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Soil physical quality changes under different management systems after 10 years in Argentinian Humid Pampa

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Abstract

The Argentinian Humid Pampa extends over about 60 million ha, 90 % of which are agricultural lands. The southeast of the Buenos Aires Province is part of the Humid Pampa (1 206 162 ha). The main crops are wheat, sunflower, corn and soybean. The
5   management systems used in the area are: moldboard plow (MP), chisel plow (CP) and no-till (NT). Excessive soil cultivation under MP causes decreases in the soil organic carbon content (SOC). Adopting NT may reduce the effects of intensive agriculture, through the maintenance and accumulation of SOC. However, the soil compaction under NT causes degradation of the soil structure, reduces the soil water availability and
10   reduces the soil hydraulic conductivity. We evaluated the evolution of the soil physical parameters in three management systems. After 10 years of experiments in four farmers' fields, we found that: soil bulk density was significantly higher under NT. The change in mean weight diameter (CMWD) of aggregates increased as the management system became more intensive. We did not find significant differences in time
15   and management systems in hydraulic conductivity at tension (h)0 cm and $h = 20$ cm. The reduction in total porosity under NT is mainly a product of a reduction in the percentage of mesopores in the soil. Time had no statistically significant effect on the SOC content. The management system did not affect the yields of crop. In this work, the results indicate a modification of some soil physical parameters (porosity, near-saturated
20   hydraulic conductivity, soil structure) due to uninterrupted agricultural production.

1   Introduction

Sustainable soil management in agriculture land is a need for a sustainable world. Efforts to achieve a sustainable management can be found in developed and non-developed countries (Perkins et al., 2013; Mekuria and Aynekulu, 2013). One of the
25   most successful soil management in agriculture land is the no-tillage (NT), and is being applied worldwide (Barbera et al., 2012; Schneider et al., 2012; Thapa et al., 2012;

Lieskovský and Kenderessy, 2014). No-tillage affects the pedological, hydrological and geomorphological processes (García-Orenes et al., 2009; Olag et al., 2014; Gao et al., 2014).

South American countries with the highest surface of land under NT are Brazil, Argentina and Chile (Lal et al., 2007). In Argentina, 78.5 % of the agricultural land is cropped under NT management (Aapresid, 2012). However, the southeast of the Humid Pampa, with 60 million ha, 90 % of which are agricultural lands, does not reflect this situation because most of the crops are managed with tillage practices. However, NT management is becoming more popular and little is known about the effects of this practice on soil properties.

Previous work demonstrated that under NT, the values of bulk density (δ_b) and the penetration resistance in the superficial layers of the soil are higher than those of the plowed soils due to soil compactation (Özcan et al., 2012). Intensive soil cultivation produces decreases in soil organic carbon (SOC) content (Studdert et al., 1997; Barbera et al., 2012; Lozano and Parras, 2014; Srinivasarao et al., 2014). The magnitude of such impact depends on the intensity of the management system, the tillage timeliness and the amount and quality of the residues: stubble, roots and exudates. Adopting NT and an adequate fertilization treatment may reduce the effects of intensive agriculture, through the maintenance and accumulation of SOC (Salinas-García et al., 1997) and the reduction in the soil and water losses (García Orenes et al., 2012).

Soil Organic Carbon has a very important role to play in other edaphic properties. Hati et al. (2006) emphasized its influence on the retention and movement of water in the soil, whereas Aparicio and Costa (2007) reported a significant and positive correlation of SOC with hydraulic conductivity ($r = 0.6$) and a negative one with the δ_b of the soil ($r = -0.6$). There is a strong relationship between soil microbiological activity, organic matter and the structural stability of the soil (Quiroga et al., 1998; García Orenes et al., 2010). Soil aggregate formation is influenced by biotic and abiotic factors and the SOC content plays an important role in the stabilization of aggregates and them on the reduction of the soil losses (Cerdà, 2000). Vegetation cover is the key factor

on the control of soil erosion (Jordán et al., 2008), and on agriculture land the use of mulches under NT is a key factor of the recovery of the soil quality (Jordán et al., 2010). The mulches use to be organic (straw, chipped pruned branches) but they can be also mineral such as rock fragments (Martínez Zavala and Jordán, 2008).

In Argentina, a number of experiments (Alvarez and Steinbach, 2009) have confirmed the improvements in soil aggregation and infiltration achieved by NT in dry land farming areas associated with increases of δ_b under NT. Averaging out soil SOC differences in various experiments under NT in Argentina showed an increase of $2.1\,\mathrm{Mg\,C\,ha^{-1}}$ over MP and the steady state was reached after 25–30 years (Alvarez, 2005). When enough nutrients were applied, there was no difference in yields between tillage.

With this scenario and the tendency to increase the surface under NT in the southeast of the Humid Pampa, we aimed to evaluate evolution of the soil physical parameters in three management systems to understand how future and past changes in management of agriculture land are affecting the soil quality.

2 Materials and methods

2.1 Experimental site

The southeast of the Province of Buenos Aires has a mean annual temperature of 13.3 °C and the frost-free period extends from the beginning of October to mid-May. It has a sub-humid to humid hydric regime (Thornthwaite, 1948) and its rainfall regime comprises three seasons: (a) *rainy* from October to March, (b) *moderately rainy* in April, May and September, and (c) *scarcely rainy* from June to August. Mean annual precipitation is about 900 mm in the region.

The Pampean region is a wide plain where Quaternary eolian sediments were partially reworked. The experiments area is located in the geological province named "Sierras Septentrionales" in the southeast of the Buenos Aires Province of Argentine. The

loess deposits of the SE of Buenos Aires Province are from the Late Pleistocene and Holocene. The mineralogical composition of loess consists of a volcaniclastic assemblage derived mainly from reworked pyroclastic deposits (Zarate and Blasi, 1991). The soils are classified as Typic Argiudoll and Petrocalcic Argiudoll (Klingebiel and Montgomery, 1961) and are fine, illitic, thermal and mixed (Fig. 1). The initial soil characteristics of the experiments are shown in Table 1.

A randomized complete block design was used for the experiment, considering each locality as a block. Each plot was 50 m in width by 100 m in length and the treatments were: no till (NT), moldboard plow (MP) and chisel plow (CP). No-till consisted of chemical weed control during the fallow period using glyphosate [N-(phosphonomethyl) glycine] as herbicide, and seeding directly into the standing residues of the previous crop. Moldboard plow consisted of two tillage operations with a moldboard plow at a depth of 20 cm and two operations with disc harrow. Chisel low consisted of two chisel plow operations at a depth of 10 cm and two operations with disc harrow each year for seedbed preparation.

The crop sequence analyzed was wheat-corn-sunflower. The crops were fertilized according with your requirements of nitrogen as follows: at the V4–V6 stage in corn, at sowing in wheat, and at star stage in sunflower.

2.2 Physical and chemical determinations in soil

The soil physical parameters, except maximum δ_b, were determined after wheat harvests in two years (2004 and 2007) during the experimental period of ten years (1997–2007).

Bulk density was measured by the cylinder method (Blake and Hartge, 1986) with 12 sub-samples per plot, per year and per depth. The samples depths were: 3 to 8 cm and 13 to 18 cm.

Total porosity (ρ) was calculated as follows:

$$\rho = 1 - \frac{\delta_b}{\left[\left(1 - \frac{SOC}{100}\right)\delta_r + \left(\frac{SOC}{100}\right)\delta_{OC}\right]} \tag{1}$$

where δ_r the particle density ($2.65\,\mathrm{Mg\,m^{-3}}$), and δ_{OC} is the SOC density ($1.3\,\mathrm{Mg\,m^{-3}}$).

Maximum δ_b was estimated from the maximum compactability using the standard Proctor method (Felt, 1965), a soil sampled from 0–20 cm depth was taken for each treatment and block in 2007. Bulk density was replaced by maximum δ_b in Eq. (1), the resulting value was considered the textural porosity (ρ_t) (Aparicio and Costa, 2007). The ρ_t values used to calculate the structural porosity (ρ_s) as following:

$$\rho_s = \rho - \rho_t \tag{2}$$

total porosity, using Eq. (2), was calculated using the average value of δ_b over time and depth for each treatment and block.

Structural stability was measured by the De Leenheer and De Boodt (1959) method. Four disturbed sub-samples from each plot were dry and wet sieved, obtaining the change in mean weight diameter (CMWD). The samples for CMWD were collected at a depth of 0 to 20 cm.

Unsaturated hydraulic conductivity (K_h) was measured using a tension infiltrometer (Soil Measurement System[®], model SW-080B), which has a 20 cm diameter baseplate that was separate from the water tower. Infiltration runs were performed at matric potential (h) of -150, -70 and -20 mm, and readings were made for 40 min at each tension, beginning with 150 mm. Wooding (1968) proposed the following equations to describe the three-dimensional movement of water under a disk:

$$Q_{(k_h)} = \pi r^2 K_h \left(1 + \frac{4}{\pi r \alpha}\right) \tag{3}$$

$$K_h = K_s \exp(\alpha h) \tag{4}$$

where: Q_s = infiltrated water volume expressed in $m^3 s^{-1}$, r = radius of the disk in mm, K_s = saturated hydraulic conductivity in $cm\,h^{-1}$, K_h = hydraulic conductivity at tension h in mm, and α is a constant. With Eq. (3) and the procedure proposed by Logsdon and Jaynes (1993), we obtained α to calculate K_s and K_h. Hydraulic conductivity was ⁵ measured with four sub-samples in each plot on wheat stubble but during the wheat fallow period.

The maximum number of effective pores per unit area (N) was calculated using the procedure of Watson and Luxmoore (1986) and the effective porosity is given by:

$$\theta_\varepsilon = N \pi R^2 \qquad (5)$$

¹⁰ where R is the minimum pore radius in each class.

Soil organic carbon (SOC) was determined by the Walkley–Black procedure (Nelson and Sommers, 1982), in composite soil samples collected at a depth of 0 to 20 cm from 10 different places in each plot per year. Samples were air-dried, ground and sieved through a 2 mm sieve. Results of SOC were expressed as concentration (%) and as ¹⁵ stock ($Mg\,ha^{-1}$) considering the soil δ_b and soil depth.

2.3 Crop yield

The yield of the summer crops (corn and sunflower) was determined by manual harvest of 14.3 m linear. The yield of wheat was determined by mechanical harvest, using an experimental harvester, in lines that were 10 m long and the width of the harvester. ²⁰ Three sub-samples per plot were taken for each of the three crops.

2.4 Statistical analyses

The Shapiro–Wilk (1965) test was used to providing evidence of normality. Under no evidence of normality log transformation of the data were made.

Analyses of variance were performed with SAS version 6.12 software (SAS Institute, ²⁵ 1989–1996). The data at different years were analyzed as repeated measurement us-

ing a mixed linear model (PROC MIXED). The random effect was block and the fixed effects were N rates and soil management. Mean comparisons were evaluated with a significance level of 0.05 using LSMEANS. Maximum δ_b, ρ, ρ_t and ρ_s were analyzed considering the block as random effect and soil management as fixed effects.

3 Results and discussion

3.1 Bulk density (δ_b)

Time ($F = 7.0$, $p < 0.009$), depth ($F = 7.98$, $p < 0.005$) and treatment ($F = 11.75$, $p < 0.0001$) had a statistically significant effect on δ_b and there were no time-per-depth ($F = 0.84$, $p < 0.36$), depth-per-treatment ($F = 1.37$, $p < 0.25$), time-per-treatment ($F = 1.84$, $p < 0.16$) and time-per-depth-per-treatment ($F = 1.15$, $p < 0.32$) interactions. Bulk density decreased over the time and was low at 3–8 cm (Fig. 2). There is a hypothesis that in the first years under NT soil δ_b increases and later decreases. Voorhees and Lindstrom (1984) suggested that three to four years are required for the soils with reduced tillage to be able to develop a more favorable porosity in the first 15 cm, which would be closely related to the biological activity and proportion of plant residues. In contrast, in another long-term experiment conducted in Argentina, no statistically significant differences in δ_b due to time were reported (Domínguez et al., 2009).

When changing the management system from conventional tillage to NT, the initial physical condition of the soil is a critical factor that can affect the soil productivity of the region under this new management system (Elissondo et al., 2001). The δ_b values decrease over time in the three management systems studied under wheat, corn and sunflower rotation (Fig. 2). In addition, δ_b was statistically different between treatments. No-till had δ_b higher values than those of other management system in several experiments carried out in Argentina (Aparicio and Costa, 2007; Fabrizzi et al., 2005; Ferreras et al., 2000; Buschiazo et al., 1999).

Finally, we found significant differences in δ_b in relation to the sampling depth of the sample. The average values were 1.19 and 1.21 Mg m^{-3} for the depths of 3 to 8 cm and 13 to 18 cm, respectively. Bermejo and Suero (1981) reported δ_b values that fluctuated between 1.22 and 1.26 Mg m^{-3} under continuous cropping on Typical Argiudolls in a similar region, whereas δ_b measurements taken in a three-year pasture were a little higher (1.35 Mg m^{-3}). In degraded soils, within the EEA Balcarce, Ferreras et al. (2000) reported δ_b values higher than 1.4 Mg m^{-3}.

Soil δ_b was significantly higher under NT, but no differences were detected between MP and CP. Although with proper rotation δ_b can be reduced in all treatments, high traffic intensity under NT (tractors used for seeding, crop protection and treatments and harvest operations) has a significant effect on increasing the δ_b. It is known that NT helps to retain a large percentage of the crop residue over the soil surface. These residues, in addition to protecting the soil, reduce soil evaporation, thereby increasing soil moisture in the upper 10 cm. Soils under conservation tillage are wetter than those under conventional tillage (Alvarez and Steinbach, 2009). When tillage operations are performed with moist soil, the chances of soil compaction increase (Botta et al., 2004). Consolidation in the surface horizon induced by no-tillage may also contribute to increase δ_b (West et al., 1990). Under MP or CP, tillage generates artificial macropores which in turn reduce δ_b.

Structural porosity is an estimator of the percentage of pores involved in water flow; a soil is considered moderately porous when total macroporosity ranges from 10 to 25 % (Pagliai, 1988). Although textural porosity measured in the year 2007 was moderate, NT structural porosity was significantly lower than the other treatments (Table 2).

3.2 Structural stability (CMWD)

The time had statistically significant effect on CMWD ($F = 70.18$, $p < 0.0001$), while treatment ($F = 2.95$, $p < 0.1280$) had not effects on CMWD and the interaction treatment-per-time was significative ($F = 3.12$, $p < 0.049$) (Fig. 3). The CMWD in 2007

increased significantly compared to 2004 in all the management systems evaluated, indicating a decrease in the structural stability of the soil due to the agricultural activities. However, the time-per-treatment interaction indicates that the MP system suffered a higher difference in the values of CMWD that the NT recorded the lowest value, and
5   MP and NT was no different from CP. The CMWD increased between 2004 and 2007 as the management system became more intensive (MP > CP > NT) (Fig. 3).

Working in similar soils, Aparicio and Costa (2007) reported that CMWD accounted for 36 % of the variability in the number of years under continuous agriculture, thus becoming the only physical parameter related to the years of agriculture. The CMWD
10 was significantly higher in MP than in NT in 2007 but was not significantly different in 2004. The CMWD was found to be higher in MP than in NT (Aparicio and Costa, 2007; Gómez et al., 2001), whereas no differences were found beween MP and NT in degraded soils (Ferreras et al., 2000) or between CP and NT in non-degraded soils (Elissondo et al., 2001). The latter authors pointed out that adopting CP in a soil with a
15 good initial physical condition does not lead to important changes in the soil structure.

In the Argentinean Humid Pampa, the increase in structural stability that took place due to the adoption of NT was agriculturally significant. The soils under NT are less susceptible to water erosion and soil crusting and as a consequence can store a higher amount of water for crops. After 11 years implementing the NT system in Mollisols with
20 silty clay loam in the north of the Humid Pampa, Micucci and Taboada (2006) observed a recovery of the CMWD, which reached values similar to those obtained in a pasture.

Overall, structural stability is usually associated with the increase in the SOC content (Tisdall and Oades, 1982), and this is also found on forest soils (Cerdà, 1996, 1998). Gramineous crops (wheat and corn) leave a large amount of stubble on the
25 soil surface after the harvest. The absence of tillage and the accumulation of plant residue in the soils under NT have contributed to reducing the loss of structural stability as a consequence of continuous cropping. Similar results have been reported with corn-wheat-soybean and wheat-soybean crop sequences (Gómez et al., 2001).

3.3 Near-saturated hydraulic conductivity ($K_{(h)}$)

We did not find significant differences in time and treatments in $K_{(0)}$ and $K_{(-20)}$ but we did find significant differences in time and treatments in $K_{(-70)}$ and $K_{(-150)}$ (Fig. 4a). No interactions were detected between time and treatments in all water h tested.

Differences of $K_{(h)}$ between treatments were not the same over the range of applied h; at near to saturation conditions ($h = -20$ mm), there were no significant differences. However, with more negative h, differences between treatments occurred. At $h = -70$ mm, the measured $K_{(h)}$ values were greater for CT and MP and significantly smaller for NT. At $h = -150$ mm, the measured $K_{(h)}$ values were greater for CT and significantly smaller for NT and MP. This finding agrees with Hu et al. (2009) and Schwen et al. (2011).

Other authors from Argentina have reported lower K under NT than under MP (Ferreras et al., 2000). In a review of Steinbach and Álvarez (2009), the authors conclude from several experiments carried out in Argentina that the infiltration rate was significantly higher under NT than in MP.

Differences of $K_{(h)}$ between years had a similar behavior than differences between treatments (Fig. 4b), and close to saturation ($h = 0$ and $h = -20$) differences among time were not significant. However, at $h = -70$ and $h = -150$, the $K_{(h)}$ reduced with time when water flow was dominated by mesopores. In a study carried out in the southeast of the Humid Pampa, a significant decrease in $K_{(-40)}$ was observed as the number of years of continuous agriculture increased ($R^2 = 0.70$), when the determinations were carried out under NT in a fallow period after a wheat crop (Aparicio and Costa, 2007).

The hydraulic conductivity values are heavily affected by temporal variability. After plowing, the soil infiltration for MP or CP is very high compared to NT, but over time the tilled soil is consolidated due to natural compaction and its hydraulic conductivity decreases. This temporal dynamic should be considered when modeling soil water flow (Strudley et al., 2008). To avoid that, in this study, the determinations were always

carried out on wheat fallow, as far apart from the last tillage as possible, in order to evaluate only the cumulative effect of the different treatments in the soil properties.

The decrease in NT K_{-70} and K_{-150} is consistent with the low value of structural porosity and the high value of δ_b (Table 2). The main impact of different techniques on

5　soil hydraulic properties is expected to occur in the structural pores, macro- and mesopores. The pore classification of Luxmoore (1981) was used, where macropores have a pressure head range $h > -30$ mm and mesopores -30 mm $< h > -0.003$ mm, corresponding to a pore radii of $r > 0.5$ mm for macropores and 0.5 mm $> r > 0.005$ mm for mesopores. The lower values of K_h for NT were found when water flow was dominated

10　by mesopores ($h > -30$).

Moldboard plow created macro- and mesoporosity in the top soil layer, while macroporosity showed a considerable reduction after harvest. As time elapses after the last plowing, through reconsolidation processes, the macropores decrease but the mesopores are kept intact. In NT, the cumulative effect of the passage of machinery exerts

15　a direct physical action upon the soil which affects both macropores and mesopores. However, macroporosity increases. This increase could be due to the fact that biological activity (the decaying roots from the predecessor crop, wheat, and the earthworms) plays a very important role in macropore origin (Shirmohammadi and Skaggs, 1984). This biological activity effect overlay the effect of structure reconsolidation. Although

20　macroporosity is a very small fraction of total porosity, it is responsible for the largest fraction of the water fluxes (Table 3 and Fig 5). The increase of δ_b of the soil under NT implies a decrease in the ρ_t (Table 2). This decrease in ρ_t should be reflected in a decrease in infiltration. However, some authors report an increase in infiltration associated with an increase in δ_b (Álvarez, Steinbach, 2009) (this would appear to be a

25　contradiction from a physical point of view). Other authors report a reduction in infiltration associated with a reduction of ρ_t (Álvarez and Steinbach, 2009). The data provided in this study show that when water flow is produced through macropores, there is no difference between soil under NT and tilled soils; significant differences between treatments are only found when water flow is produced via mespores (Fig. 3a). As the water

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flow via mesopores accounts for a small percentage of total water flow (Fig. 5) we can attribute to this the fact that in some studies no significant differences were found in infiltration between soil under NT and tilled soils even though ρ_t is less. We can, therefore, conclude that the reduction in ρ_t under NT is mainly a product of a reduction in

5   the percentage of mesopores in the soil.

3.4   Soil Organic Carbon (SOC)

Time had no statistically significant effect on the SOC content when expressed either as a concentration or as SOC stock. The SOC content, did not show a statistically significant effect among management systems while, when the results were expressed as a

10   stock; NT presented the higher stock of SOC than the other treatments. Álvarez (2005) suggest that, at the same sampling depth, in soils under NT, a larger amount of soil mass is sampled compared to other management systems, because in NT the δ_b is generally higher than in other tillage systems. Thus, the SOC stock could be overestimated. In the current study, MP and CP presented the lowest values of δ_b, and the

15   SOC stock was significantly lower from NT, which showed the highest values of δ_b.

The stock and the concentration of SOC followed the same trend as the concentration. When the content of SOC is expressed in stock, the experimental error is reduced, compared to expressing it as a concentration. Using SOC as stock made it possible to detect statistically significant differences between NT and the other treatments.

20   In the southeast of the Humid Pampa, Domínguez et al. (2009) have reported that the SOC content expressed both as concentration and as stock, was not affected by the tillage systems. Moreover, after 11 years of cropping under MP, Studdert and Echeverría (2000) found a decrease in the soil SOC content. The high SOC content that characterizes the soils of the southeast of the Humid Pampa may be preserved by

25   means of both a careful choice of the crops to be included in the rotation and pastures (Studdert et al., 1997). Also the use of conservation tillage systems reduces the SOC loss (Havlin et al., 1990; Eghball et al., 1994).

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In the Sub-humid Pampa, Díaz Zorita and Grove (1999) observed an accumulation of SOC in NT four years after the implementation of this tillage system. When the proportion of corn in the crop sequence was higher, the accumulation of SOC content tended to increase. In an analysis of mega-environments, involving test data distributed in several sites across the Argentinian Pampas, Alvarez (2005) observed an increase in the SOC content in NT and till. Fabrizzi et al. (2003) have reported increases in the SOC content in NT when the soil was degraded after eight years of continuous agriculture, but not in non-degraded soils with five years of continuous agriculture.

The contribution of crop residues and the soil management practices influences the balance of SOC in the soil. In the present work, the contributions of wheat ($2.18\,\mathrm{Mg\,ha^{-1}}$), corn ($1.26\,\mathrm{Mg\,ha^{-1}}$) and sunflower ($0.96\,\mathrm{Mg\,ha^{-1}}$) residues were similar among the management systems and did not explain the difference of stock found between NT and the other treatments (Alvarez, 2005). This result is also supported by the absence of significant differences in crop yield among the different management systems (Fig. 6). Our results showed that most of the SOC stock in NT, as compared to that in MP and CP, may cause this effect of reduction in the losses of SOC, whereas in MP and CP similar contributions were lost rapidly by effect of the tillage.

Whereas a significant difference was detected in the SOC stock after the 10-year experiment, we could assume that, as suggested by Steinbach and Alvarez (2005), this difference is due to an overestimation by considering higher soil mass in NT.

3.5 Crop yield

By analyzing the crop yield of the first ten years of this work, we found that the management system did not significantly affect crop yield (Fig. 6). The crop yield in the wheat-corn-sunflower rotation does not behave differently depending on the management system in which they are developed.

The absence of effect of the management system on crop yield has been previously reported for the Humid Pampa (Domínguez et al., 2009; Fabrizzi et al., 2005; Elissondo et al., 2001) as well as for other regions of Argentina (Díaz Zorita et al., 2002). How-

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ever, in the Sub-humid and Semi-arid Pampas, the crop yields of soybean, wheat and sorghum have been found to be higher with conservation tillage systems (NT and CP). Corn and sunflower have not evidenced the same result (Buschiazzo et al., 1999). Díaz Zorita et al. (2002) in the sub-humid area, found that the yields were favorable to NT only after a five-year sequence. The Semi-arid and Sub-humid Pampas predominant soils are Hapludol and Haplustol and the precipitations do not meet the requirements of water needed by the crops and thus normally limit the yield in MP. The higher moisture content in NT in the first 10 cm of soil in semi-arid areas makes a significant difference in yields (Quiroga et al., 2005). Changes in crop production were also found in other regions due to land management (Ahmad et al., 2013; Nabahungu and Visser, 2012).

4 Conclusions

The continuously agricultural activity for the last 10 years in the humid Pampa is changing the soil properties. Those changes were due to different land managements: (i) the δ_b values showed a tendency to decrease over time in the three management systems studied under wheat-corn-sunflower rotation. In addition, soil δ_b was significantly higher under NT, but no changes were detected between MP and CP. The δ_b values showed differences in relation to the sampling depth of the sample; (ii) the CMWD values showed a decrease in the structural stability of the soil due to the agricultural activities. The CMWD increased more between 2004 and 2007 as the management system became intensive (MP > CP > NT); (iii) we did not find significant differences in time and treatments in $K_{(0)}$ and $K_{(-20)}$ but we did find significant differences in time and treatments in $K_{(-70)}$ and $K_{(-150)}$. The decrease in NT K_{-70} and K_{-150} was consistent with the low value of structural porosity and the high value of δ_b. We can conclude that the reduction in ρ_t under NT is mainly a product of a reduction in the percentage of mesopores in the soil; (vi) no statistically significant effect on the SOC content when expressed either as a concentration or as SOC stock. The SOC content, expressed as a concentration (%), did not show a statistically significant effect among management

systems while, when the results were expressed as a stock, NT presented the higher stock of SOC than the other treatments; (v) the management system did not affect the yields of the wheat-corn-sunflower crop rotation.

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Table 1. Initial soil characteristics of the experiments: pH, phosphorous content, soil OC stock, cation exchange capacity (CEC), sand, silt and clay content.

Sites	Deph	pH	Phosphorous (ppm)	SOC stock ($g\,m^{-2}$)	CEC ($cmol_{(+)}\,kg^{-1}$)	Sand	Silt %	Clay
Napaleofú	0–20	5.9	11.5	86 255	26.5	24.4	48.7	27.0
Balcarce	0–20	5.8	12.2	82 272	22.2	36.8	44.5	18.7
Tandil	0–20	5.8	12.2	81 226	24.0	25.9	46.2	27.9
Miramar	0–20	5.8	12.9	84 125	25.2	29.0	50.7	20.3

Table 2. Maximum soil density (δ_{bmax}), total porosity (ρ) textural porosity (ρ_t) and structural porosity (ρ_s) by no till (NT), moldboard plow (MP) and chisel plow (CP).

Treatment	δ_{bmax} $Mg\,m^{-1}$	ρ	ρ_t $m^3\,m^{-3}$	ρ_s $m^3\,m^{-3}$
NT	1.50 a	0.52 b	0.42 a	0.11 b
MP	1.60 a	0.54 a	0.38 a	0.16 a
CP	1.56 a	0.54 a	0.40 a	0.15 a

Different letters meaning significantly different.

Table 3. Effective porosity calculated as a percentage of total porosity for each pore class and tillage treatment: moldboard plow (MP), chisel plow (CP), and no till (NT).

Treatment	$R^*>0.7$	$0.7 > R > 0.2$	$0.2 > R > 0.1$
	$m^3\,m^{-3}$		
NT	0.00013	0.0007	0.024
MP	0.00015	0.0010	0.045
CP	0.00009	0.0008	0.055

* is the pore radius (mm).
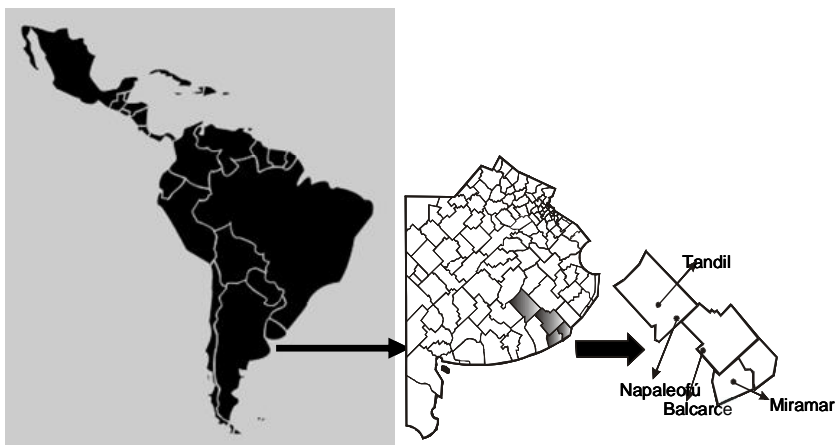
Figure 1. Experiment geographic location.
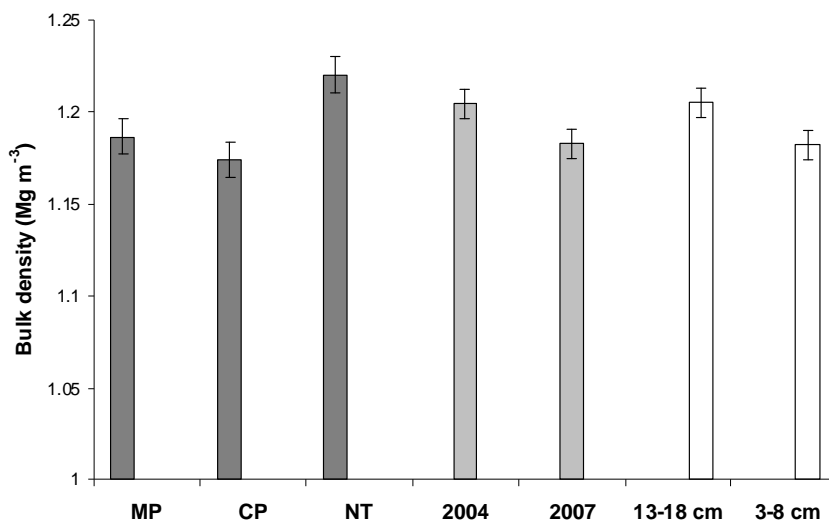
Figure 2. Effect of time, depth and tillage systems on soil bulk density (δ_b, Mg m^{-3}). Bars indicate significant differences (LSMEANS, $p < 0.05$).
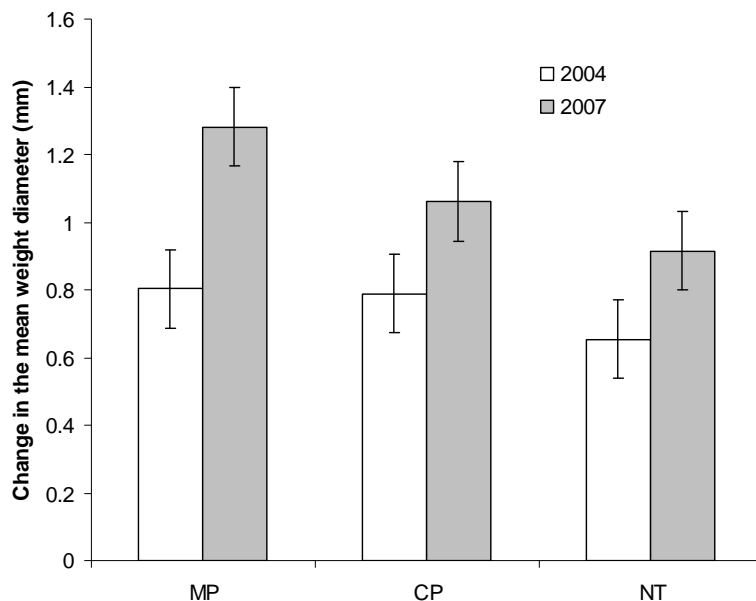
Figure 3. Effect of time on change in the mean weight diameter (CMWD, mm). Bars indicate significant differences (LSMEANS, $p < 0.05$).

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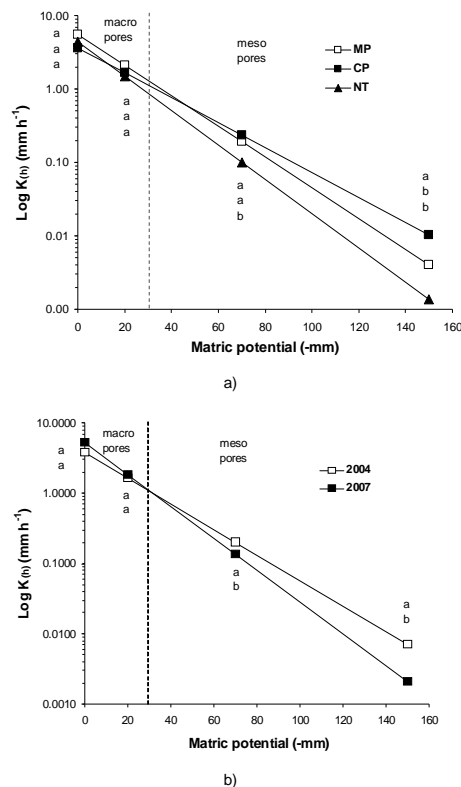
Figure 4. Near-saturated hydraulic conductivity $K_{(h)}$ as a function of the matric potential (h). **(a)** of the treatments: moldboard plow (MP), chisel plow (CP) and no till (NT) and **(b)** of the time (years 2004, 2007). Different letters indicate significant differences among treatments ($p < 0.05$).

Figure 5. Comparison of pores contribution to flow (% of the total flow) among tillage treatment: moldboard plow (MP), chisel plow (CP), and no till (NT).
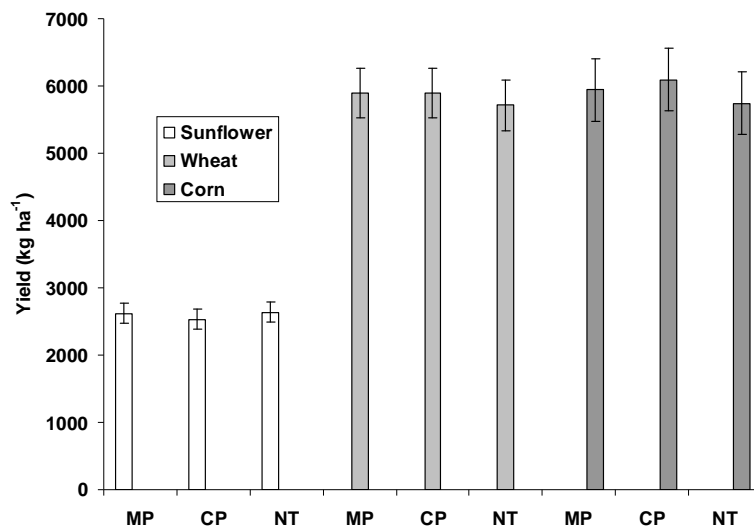
Figure 6. Ten years of average grain yield for Sunflower, Corn and Wheat under moldboard plow (MP), chisel plow (CP) and no till (NT). Bars indicate significant differences (LSMEANS, $p < 0.05$).