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PM10 emissions from aggregate fractions of an Entic Haplustoll under two contrasting tillage systems

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ABSTRACT

Tillage systems affect physical and chemical properties of soils modifying its aggregation. How changes of the aggregate size distribution affect the capacity of the soil to emit fine particulate matter (PM10) to the atmosphere during wind erosion processes, is a less investigated issue. In order to answer this question, PM10 emissions from an Entic Haplustoll submitted to 25 years of continuous conventional tillage (LC) and no-till (NT) were analyzed. Soil samples were sieved with a rotary sieve in order to determine the aggregate size distribution (fractions : <0.42 mm, 0.42–0.84 mm, 0.84–2 mm, 2–6.4 mm, 6.4–19.2 mm, and >19.2 mm), the dry aggregate stability (DAS) and the erodible fraction (EF). The organic matter contents (OM), the particle size composition and the PM10 emission of each aggregate fraction were also measured. Results showed that NT promoted OM accumulations in all aggregate fractions which favored DAS and soil aggregation. The <0.42 mm sized aggregates (27%) predominated in CT and the >19.2 mm (41.7%) in NT, while the proportion of the other aggregate fractions was similar in both tillage systems. As a consequence of the smaller proportion of the <0.42 mm aggregates, the erodible fraction was lower in NT (EF: 17.3%) than in CT (30.8%). PM10 emissions of each aggregate fraction (AE) decreased exponentially with increasing size of the fractions in both tillage systems, mainly as a consequence of the smaller size and higher specific surface. AE was higher in CT than in NT for all aggregate fractions, but the higher differences were found in the <0.42 mm aggregates (18 μg g^{-1} in CT vs 8 μg g^{-1} in NT). The PM10 emission of the whole soil was three times higher in CT than in NT, while the emission of the erodible fraction (EFE) was in CT four times higher than in NT. PM10 emissions of the <0.42 mm aggregates represented over 50% of SE and 90% of EFE. We concluded that NT reduced the capacity of soils of the semiarid Pampas to emit PM10 because it produced a better aggregation that reduced the proportion and emission of the <0.42 mm aggregates. These aggregates had, by far, the highest emission potential.

1. Introduction

The emission of particles with a geometric diameter smaller than 10 μm (PM10) is a product of wind erosion of soils, tillage or vehicle traffic on unpaved roads. Studies about PM10 emissions increased in the last years because of the multiple effects of these on the ecosystem, including human health. It is known that human exposure to PM10 can increase mortality and morbidity (Pope et al., 1995; U.S. EPA, 1995; Pope and Dockery, 1999) and can modify the formation of clouds and the radiation balance (Seinfeld and Pandis, 1998), affecting the global climate change (McConell, 2007).

Recent studies showed that 20% of the global PM10 emissions are generated by vegetated surfaces, deserts, shrublands and agricultural lands (Ginoux et al., 2012). In this regard, European studies reported that the emission of PM10 in natural areas is 6–8 times lower than in livestock and agricultural areas (Korcz et al., 2009). The importance of agricultural soils as a source of PM10 emissions has been also demonstrated for soils of the central semiarid region of Argentina (Buschiazzo et al., 1999; Aimar et al., 2012).

The development of mathematical models to predict PM10 emissions during the process of wind erosion is one of the current challenges. In this context, wind tunnel and laboratory experiments carried out by Gill et al. (2006), U.S. EPA (1995) and Carvacho et al. (2004) determined that PM10 emissions increased

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with silt and clay contents of the soils. Other studies demonstrated that organic matter contents of the soils (OM) can also affect PM10 emissions in similar textured soils (Gill et al., 1999; Alfaro, 2008; Aimar et al., 2012). Such studies indicate that OM determines PM10 emission of soils because it modifies the aggregate size distribution and the stability of aggregates, changing their emission potential (Gill et al., 1999; Alfaro, 2008). Most of these studies performed PM10 emission simulations on 2 mm sieved soil samples. Less information is available on PM10 emissions produced from aggregates of different sizes. Amante-Orozco (2000), using cultivated soils of the Southern High Plains of West Texas, found that smaller fractions had the lowest emissions and that intermediate fractions had the highest.

Tillage systems are known to affect physical and chemical properties of the soil like the aggregate size distribution, OM contents and the aggregate particle composition (Hevia et al., 2007), which are probably related to PM10 emissions (Aimar et al., 2012; Gao et al., 2014). Less aggressive tillage like no-till, promotes OM accumulation and increase soil aggregation and the dry aggregate stability (Apezteguia and Sereno, 2002; Quiroga et al., 1998, 2012; Barraco et al., 2004). Under these conditions lower PM10 emissions are expected. Gao et al. (2014), using the Single-Event Wind Erosion Evaluation Program (SWEEP), showed that PM10 emissions are potentially higher in conventional tillage and lower in no-till in a silt loam soil of Alaska. Sharratt et al. (2010), using a portable wind tunnel, showed that PM10 flux generally decreased with a decrease in the number or the intensity of tillage operations during winter wheat–summer fallow in the Columbia Plateau (Pacific Northwest United States). Singh et al. (2012) found that PM10 vertical flux was generally less for no-till than for traditional tillage systems carried out with a tandem disk, due to the large amount of surface residues and the surface soil crusting.

Aim of this study is to evaluate how different tillage systems can affect soil aggregation and how these variations influence the PM10 emission potential of different aggregate fractions.

2. Materials and methods

Soil samples were obtained from a long term tillage experiment placed in the Faculty of Agronomy of the University of La Pampa (S36° 46′; W64° 16′; 210 m a.s.l.). The soil of the experimental site is a fine-sandy loam Entic Haplustoll (USDA Classification), has a A-AC-C-Ck horizon sequence and is representative of the soils of a large area of the central semiarid Pampa of Argentina (Instituto Nacional de Tecnología Agropecuaria et al., 2004). More details of the A horizon properties of the soil at experiment start are detailed in Table 1.

Table 1
Main characteristics of the studied soil.

Horizons	A	AC	C
pH	5.9	7	7.8
Cation exchange capacity (cmol/kg)	9.6	11.4	11.5
Exchangeable cations (cmol/kg)			
Ca++	6.35	8.7	21.6
Mg++	1.7	1	1.6
K+	1.4	1.4	1.3
Na+	0.3	0.3	0.5
Water holding capacity (%)	11.5	11.8	10.3
Clay, 0–2 μm (%)	10.2	9.9	11.9
Fine silt, 2–20 μm (%)	7.4	10.9	12.1
Coarse silt, 20–50 μm (%)	9.7	13.8	12.5
Very fine sand I, 50–74 μm (%)	11.7	14.1	16.6
Very fine sand II, 74–104 μm (%)	15	17.6	12.4
Fine sand, 104–246 μm (%)	30.2	27.4	29.8
Mean and coarse sand, 246–2000 μm (%)	15.7	6.5	4.8

The experimental site consisted of a 20 ha field placed in a plane relief position with a slope smaller than 0.5%. This field was subdivided into two 10 ha plots. The same crops rotation was implemented in both plots but one of them had continuous conventional tillage (LC) and the other continuous no-till (NT) since 25 years. The rotation consisted in periods of 4 years of agriculture and 4 year of pastures. Agriculture included two summer crops (sunflower – *Helianthus annuus*, corn – *Zea mays* or soybean – *Glycine max*) and one winter crop: wheat (*Triticum aestivum*).

Three undisturbed soil samples were randomly taken from the upper 5 cm of three 1 m^2 surfaces in each CT and NT macro plots. According to Gili (2012) the A horizon of the 20 ha field presented a spatial variation coefficient lower than 5%, which guaranties that differences of the main soil properties between macroplots, like soil texture and OM contents, were due to tillage effects and not to variations of the parent material. Because of that soil samples of each 1 m^2 area were considered as replicates.

Soil samples were air dried and then sieved with a rotary sieve (Chepil, 1942) in order to separate the following aggregate fractions: <0.42 mm, 0.42–0.84 mm, 0.84–2 mm, 2–6.4 mm, 6.4–19.2 mm, and >19.2 mm. After the first sieving, each one of these aggregates was sieved for a second time.

Dry sieving allowed the determination of the erodible fraction (EF, aggregates <0.84 mm in diameter) and the dry aggregate stability of the soil and each aggregate fraction.

EF was calculated with Eq. (1).

$$\mathrm{EF}\ (\%) = \frac{W_{<0.84}}{T} \times 100 \tag{1}$$

where $W < 0.84$ is the weight (g) of the <0.84 mm sized aggregates after the first sieving, and T the initial weight (g) of the total sample.

The dry aggregate stability for the whole soil (DASt) was estimated with Eq. (2).

$$\mathrm{DASt} = \frac{(W_{>0.84})_1 - (W_{<0.84})_2}{(W_{>0.84})_1} \times 100 \tag{2}$$

where $(W_{<0.84})_2$ is the weight of the <0.84 mm sized aggregates that passed the 0.84 mm sieve after the second sieving, and $(W_{>0.84})_1$ is the total weight of the aggregates retained by the 0.84 mm sieve after the first sieving.

The dry aggregate stability of each aggregate fraction coarser than 0.84 mm (DASi) was calculated with Eq. (3).

$$\mathrm{DASi} = \frac{A_1 - A_2}{A_1} \times 100 \tag{3}$$

where A_1 is the weight (g) of the "*i*" sized aggregates after the first sieving, and A_2 is the weight (g) of the "*i*" sized aggregates passing the 0.84 mm sieve after the second sieving.

The following determinations were carried out in each aggregate fraction after the first sieving: organic matter contents (OM) by means of the wet digestion method (Walkley and Black, 1934), the easy available PM10 (PM10e) and the total PM10 emissions (PM10t).

To obtain the PM10e, each aggregate fraction was sieved through 2 mm without eliminating OM. The amount of PM10 was then measured with a laser particle counter in water suspension conditions (Malvern Mastersizer 2000). PM10e was generated during both processes: the 2 mm sieving and the particle size distribution determination with the laser counter. This is because weak aggregates were destroyed during sieving and grains glued to the aggregates were detached by the water as some dispersion occurred during the particle size distribution determination with the laser counter. We assumed, therefore, that PM10e is representative of the PM10 available for emissions when tillage operations are performed or wind erosion occurs, situations that do not affect OM contents.

The EDG (Fig. 3) was used for PM10t emission simulations. This device is composed by two parts: (1) a dust generating chamber and (2) a concentration chamber (Fig. 1). For PM10 determinations, the soil sample is dropped inside the generating chamber that rotates and mixes the soil sample, producing frequent falls from the top to the bottom. During these falls, the dust particles collide and impact with the chamber wall producing new dust particles. The released dust is transported to the concentration chamber by the air flow produced by the vacuum pump. The air loaded with PM10 particles entering to the concentration chamber are lately aspirated by the dust monitor, which measures PM10 concentrations. The remaining air continues to the vacuum pump where it is discharged outside the system. The dust monitor must be regulated to measure and register the average PM10 concentration (expressed in $\mu g\, m^{-3}$ of air) each 3 s (Fig. 1). The dust monitor counts the particle number during 3 s and then divides this by the air volume aspirated in the same time. The Kanomax model 3442 is a light scattering digital dust monitor with a particle range from 0.1 to 10 μm, flow rate 1 L min^{-1} and measuring range from 1 to 10,000 $\mu g\, m^{-3}$. More constructive details and calibration data can be consulted in Mendez et al. (2013).

PM10t emissions of all aggregate fractions were determined using different amounts of samples in order to obtain similar PM10 concentrations in the concentration chamber. This was made in order to avoid errors during measurements. The amount of sample considered for each aggregate size fraction was the following: 1 g for both the <0.42 mm- and the 0.42–0.84 mm sized aggregates; 2 g for the 0.84–2 mm aggregates and 3 g for the >2 mm aggregates. The PM10 concentration range in the concentration chamber during the experiment varied between 100 and 1000 $\mu g\, m^{-3}$, the range within the dust monitor can provide the most reliable PM10 measurements. Measurements of PM10t lasted 5 min. Longer lasting measurements were not performed in order to avoid excessive break-down of soil aggregates. In previous tests we found that after 5 min of PM10 simulation with the EDG, aggregates coarser than 2 mm were completely destroyed. Therefore, we decide to develop this measurement during 5 min, in order to simulate only the effect of sandblasting during wind erosion or tillage operations on aggregates destruction, considering that their destruction is not total during these processes.

Measurements of PM10t were performed by quadruplicate, so that twelve PM10 emission measurements were obtained for each aggregate fraction and tillage system.

The PM10 emission of each aggregate fraction (AE) was calculated with Eq. (4).

$$AE_x\ (\mu g\, g^{-1}) = \frac{PPM10_x * VARB * DE}{PMS} \tag{4}$$

where, AE_x is the PM10 emission of the fraction x ($\mu g\, g^{-1}$), $PPM10_x$ the averaged PM10 concentration along the experiment for the fraction x ($\mu g\, m^{-3}$), VARB the air volume removed by the vacuum pump ($m^3\, min^{-1}$), DE the experiment duration (min) and PMS the soil sample weight (g).

The contribution of each aggregate fraction to the total PM10 emission of the soil (CAFSE) was calculated with Eq. (5)

$$CAFSE_x\ (\mu g\, g^{-1}) = AE_x * PF_x \tag{5}$$

where AE_x is the PM10 emission of the fraction x and PF_x the proportion of the fraction x in the soil.

The PM10 emission of the soil (SE) was calculated with Eq. (6).

$$SE = \sum_{<0.42}^{>19.2} CAFSE\ (\mu g\, g^{-1}) \tag{6}$$

where CAFSE is the contribution of the fraction x to the total soil PM10 emission.

The PM10 emission index of the erodible fraction (EFE) was calculated with Eq. (7)

$$EFE = \sum_{<0.42}^{0.84-0.42} CAFSE\ (\mu g\, g^{-1}) \tag{7}$$

where CAFSE is the contribution of the fraction x to the total soil emission.

All results were compared between tillage systems and aggregate fractions by means of ANOVA and LSD multiple comparison tests using the Infostat programm (Di Rienzo et al., 2002) using a 0.05 probability level. Relationships between variables were analyzed by means of simple regression analysis.

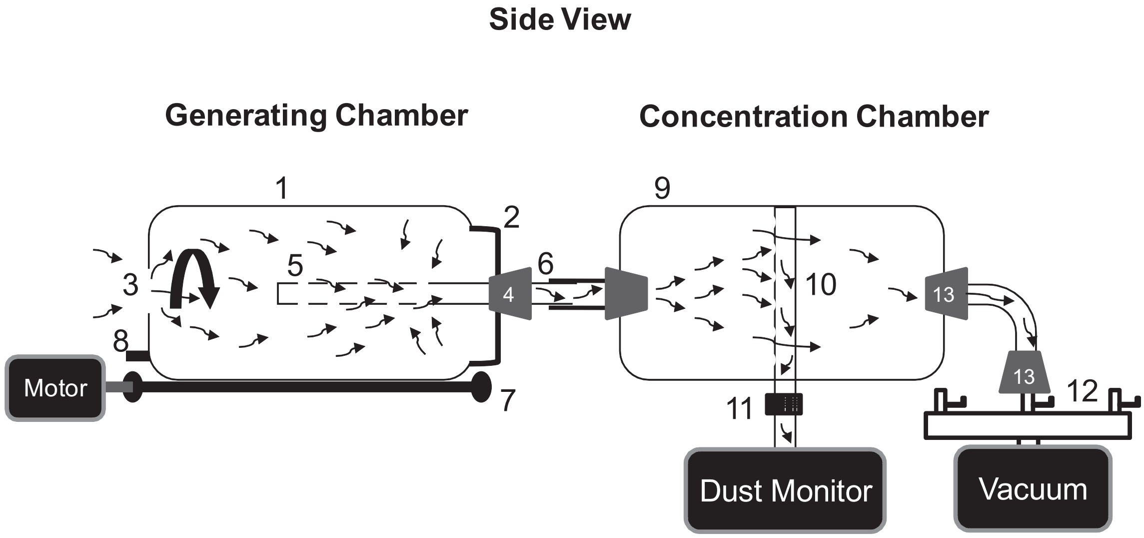

Fig. 1. Schematic view of the Easy Dust Generator (EDG), where: 1 is the plastic bottle of the generating chamber, 2 the screw cap, 3 an orifice, 4 a rubber stopper, 5 a plastic tube with holes, 6 the connection between the generation chamber and the concentration chamber, 7 the mobile cylinder, 8 the passive cylinder, 9 a plastic bottle of the concentration chamber, 10 a plastic tube with holes connecting the concentration chamber to the dust monitor, 11 a filter, 12 pipes with taps, and 13 rubber stoppers. The bigger curve arrow shows the generating chamber rotation sense and the smaller arrows the direction of the air circulation.

3. Results and discussion

3.1. Soil properties

Fig. 2 shows that organic matter contents (OM) were similar in all aggregate fractions in CT but highly variable in NT. The OM were higher in no-till (NT) than in conventional tillage (CT) in all aggregate fractions (Fig. 2, $p < 0.01$). These results agree with those of Paustian et al. (2000), Six et al. (1998) and Hevia et al. (2003) who found that NT promotes the accumulation of OM in the soil in relation to CT as a product of the higher deposition of plant residues. On the other hand, CT reduces OM as a consequence of the acceleration of the decomposition rate of residues incorporated into the soil (Dalal and Mayer, 1986; Doran, 1987; Balesdent et al., 1990). The higher accumulation of OM in NT in relation to CT occurred mainly in the >19.2 mm- and 0.84–2 mm sized aggregates (Fig. 1).

The coarsest- (>19.2 mm and 6.4–19.2 mm) and the finest aggregates (<0.42 mm) were the most abundant in both tillage systems (Fig. 3). However, the <0.42 mm sized aggregates predominated in CT and the >19.2 mm in NT ($p < 0.05$). The proportions of the remaining aggregate fractions were similar in both tillage systems. These results indicate that tillage produced larger changes in the amount of the coarsest and finest aggregates and not in the medium sized.

As a consequence of the smaller proportion of the <0.42 mm aggregates, NT had the lowest erodible fraction (EF: 17.3%) (Fig. 3). The higher amount of EF in CT (30.8%) can be attributed to the destruction of coarse aggregates by tillage. This process has been frequently reported by different authors for soils of other parts of the world (Six et al., 1998; Gale et al., 2000) and Argentina (Bravo and Silenzi, 2000; Hevia et al., 2003; Colazo and Buschiazzo, 2015). On the other hand, the higher contents of OM of NT increased soil aggregation, bonding the finest aggregates into coarse ones (Wright and Hons, 2004; Colazo and Buschiazzo, 2015). Bravo and Silenzi (2000) reported EF values of 35% in CT for soils of the semiarid Argentina. Such values are smaller than in our study (51%), probably due to the better aggregation of the Petrocalcic Paleustoll studied by these authors than in the Entic Haplustoll studied here.

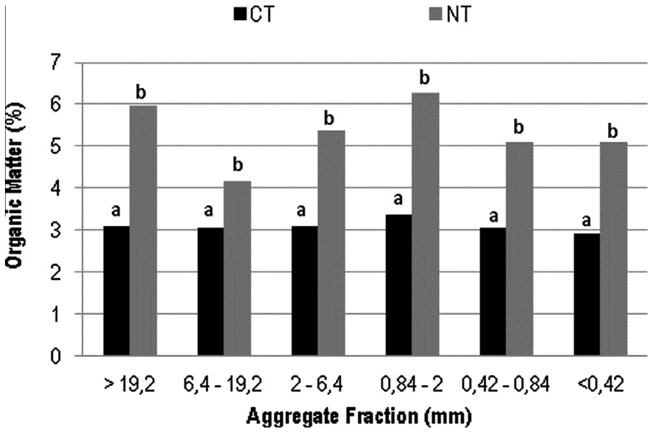

Fig. 2. Organic matter contents (OM) of each aggregate size fraction in conventional tillage (CT) and no-till (NT).

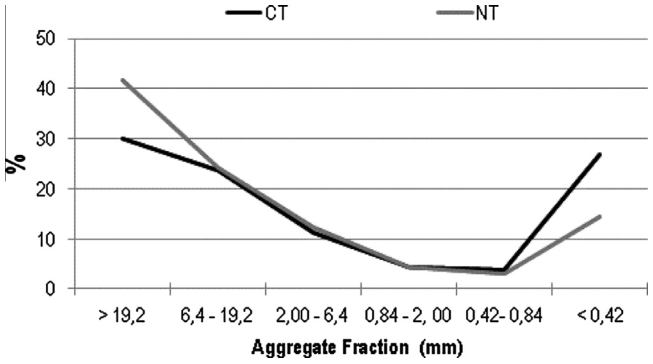

Fig. 3. Dry aggregate distribution in conventional tillage (CT) and no-tillage (NT).

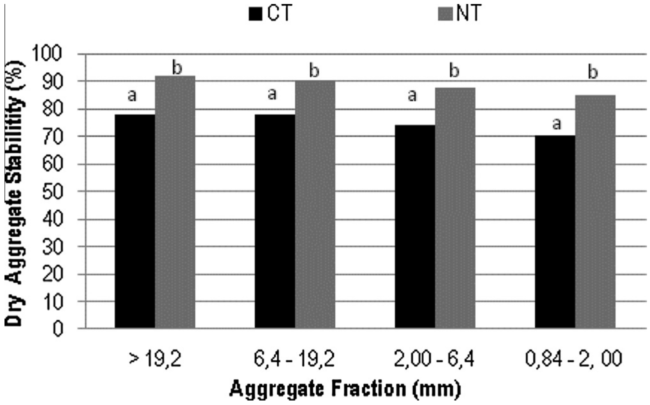

Fig. 4. Dry aggregate stability of each aggregate size fraction in conventional tillage (CT) and no-till (NT). Different letter indicate statistical differences <0.05.

The dry aggregate stability of the whole soil (DASt) was higher in NT (90.8%) than in CT (70.3%) ($p < 0.05$). The stability of each aggregate fraction (DASi) decreased with finer aggregate size in both tillage systems, being in all cases higher in NT than in CT (Fig. 4). Previous studies have shown that cultivation reduces more the aggregate stability with increasing tillage intensity. Hernández et al. (2000) found that the aggregate stability of an undisturbed soil decreased by 70% after 8 years of tillage and that the aggregate stability increased 30% after 5 years of no-till. Hevia et al. (2007), who studied the same soils than here, found lower DASt and DASi values and higher EF contents for CT. These differences are probably related to the drier conditions of the soil when tilled in the Hevia et al. (2007) study. It is known that plowing of dry soils produces a large destruction of aggregates and that plowing under wet conditions originates clods which are resistant to dry sieving (Tisdall and Adem, 1986; Barzegar et al., 1995; Colazo and Buschiazzo, 2015).

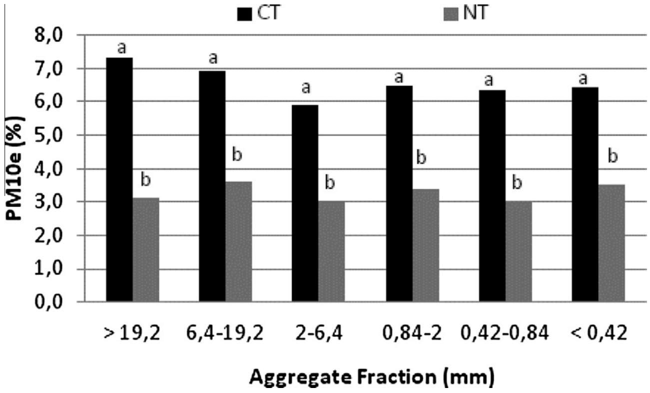

Fig. 5. Contents of the easily available PM10 fraction (PM10e) from different sized aggregates in conventional tillage (CT) and no-till (NT).

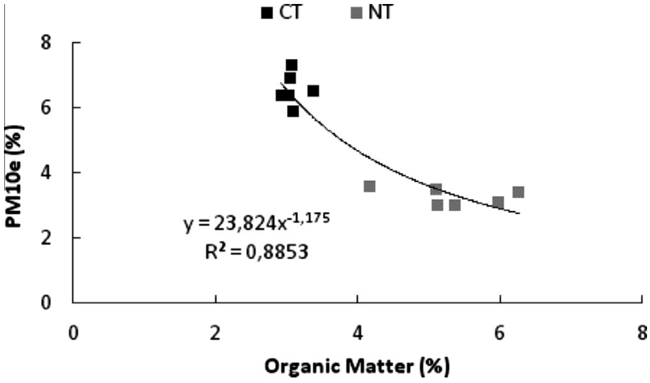

Fig. 6. Contents of the easily available PM10 fraction (PM10e) from different sized aggregates in CT and NT, as a function of OM contents.

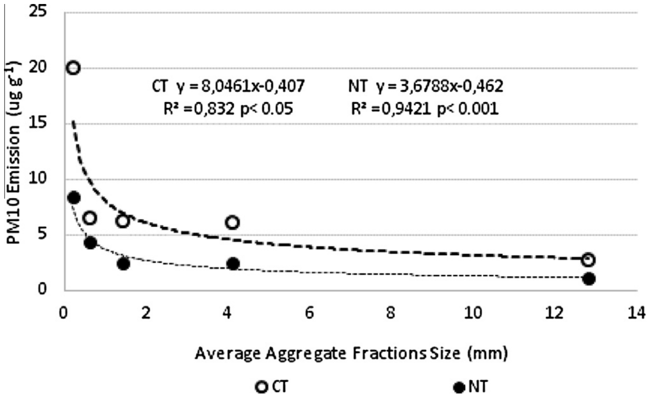

Fig. 7. PM10 emission of each aggregate fraction (AE) in conventional tillage (CT) and no-tillage (NT). The average size of each fraction was considered: <0.42 mm (0.21 mm), 0.42–0.84 mm (0.63 mm), 0.84–2 mm (1.42 mm), 2–6.4 mm (4.2 mm) and 6.4–19.2 mm (12.8 mm).

Fig. 5 shows the contents of PM10e, which represent the potential of each aggregate fraction to generate PM10 by brittle fragmentation. Results indicate that PM10e was similar in all aggregate fractions in NT and more variable in CT (Fig. 5). This behavior was similar to that of OM. As a matter of fact, PM10e correlated negatively with OM contents of each aggregate fraction (Fig. 6). Results also indicate that PM10e contents were higher in CT than in NT for all aggregate fractions ($p < 0.05$) (Fig. 5). Gao et al. (2014) concluded that NT promoted aggregation of fine soil particles and resulted in the lowest freely-available PM10 content as compared with other tillage treatments. Our results may be explained on the basis of the lower amounts of fine loose material from each aggregate fraction in NT, due to the high OM contents that promoted soil aggregation (Buschiazzo et al., 1999; Wright and Hons, 2004). Under these conditions, the inter-grains bonding was probably not destroyed (Kok et al., 2012). According with Fig. 6, PM10e decreases potentially when OM increases. This suggests that, the potential for PM10 production by brittle fragmentation was similar in all aggregate fractions in NT and more variable in CT. It can be also deduced that PM10 emissions were lower for NT than CT in all aggregate fractions.

Fig. 7 shows that PM10 emissions of each aggregate fraction (AE) decreased exponentially as the size of the fraction increased in both tillage systems. These results are different from those reported by Amante-Orozco (2000), who, analyzing fine sand-, sandy clay loam- and clay loam soils, found that smaller fractions had the lowest emissions and that the intermediate fractions (between 0.84 and 6.4 mm) the highest. The disagreement between results of both studies are unexpected, since the dust generators used in both studies (Amante-Orozco, 2000 and in the present study) are class "C" (Mechanical dispersion/agitation) with similar operation principles (Gill et al., 2006; Mendez et al., 2013), but they may be related to the length of experiments used for the PM10 emission determination, which was longer in the Amante-Orozco study (30 min) than here (5 min). Gill et al. (2006) considered that differences in the experiment duration are one of the main causes that limit the comparison of results of PM10 emission studies.

PM10 emission of the <0.42 mm aggregates increased during the first steps of the experiment, decreasing thereafter. The emissions of the 6.4–19.2 mm aggregates showed different trends: they increased continuously along the whole experiment (Fig. 8). These results indicate that longer experiment duration favored the emission from the coarsest aggregates. This may be related with the progressive destruction of these aggregates during their handling in the dust generator and the more continuous production of fine particulate matter. Amante-Orozco (2000) also showed that longer experiment duration favors PM10 emission of coarser aggregates.

The decreasing AE with increasing size of aggregates is related with the specific surface of each aggregate fraction, i.e. smaller fractions, with larger contact surfaces, are more likely to release PM10 particles but also to generate new ones due to the breakdown of larger particles during the emission simulations with the EGD.

The PM10 emission of the soil (SE) was, in CT, three times higher than in NT ($p < 0.01$) (Fig. 9). The contribution of each aggregate fraction to the PM10 emission of the whole soil (CAFSE) was also higher in CT than in NT. As a consequence of that, AE was in

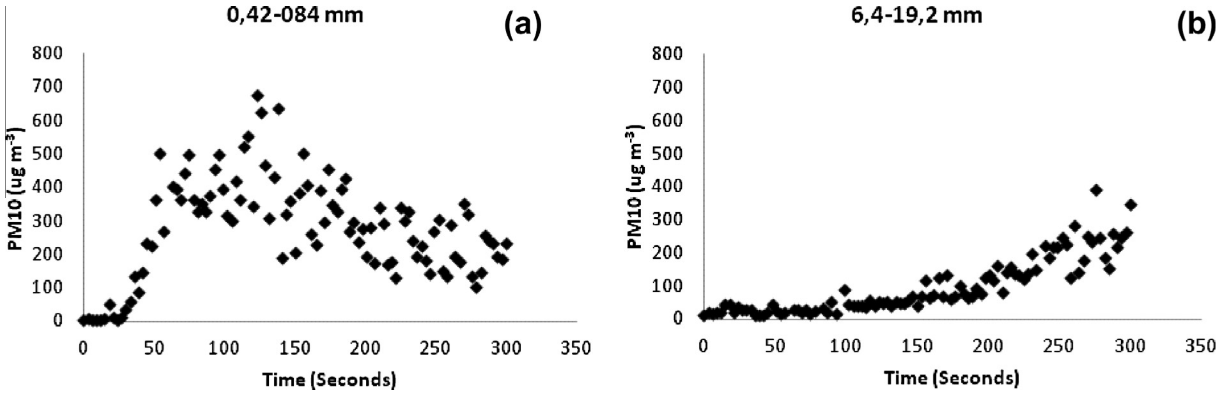

Fig. 8. Evolution of PM10 emissions during simulations carried out with the Easy Dust Generator (EDG) for (a) the 0.42–0.84 mm and (b) the 6.4–19.2 mm sized aggregates.

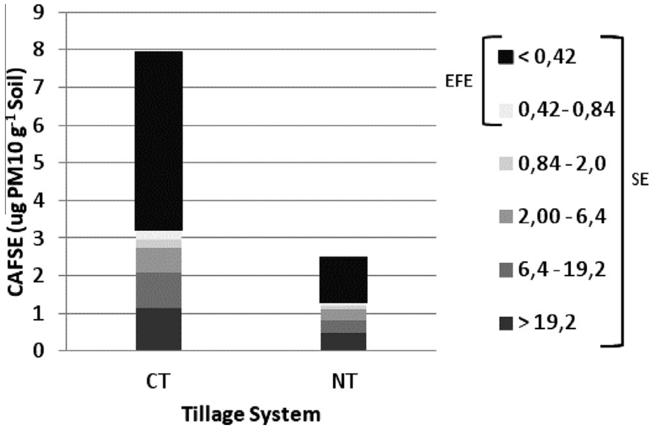

Fig. 9. PM10 emissions of the whole soil (SE), the erodible fraction (EFE) and each aggregate fraction (CAFSE). CAFSE is the contribution of each aggregate fraction to the soil emission, CT = conventional tillage, NT = no-till.

CT higher than in NT for all aggregate fractions. CAFSE differences between tillage systems decreased with decreasing size of aggregates, excepting for the >0.42 mm aggregates that showed the largest differences. CAFSE of the <0.42 mm aggregates was much higher in CT than in NT due to both, their larger amounts and their higher emission rates (Figs. 3 and 7). Though the >19.2 mm aggregates were the most abundant in both tillage systems, their CAFSE was not so high because of their low PM10t (Figs. 3 and 7). The other aggregate fractions had similar (and relative low) CAFSE in both tillage systems as a consequence of their low proportions in the soil.

Taken into account that CAFSE of the <0.42 mm aggregates represents over 50% of SE and 90% of EFE, CAFSE of aggregates <0.42 mm can be a good indicator of the emission potential of the whole soil.

4. Conclusions

The capacity of one agricultural soil of the Argentinean Pampas to emit PM10 is reduced in NT compared to CT. This is because NT favors the accumulation of OM and, therefore, the dry aggregate stability. These changes also reduced PM10 emissions of all aggregate fractions in relation to CT.

PM10 emissions decreased with increasing size of aggregates, being the <0.42 mm those with the highest emission potential (more than 50% of total soil emissions and more than 90% of emissions of the erodible fraction). This is probably due to the lower liberation of fine particulate matter in association with low specific surfaces from coarser aggregates.

More studies are necessary in order to assess the effects of tillage systems on soil aggregation and PM10 emissions in other soil conditions.

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