover was enough to control wind erosion (see Figs. 2 and 3). The previous crops to sunflower and corn in each year and tillage system are showed in Figs. 2 and 3. During the fallow of each crop, weeds were treated with a disk in CT and with a disk and a chisel in VT. After planting in VT and CT, and along both periods in NT, weeds were treated with herbicides (Glyphosate, 2–4D, Imazethapyr). Tillage and chemical weed control operations are indicated in Figs. 2 and 3.

A meteorological station was installed 500 m away from the experimental field in order to record the wind speed at 2 m height, as well as the air temperature and precipitation each hour. The monthly climatic erosivity (also called the C-factor) was calculated based on the average measured wind velocity, air temperature, and rainfall (Panebianco and Buschiazzo, 2008) (Eq. (12)). The climatic data are listed in Table 2.

$$\text{C-factor} = 386 \left[\frac{U^3}{\left(\frac{P/2.54}{1.8T+32}\right)^{10/9}} \right] \quad (12)$$

where U is the mean monthly wind speed at 10 m height expressed in m s^{-1}, P is the mean monthly precipitation expressed in mm and T is the mean monthly temperature expressed in °C.

The 1 h meteorological records, soils characteristics and the soil coverage measurements were used to estimate 10 days wind erosion with a spreadsheet version of RWEQ (Fryrear et al., 1998; Guo et al., 2013). The RWEQ was found to be adequate to predict wind erosion in the semiarid Pampas of Argentina (Buschiazzo and Zobeck, 2008). Wind erosion occurred within each 10 days period was calculated by means of the RWEQ model using the following information: soil organic matter content (%), clay and silt (%); average 1 min wind speed (m s^{-1}) and soil coverage with plant residues (%), crop canopy (%), weeds (%) or non-erodible aggregates (%). The soil wetness factor was 1 (no wetness limitation) in all cases and no erosion was calculated during the first three days after a rain event. Wind erosion amounts were calculated for periods of time with wind speeds higher than 5 m s^{-1} at 2 m height, the threshold wind velocity considered by RWEQ (Fryrear et al., 1998). Results were analyzed with INFOSTAT program (Di Rienzo et al., 2002).

3. Results and discussion

Figs. 2 and 3 show the soil coverage evolution with non-erodible aggregates, residues, weeds and crop canopy, and the soil losses estimated with the RWEQ each 10 days. Soil protection, soil coverage composition and soil loss were variable among crops, years and tillage systems. However, estimated soil losses in 2006 were higher than in 2005 while estimated soil losses after planting were higher than during fallow (Table 3). Consequently, soils loss, total soil coverage (TSC) and soil coverage composition were analyzed during the fallow period and after planting each year.

3.1. Fallow period

Estimated soil losses during fallow 2005 varied from 0 kg ha^{-1} to 255 kg ha^{-1} (Table 3). Estimated soil loss values close to zero were obtained in NT while the highest values were obtained in CT and VT. Though TSC was lower than 30% on corn-2005 and sunflower-2005 in CT, estimated soil losses were low due to the low climatic erosivity of that period (Figs. 2 and 3, Table 2). Soil protection was provided mainly by residues in sunflower-2005 planted on corn residues in CT, VT and NT, while in corn-2005, planted on soybean residues, soil protection was given mainly by

Table 1
Organic matter (OM), clay, silt, sand and $CaCO_3$ contents of the soil on each tillage system.

Tillage system	OM%	Clay%	Silt%	Sand%	$CaCO_3$
NT	3.08	16.4	23.5	60.1	0
VT	2.72	14.1	22.6	63.3	0
CT	2.85	13.9	22.8	63.3	0

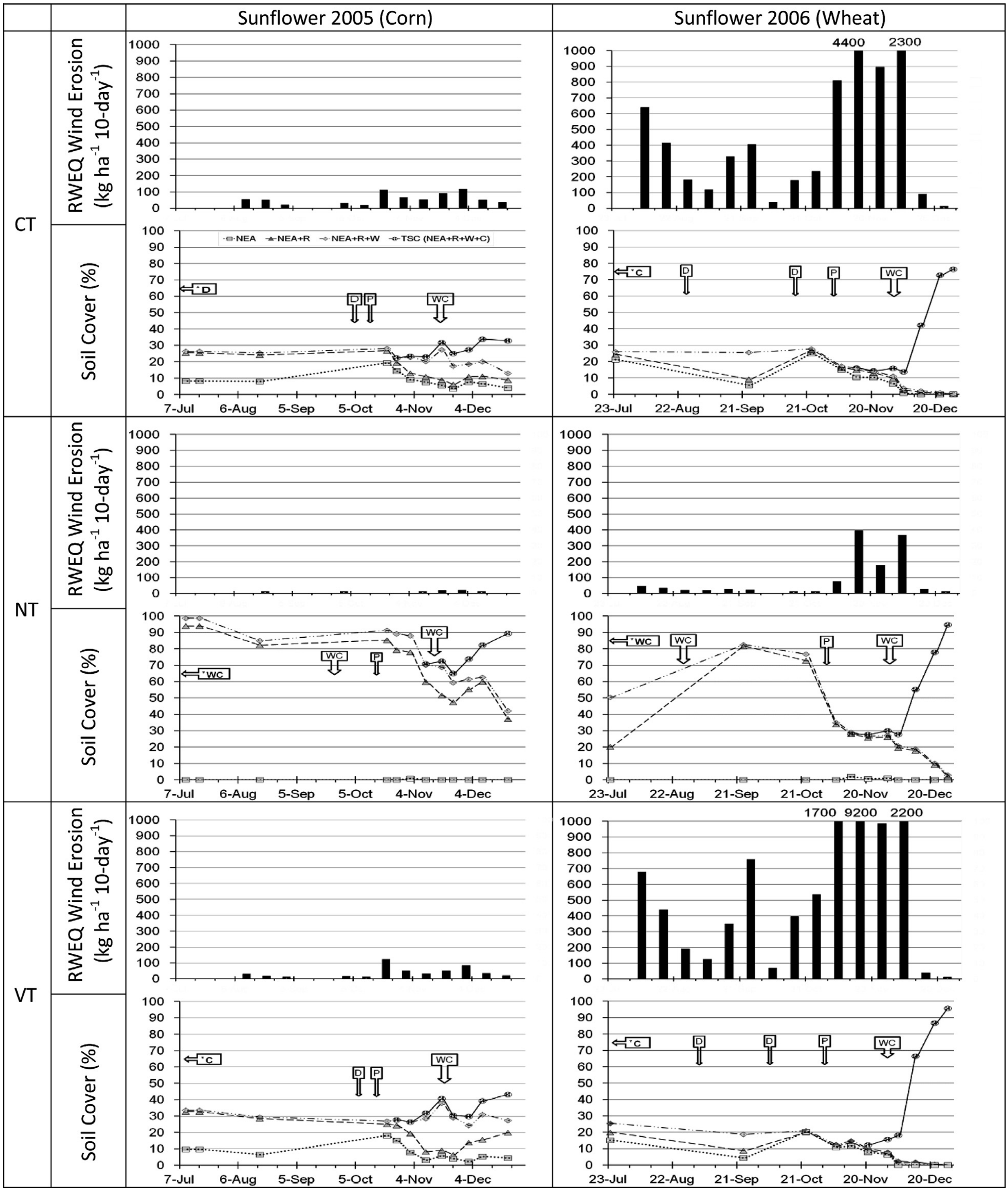

Fig. 2. Wind erosion as calculated by RWEQ for 10 days periods of time and soil cover evolution for sunflower planted in conventional tillage (CT), no-tillage (NT) and vertical tillage (VT) during 2005 and 2006. NEA = non-erodible aggregates, R = residues, W = weeds, TSC = total soil coverage, C = crop, D = is disk, C = chisel, WC = weed control and P = planting. In parentheses the previous year's crop. Numbers above bars indicate wind erosion amounts for cases higher than maximum scale values.

non-erodible aggregates in CT and VT (Fig. 2 and 3). This difference can be explained by the amount of residues left by previous crops. It is known that the amount and persistence of corn residues are higher than those of soybean (Ormeño and Quiroga, 2001; Broder and Wagner, 1988). These authors also showed that the persistence of corn residues was larger than that of soybean, a fact that was confirmed here, as soybean residues decayed faster than corn residues during NT-fallows in 2005 (Figs. 2 and 3). The TSC increased at the end of sunflower- and corn fallows in 2005 in NT due to weeds growth. Weeds were treated with herbicides few days before crops planting. Once dry, the remaining weeds biomass made a significant contribution to the total residue soil coverage. It must be noted that weeds were killed in vegetative stages, when their tissues apparently had relatively high *N* concentrations

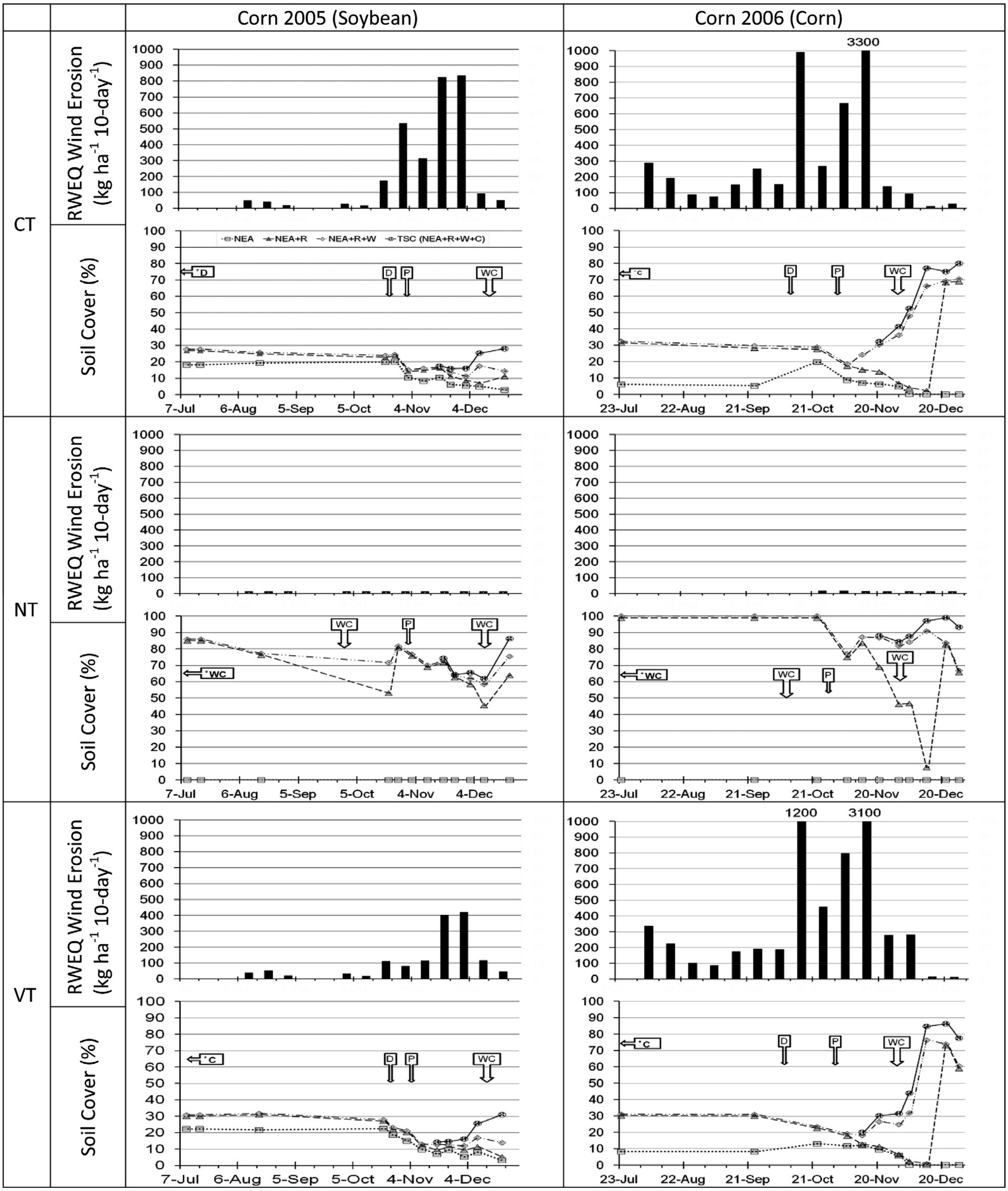

Fig. 3. Wind erosion as calculated by RWEQ for 10 days periods of time and soil cover evolution for corn planted in conventional tillage (CT), no-tillage (NT) and vertical tillage (VT) during 2005 and 2006. NEA = non-erodible aggregates, R = residues, W = weeds, TSC = total soil coverage, C = crop, D = is disk, C = chisel, WC = weed control and P = planting. In parentheses the previous year's crop. Numbers above bars indicate wind erosion amounts for cases higher than maximum scale values.

which promoted a rapid decomposition (Greenwood et al., 1990, 1991; Tian et al., 1992; Johnson et al., 2007).

A different situation was found in the fallow of 2006, where a high climatic erosivity (C-factor) existed (Table 2). In this case, estimated soil losses during the fallows varied between 4 kg ha^{-1} and 3438 kg ha^{-1} (Table 3). In NT, estimated soil losses during the fallows were lower than 100 kg ha^{-1} while in CT and VT it was higher than 2000 kg ha^{-1} (Table 3). A 30% TSC, like that of corn-2006 in CT, was not enough to reduce soil losses to values lower than 2000 kg ha^{-1} when the climatic erosivity was high (Fig. 3). Conversely, soil coverage higher than 50%, like that of sunflower-2006 in NT, was enough to maintain soil losses below 100 kg ha^{-1} (Fig. 2). When corn-2006 was planted on corn residues, TSC was higher than 20% in all tillage systems and TSC was mainly provided

Table 2
Meteorological parameters and climatic erosivity (C-factor) from July to December for each year of the study.

Parameter	Year	Months						
		July	August	September	October	November	December	Average
Precipitation (mm)	2005	6.8	13.6	58.4	47.9	24.0	61.5	35.4
	2006	3.0	19.2	7.0	141.7	14.9	65.0	41.8
Temperature (°C)	2005	8.5	9.7	11.9	15.3	21.0	21.6	14.7
	2006	9.7	10.0	13.7	17.5	19.6	23.4	15.6
Wind speed at 10 m height (m s^{-1})	2005	2.8	3.1	3.8	3.2	3.9	4.1	3.5
	2006	4.1	4.8	4.9	5.0	5.7	4.8	4.9
Climatic erosivity (C-factor)	2005	20.6	27.4	50.6	30.3	56.5	66.0	41.9
	2006	66.5	105.1	109.8	118.3	170.6	101.8	112.0

Table 3
Wind erosion estimated with RWEQ in the fallow, crop growth and total of sunflower and corn planted in conventional tillage (CT), no-tillage (NT) and vertical tillage (VT).

Tillage	Crop	Fallow (kg ha^{-1})		Crop Growth (kg ha^{-1})		Total (kg ha^{-1})	
		2005	2006	2005	2006	2005	2006
CT	Sunflower	110	2432	447	8287	557	10,719
	Corn	255	2334	2460	4179	2715	6512
NT	Sunflower	0	102	15	987	15	1089
	Corn	1	4	5	9	6	13
VT	Sunflower	33	3438	311	13,971	344	17,409
	Corn	203	2898	1084	4428	1287	7326

Total = sum of wind erosion in the fallow and crop growth.

by residues. In CT and VT, TSC was composed by corn- (previous crop) and dead weeds residues. In NT, most of TSC was provided by *Eleusine indica* weeds (Pata de Gallo). It is a weed that produced a large amount of residues and seeds during the autumn previous to the planting date of the summer crop (Fig. 4). *E. indica* is a spring–summer weed affecting mainly corn and it emerges when the corn is tall and so it cannot be treated chemically. Few wind erosion studies have documented the presence of weeds (Nokes et al., 1997) and there is little information about of wind erosion control given by weeds.

In sunflower-2006, planted in CT and VT on wheat residues, TSC varied between 20% and 30%, having similar proportions of residues, non-erodible aggregates, and weeds (Fig. 2). The low residue coverage in sunflower-2006 compared to corn has to do with the 11 months last since wheat harvest to sunflower plantation. During this long period of time a high decomposition of wheat residues occurred. In sunflower-2006 planted in NT, TSC was produced mainly by living weeds (Fig. 3). If weeds coverage were not considered, the estimated soil loss was 3680 kg ha^{-1}. When living weeds coverage was not considered in CT and VT, estimated soil losses varied between 4300 kg ha^{-1} and 8500 kg ha^{-1}. These results demonstrated the important role of weeds in controlling wind erosion during the fallows made prior to summer crops planting.

Fig. 4. Residues of *Eleusine indica* (Pata de Gallo) in the fallow of corn under NT in 2006.

3.2. After planting period

Estimated soil losses after planting ranged from 5 to 2500 kg ha^{-1} when the climatic erosivity was low (year 2005) (Table 3). Values close to zero were obtained in NT while in CT and VT estimated soil losses were lower than 1000 kg ha^{-1} for sunflower-2005 planted on corn residues, and higher than 1000 kg ha^{-1} for corn-2005 planted on soybean residues. These results were related with the TSC decrease after planting and the period of time needed to achieve soil coverage levels similar to those existing before crop planting (called recovery time) (Figs. 2 and 3). This result is in agreements with many others studies that demonstrated that TSC decreases after crops planting (Guy and Lauver, 2006; Merrill et al., 2006; López et al., 2003; Lampurlanés and Cantero-Martínez, 2006).

After corn planting in 2005, TSC decreased 10% and the recovery time was approximately 30 days (Fig. 3). The coverage decrease was due mainly to the destruction of non-erodible aggregates during planting operations and rains in CT and VT (Romkens and Wang, 1987; Mendez and Buschiazzo, 2010). In NT, the soil coverage decrease after planting was due mainly to the burying of residues during planting operations and the decomposition of residues. The burying of residues during planting operations was also documented by Guy and Lauver (2006). Part of the residues present after planting of corn (2005) were weeds, which had a fast decomposition as consequence of they were killed with the herbicides in vegetative stage when their tissues had a high nitrogen concentration (Fig. 3). On the other hand, after CT and VT sunflower planting in 2005, TSC decreased less than 5% and the recovery time was shorter than 15 days, though soil coverage with non-erodible aggregates and residues decreased after planting (Fig. 2). This happened because of the rapid development of the *E. indica* that compensated the soil cover loss with non-erodible aggregates and crops residues. A delay in the evolution of crops canopy may have been produced by the competition of weeds for light and nutrients. Though crop yield was not measured, yield losses were not expected because the critical period for a crop–weed competition occurs 2–4 weeks after corn plantation, and after 4 weeks for sunflower (Bedmar et al., 1983, 1999). The critical period of crop–weed competition has been defined as the length of time that weeds which emerge with the crop can remain untreated before they begin to compete with the crop and cause yield loss (Zimdahl, 1980). Although the critical period of crop weed competition varies from year to year and site to site, a period of time exists when crops can grow together with weeds without yield losses (Halford et al., 2001). This should be taken into account in order to maintain high soil coverage after planting in order to reduce wind erosion. If living weeds coverage were not considered for wind erosion calculations in CT and VT, soil loss was higher than 1300 kg ha^{-1} in sunflower-2005 planted on corn residues and higher than 1500 kg ha^{-1} in corn-2005 planted on soybean residues. On the other hand, when living weeds were not taken in account in NT, soil losses were lower than 100 kg ha^{-1}.

Under high climatic erosivity conditions (year 2006), estimated soil losses after planting varied between 9 and 14,000 kg ha^{-1} (Table 3). The lowest soil loss was obtained on corn-2006 in NT when TSC was always higher than 75% (Fig. 3). However, the estimated soil loss reached 1000 kg ha^{-1} in NT when TSC fell below 30% in sunflower-2006 (Fig. 2). This was explained on the basis of the long period of time existing between wheat harvest and sunflower planting (11 months), which allowed a high decomposition of plant residues. In CT and VT, estimated soil losses were always higher than 4000 kg ha^{-1}, reaching values of 14,000 kg ha^{-1} (Table 3). When corn was planted on corn residues, TSC decreased less than 5% and the recovery time was shorter than 15 days as a consequence of *E. indica* emergence (Fig. 3). Due to this, TSC remained above 20% and the estimated soil loss was close to 4000 kg ha^{-1} (Table 3). On the other hand, when sunflower-2006 was planted on wheat, TSC decreased 10% after planting and the recovery time was 30 days. The TSC decrease was a consequence of the destruction of non-erodible aggregates by planting operations and by rains (Romkens and Wang, 1987; Mendez and Buschiazzo, 2010) (Fig. 2). Due to this, TSC fell below 20% (reaching values of TSC of 12% in VT) and the estimated soil loss was higher than 8000 kg ha^{-1}. When living weeds were not taken in account in CT and VT, the estimated soil loss was higher than 8800 kg ha^{-1} in sunflower-2006 (planted on wheat residues) and higher than 11,000 kg ha^{-1} in corn-2006 (planted on corn residues). On the other hand, when living weeds were not taken in account in NT, estimated soil losses were higher than 1000 kg ha^{-1}. These results also show the important role of weeds in protecting the soil against wind erosion in the first 30 days after crop planting. In the semiarid Pampas of Argentina, weeds can grow for 4 weeks after crop planting date without affect crops yields (Bedmar et al., 1983, 1999). This can be an efficient management strategy to reduce soil loss by wind erosion on summer crops.

Estimated soil losses after planting of summer crops was from 2 to 10 times higher than that occurred during fallows, as a consequence of the combination of high climatic erosivity and low soil protection (Tables 2 and 3). This result confirms that the most critical period for wind erosion in the semiarid Pampas occurs just after summer crops planting (Figs. 2 and 3). These results agree with those of Guy and Lauver (2006), who found similar trends in the Palouse region of Idaho.

Estimated soil losses during the whole crop season (since fallow start until the full crops development) varied between 6 kg ha^{-1} (Corn-2005 in NT) and 17,409 kg ha^{-1} (Sunflower-2006 in VT) (Table 3). The tolerable soil loss values observed by Verheijen et al. (2009), which varied between 300 and 1400 kg ha^{-1} year^{-1}, were overcame, even in NT when the previous crop was wheat and the fallow lasted 11 months but it was negligible when the fallow was shorter than 6 months. However, when living weeds coverage was not considered, soil loss in NT exceeded the tolerable levels when climatic erosivity was high, as in 2006 (sunflower 4700 kg ha^{-1} and corn 1500 kg ha^{-1}). In CT and VT, estimated soil losses were lower than tolerable levels only under low climatic erosivity conditions (2005) and when the infestation with *E. indica* maintained soil coverage above 20%. When living weed coverage was not considered, estimated soil loss was always higher than the tolerable levels in CT and VT, reaching 22,500 kg ha^{-1} in sunflower under VT in 2006. Those results show that soil protection given by living weeds was necessary to maintain soil loss values below the tolerable levels. Therefore, living weeds should be taken in account when wind erosion models are run and when theoretical analysis are made.

Estimated soil losses were 1.2–9.4 times higher than those estimated by Mendez and Buschiazzo (2010) for winter crops in the same region. These results are related with the higher climatic erosivity existing in the spring and the summer (fallow and growing seasons of summer crops) than in the autumn and the winter (fallow and growing seasons of winter crops). As a matter of fact, the calculated C-factor for the spring-summer period was twice than that for the autumn–winter period (Mendez and Buschiazzo, 2010 and Table 2). According to these results summer crops under CT and VT exhibits greater soil loss than winter crops in the studied region.

4. Conclusions

Wind erosion was mostly negligible during the whole growth period of summer crops (from fallow start to full crops canopy development) grown in no-till, but it mostly exceeded the tolerable levels in both, conventional and vertical tillage. Wind erosion amounts were the highest after crops planting in all tillage systems, including no-till. These high erosion amounts occurred during a period within which the soil was less covered and climate showed high erosivity. The low soil coverage was due to the destruction of non-erodible aggregates by rains and planting operations, which also buried plant residues. The growth of weeds 2–4 weeks after crops planting, contributed to reduce wind erosion without affecting their yields. Adequate weeds management can be a useful tool in controlling wind erosion in semiarid regions.

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