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Comparing adjacent cultivated and “virgin” soils in wind erosion affected environments can lead to errors in measuring soil degradation

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ABSTRACT

Soil degradation has been frequently evaluated by comparing cultivated soils with paired reference pedons. Evaluated were some physical and chemical properties of cultivated and reference soils of a semiarid environment in a nine year period in order to evaluate possible changes in both management situations. Analyzed were seven degraded soils of variable textures, which are cultivated since more than 50 years, and seven paired neighbor pedons placed in the less disturbed *Caldenal* savanna-like ecosystem of the central semiarid region of Argentina. Results indicated that soil properties of both, cultivated and reference soils changed in this period. The driving factor of these changes was wind erosion, which produced a decrease in the proportion of the fine sized particles (silt and clay) in cultivated soils due to deflation processes, and an increase in reference soils due to the sedimentation of material transported from neighbor eroded soils. Medium textured soils (loamy sand) suffered the largest textural changes in agreement with more aggressive management practices that promoted wind erosion. The coarsest- (sandy) and the finest textured soils (sandy loam) did not show textural changes because they were managed with more conservative practices and were more resistant against erosion than medium textured soils. Under the moist conditions of the studied period contents of total carbon (OC), total carbohydrates (CHt) and nitrogen (N) increased by 50% in most reference soils. Cultivated soils presented 64% less OC, CHt and N than reference soils, but these differences were produced mainly by increases in reference soils rather than by decreases in cultivated soils. The C/N and C/CHt ratios decreased mainly in medium textured cultivated soils. The wind erodible fraction (EF, the <0.84 mm sized aggregates) showed increases mainly in medium textured cultivated soils and decreases in all reference soils. This was associated with losses of the fine textural fractions and OC in cultivated soils and their increase in reference. Values for pH were higher only in some cultivated soils compared with reference pairs, but such differences were produced mainly by pH decreases in reference soils rather than by increases in the cultivated soils. The comparison of contrasting management systems considering that reference soils remain unchanged, may lead to overestimations of OC, CHt, N, EF and pH variations occurring in cultivated soils of 20 to 123%. Variations of C/N and C/CHt can be underestimated by 5 to 20%. We concluded that the simple comparison of cultivated and reference soils can lead to important errors in measuring soil degradation in semiarid environments. This may happen if changes eventually occurring in reference soils are not considered.

1. Introduction

Soil degradation is a main concern at a global scale due to its negative effects on soil productivity but also on the capacity of soils to provide ecosystem services, like carbon sequestration or biodiversity (Nziguheba et al., 2013).

The most reliable studies on soil degradation were carried out on long term plot experiments like those of Rothamsted (Sverdrup et al., 1995) or the Morrow Plots (Aref and Wander, 1977), which allowed a very precise evaluation and monitoring of different properties and the development of very accurate prediction models. Nevertheless, such long-term studies are time consuming, costly and therefore, not commonly available. Because of this, the evaluation of soil properties for assessing soil degradation has been more frequently done by comparing paired reference of cultivated pedons with commonly less disturbed forest or pastures soils. Many soil properties have been analyzed by means of this methodology, including the movement of water in the soil comparing virgin and adjacent cultivated soils in Wisconsin (Bouma et al., 1977), the carbon contents of soils of central USA (Mann, 1985), the K contents on soils of USA (Sharpley and Smith,

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1988), the humus characteristics of soils of central Brazil (Nascimento et al., 1992), the contents of C, N and P in the central Pampas of Argentina (Buschiazzo et al., 2001), the organic matter contents of Canadian soils (Schnitzer et al., 2006), the organic fractions of soils of the semiarid Argentina (Duval et al., 2013), and C variations in some soils of Africa (Traoré et al., 2015). In these studies different time-cumulative effects and soil types were considered, but in all cases the differences between soils were attributed to changes occurring only in the most degraded situation, assuming that reference conditions remained unchanged. Nevertheless, it is known that reference soils can also change, particularly in semiarid environments. This is because wind erosion can occur in agricultural soils but dust accumulation can also occur in plant-covered soils, where trees, shrubs or grasses can act as a sink for wind transported materials. Some evidences of this process have been frequently reported in the literature. Hevia et al. (2007) described soils of the natural *Caldenal* forest ecosystem of the semiarid Argentina, which have been frequently used as references for degradation studies, contain a volcanic ash layer accumulated during the Quizapú volcano eruption that occurred in 1932 (INTA, 1980). This layer lies at approximately 30 cm depth and is covered by sediments accumulated by wind during the last 90 years. Colazo and Buschiazzo (2010) also detected changes in *Caldenal* soils, mainly the accumulation of silty materials. Zhao et al. (2006) demonstrated that sands coming from neighbor eroded soils were sedimented in areas with plant-cover in China. Reiche et al. (2014) found similar results in grassland soils of Mongolia. Buschiazzo et al. (2007) demonstrated that no-tilled soils of the semiarid Argentina, which were covered with plant residues, accumulated 500 kg/ha of wind transported sediments coming from neighboring eroded areas during a time-period of few months. Eger et al. (2012) found that pedogenesis was modified by dust deposition even in humid loess environments of USA.

Changes occurring in forest or grassland soils of semiarid regions can be also explained on the basis of the classical theory of the balance-sheet between pedogenesis (processes occurring in the soil mainly in vertical direction, for example clay leaching, decalcification or salinization) and morphogenesis (processes occurring in the soil mainly in horizontal direction, mainly wind and water erosions) described by Tricart (1965) and Phillips (1995). Such theory describes that morphogenesis predominates in arid environments, with pedogenesis being particularly slow. The opposite occurs in humid environments. According to these findings, and considering that in semiarid environments, changes in reference soils should be produced mainly by dust sedimentation and in cultivated soils by deflation, we expect larger changes in the textural composition of soils (reference soils will become more silty and cultivated soils more sandy), and in soil aggregation as a product of these textural changes (increases in reference soils and decreases in cultivated soils). Considering that pedogenesis should be limited in the studied soils due to the prevailing climatic dry conditions, we expect small increases in the contents of organic matter particularly of its labile organic matter forms, produced by the decomposition of plant debris (Martín Jiménez, 1996; Puget et al., 1999; Jolivet et al., 2006.). In cultivated soils we expect opposite tendencies as a product of cultivation and wind erosion.

The objective of this study was therefore, to analyze the impact of wind erosion, soil management conditions, and both, morphogenesis and pedogenesis, on some physical and chemical properties of reference and cultivated soils of a semiarid environment of the Argentinean Pampas, and to detect possible errors in measuring soil degradation rates of cultivated areas when considering reference soils as unchanged.

2. Materials and methods

This study was carried out in the semiarid Pampas of Argentina, a region with a mean annual rainfall of 640 mm and a mean annual temperature of 15.8 °C (INTA, 1980). The parent material of the soils is holocenic and pleistocenic aeolian material, composed by a mixture of loess and volcanic glasses (Zárate and Tripaldi, 2012).

Soil samples were collected for this study from seven sites placed in flat relief positions of the semiarid Pampas of Argentina in Spring 1996 and Spring 2005, following the same sampling methodologies in both dates. Sampling sites were selected geo-referenced, which guaranteed the sampling of the same soil in both sampling dates. The placement of all samples in flat topographic positions excluded the occurrence of water erosion.

Three soil sub-samples were randomly taken from the upper 20 soil cm from three 10 m^2 plots in each site. The three sub-samples of each plot were selected following the same sampling routine in both sampling dates and mixed to obtain a unique representative sample from each plot, which was considered a one replicate.

In each site, two pedons of contrasting management situations 100 m apart were sampled. The two management conditions were an uncultivated condition- and a cultivated condition. The uncultivated condition was considered as reference (RS) and was sampled in the savanna-like *Caldenal* ecosystem. This ecosystem is composed by a tree strata dominated by *Caldén* (*Prosopis caldenia*, Burkart) and a grass strata dominated by *Stipa tennuis Phil.*, *Stipa speciosa*, and *Panicum* sp. Soils of this ecosystem have never been plowed nor used for crop production, but are extensively grazed by cattle for more than 50 years. Stocking rates currently range from 5 to 7 ha cow^{-1} $year^{-1}$ (Distel and Bóo, 1996). Soil samples were taken between adjacent *Calden* trees.

The other sampled pedon has been under continuous agriculture (CS) since approximately 70 years, when the *Caldenal* was cleared and soils put in crop production (Dussart et al., 2011). This soil has been used for annual crop and pasture production. Annual crops were grown under conventional tillage systems, consisting in the preparation of the soil for seeding or planting of crops with diskers or harrow-disk that plow the soil to 20 cm depth. The most common annual crops grown in these soils have been wheat (*Triticum aestivum*), oats (*Avena* sp.), corn (*Zea mays*), sorghum (*Sorghum* sp.) and sunflower (*Elianthus annus*). Pastures were composed mainly by alfalfa (*Medicago sativa*), which lasted between four and five years, and were used for direct cattle grazing. None of these crops were fertilized nor irrigated.

Placement of the studied sites, the main characteristics of their soils and their management conditions are detailed in Table 1. The studied soils were ordered according to their increasing silt + clay contents all along this study.

Detailed records of management conditions were available for the period 1996–2005, but not for the period before 1996. During the nine year period between 1996 and 2005, the management intensity (number of crops and tillage practices) increased from the sandy- to the fine textured soils. Sandier soils of sites GA and SL were mostly not tilled as they were under permanent alfalfa pastures (*M. sativa*), with crops used only for cattle grazing like oats or vicia (*Vicia sativa*) or under fallow. These management conditions left the soil surface with a high plant or residue coverage during most of the analyzed period, minimizing wind erosion. Medium textured soils of sites W, C and LV presented more intense management conditions than sandy soils. They also had a rotation composed of a four year period with alfalfa pastures followed by four or five years of winter (mainly wheat) or summer crop (mainly sunflower or corn) grown under conventional tillage systems. These systems included clean fallows maintained with soil tilling, leaving the soil bare and smooth for a few months in the Spring, a period where wind erosion is highly probable (Mendez and Buschiazzo, 2015). It must be considered that wind erosion during the growth of winter crops, even when planted with conventional tillage systems, is not high (Mendez and Buschiazzo, 2010). The finest textured soils of T and LP presented the more intensive management conditions as they had shorter periods with permanent pastures (two to three years) and five to six years of crop production, mainly summer crops (corn or sunflower) planted with conventional management practices, with the soil mostly bare and smooth during the Spring.

The following determinations were carried out in each soil sample: grain size distribution by the combined wet sieving and pipette method,

Table 1
Placement of sampled sites, soil type, and management conditions of the period 1996–2005.

Site	Placement (lat., long.)	Soil	Management	Crop sequence	Cultivation intensity[a]
Gral. Acha (GA)	37° 22′ S–64° 55′ W	Typic Ustipsamment	Reference	None	
			Cultivated	P (4 years)–RG–V–F (2 years)	L
San Lorenzo (SL)	37° 10′ S–64° 00 ′W	Typic Ustipsamment	Reference	None	
			Cultivated	P (4 years)–O–V–F (2 years)	L
Winifreda (W)	36° 13′ S–64° 15′ W	Entic Haplustoll	Reference	None	
			Cultivated	S–O–V–RG–F (2 years)–O	M
Castex (C)	35° 55′ S–64° 18′ W	Entic Haplustoll	Reference	None	
			Cultivated	P (4 years)–C–O–F (2 years)	M
La Victoria (LV)	36° 34′ S–64° 16′ W	Entic Haplustoll	Reference	None	
			Cultivated	P (4 years)–So–F (2 years)–O	M
Trenel (T)	35° 41′ S–64° 07′ W	Entic Haplustoll	Reference	None	
			Cultivated	O–C–P (2 years)–O–C–W–C	H
La Primavera (LP)	36° 30′ S–64° 16′ W	Entic Haplustoll	Reference	None	
			Cultivated	O–C–O–P (2 years)–C–W–C	H

P = alfalfa (*Medicago sativa*) pasture, RG = rye grass (*Lolium multiflorum*), F = fallow, O = oats (*Avena sativa*), S = sunflower (*Helianthus annus*), V = vicia (*Vicia sativa*), So = sorghum (*Sorghum* sp.), W = wheat (*Triticum aestivum*), C = corn (*Zea mays*).

[a] Intensity: L = low, M = medium, H = high.

using sodium hexametaphosphate as dispersant (Schlichting et al., 1995), pH by potentiometry in a 1:2.5 soil:water extract, organic carbon (OC) by wet digestion (Walkley and Black, 1934), total nitrogen (N) by the semimicro Kjeldahl procedure (Bremner and Mulvaney, 1982), and total soil carbohydrates (CHt) determined colorimetrically after a hot-acid extraction. Briefly, this method consisted of the following steps: 1 g of soil was hydrolyzed with 5 mL of H_2SO_4 12 mol/L for 12 h at room temperature. Once cooled, the sample was bought to 100 mL with distilled water and then heated to 100 °C for 5 h. After that, it was centrifuged and filtered. Contents of hydrolyzed saccharides were determined by the anthrone method (Doutre et al., 1978). The wind erodible fraction of the soils (EF) was determined with a rotary sieve (Chepil, 1962) in all samples.

All measurements were performed by duplicate and data were expressed on oven-dry soil basis. In order to express the results on volume basis (kg ha^{-1}), results were corrected by the bulk density data of each soil. All studied parameters were compared between management systems and soil types by means of ANOVA for each sample date, with soil and management as fixed factors. Comparisons between management systems and sampling years within each site were performed with mean comparison tests ($p < 0.05$). Results were compared in two ways: a) a “direct” comparison, in which each parameter was compared between reference and cultivated soils in each sampling date (1996 and 2005) separately, and b) a “corrected” comparison in which reference soils were compared with cultivated soils, after subtracting the variations prior to 1996 in both management conditions. The first analysis allowed the measurement of the accumulated effect of all factors together (pedogenesis, wind erosion — morphogenesis — and management) between reference and cultivated soils for each sampling date. In this case, the influence of each individual variable remained uncertain, as management history prior to 1996 was not recorded. Nevertheless, this analysis allowed the measurement of changes with time in both reference and cultivated soils. The second analysis allowed a precise evaluation of management, morphogenesis and pedogenesis effects on soil properties in the period 1996–2005.

The variances of all soil parameters studied were not significantly different in both years of analysis, which allowed the comparison between sampling dates by means of triple ANOVA, using two fixed factors (soil and management) and one random factor (sampling date) in all cases.

3. Results

3.1. Direct comparison of reference and cultivated soils

Fig. 1 shows that, in 1996, differences in the textural fractions between management systems were variable: sand contents were lower in RS than in CS in two sites (SL and T), higher in three (W, C and LV) and similar in two (GA and LP). Silt contents were higher in RS than in CS only in two sites (SL and T) and similar in the others. Clay contents were higher in two sites (GA and T), lower in three cases (W, C and LV) and similar in the rest. Considering the averaged contents of all soils, sand, silt and clay contents were not different between RS and CS in 1996 ($p > 0.05$). Conversely, in 2005, all RS soils presented lower sand contents than CS, and mostly lower silt and clay contents. In average of all soils, RS had lower sand contents (36.7%) than CS (47.5%), and higher silt (43.2% and 36.2%, respectively) and clay contents (20% and 16.3%, respectively) ($p < 0.01$).

Sand contents decreased in RS in four sites between 1996 and 2005 (GA, SL, W and T), increased in one (LV) and remained unchanged in one (LP). Silt contents of RS remained unchanged between sampling dates in four sites (GA, SL, LV and LP) and increased in the rest (W, C and T), and clay contents increased in four sites (W, C, T and LP), decreased in one (LV), and remained unchanged in two (GA, SL).

In the period 1996–2005, sand and silt contents remained mostly unchanged in CS, increasing sand and decreasing silt only in LV and LP. Clay contents decreased in three sites (SL, LV and LP), increased in one (C) and remained unchanged in the rest.

The ANOVA analysis showed that the variability of sand (51.7%) and clay (55.5%) was affected by the interaction year $*$ soil and the variability of silt by the interactions year $*$ soil $*$ management (33.4%) and year $*$ soil (31.4%). These results indicate that the total variability of sand, silt and clay was more affected by both, the soil and year factors.

Fig. 1 shows that in 1996, the erodible fraction (EF) was lower in RS than in CS in three sites (GA, SL, T), similar in other three (W, C, and LP) and higher only in one (LV). In 2005, EF was higher in all CS sites than in RS. EF tended to decrease in both management systems and sampling dates from coarse to fine textured soils, showing a maximum of 72% and a minimum of 18%.

Between 1996 and 2005, EF decreased in most RS sites, excepting LV where it increased, and remained unchanged in most sites in CS, excepting W, LV and LP, where it increased. It must be considered that differences between RS and CS increased between 1996 and 2005 and that EF largely increased (more than 100%) in LV between 1996 and 2005. The variability of EF was higher in CS than for RS in both sampling dates and in 2005 than in 1996 for both management conditions.

Fig. 2 shows that RS soils had more OC contents than CS in all sites, in both sampling dates. Nevertheless, differences between both management systems were higher in 2005 than in 1996, mostly as a product of increases in RS (on average, all sites had a 122% increase). On average for all sampled sites, RS had 76% more OC than CS in 1996, and 272% more in 2005.

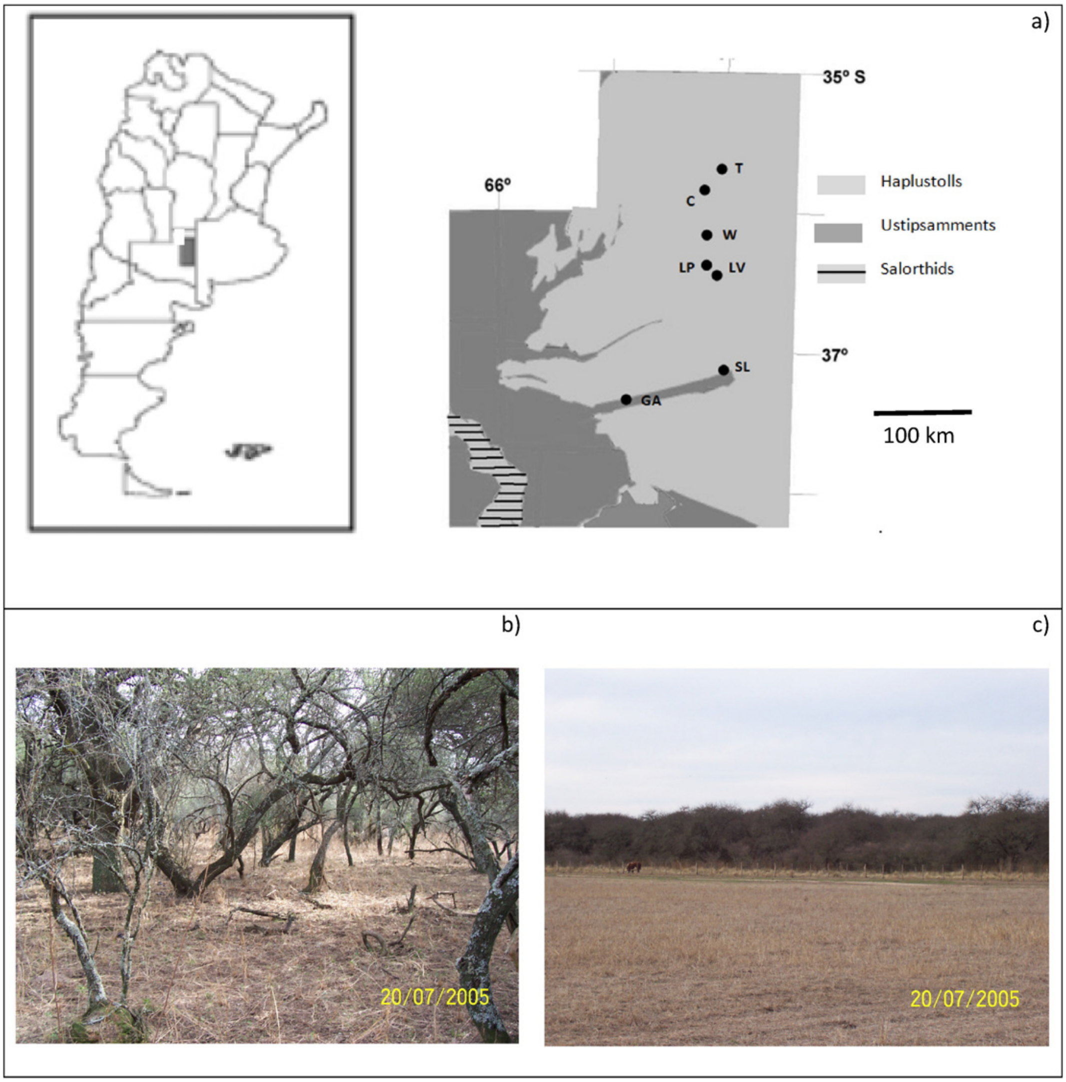

Fig. 1. a) Placement of the studied sites within Argentina and the semiarid Pampas, and views of a) the Caldenal ecosystem and c) the neighbor cultivated soil, in the site Trenel (T).

OC, N and CHt showed similar tendencies between sites and sampling years. As a matter of fact, OC was highly correlated with the other two variables in a linear way ($p < 0.001$) when all soil and management data were considered together.

In RS, OC and CHt increased more than 120% from 1996 to 2005, while N increased 86%. In CS tendencies of OC and N were unclear: OC decreased in four sites (W, C, LV and LP), remained unchanged in two (T and LP), and increased in other two (GA and SL); N decreased in three sites (W, LV and LP), increased in other four (GA, SL C and T) and remained unchanged in the RS site. OC showed increases in the sandiest soils, decreases in the medium textured, and remained unchanged in the finest soils, while N showed increases in five soils and decreases only in two medium textured soils. CHt increased in all CS sites between 1996 and 2005.

OC, N and CHt variability was much higher in RS than for CS in both sampling years (CV = 5.2% for OC, 4.0% for N and 11% in 1996, and 31.0% for OC, 36% for N and 11% in 2005), than in CS (CV = 1.2% for OC and 0.7% for N and 3% in 1996 and 11.2%, 16.0% and 31% in 2005, respectively).

The C/N ratio (Fig. 3) was not different between RS and CS in any the studied cases in 1996 and in most cases in 2005. An exception to this general trend was the medium textured soils of C, LV and T in 2005, where C/N ratios of RS were higher than of CS.

C/N values of sandy CS and RS soils, particularly in 2005, tended to be higher (14.4 as average of soils of GA and SL) than in fine textured soils (10.3 as average of the medium and fine textured soils). The C/N variability tended to be higher in RS than in CS, mainly in 2005. Five sites (CG, SL, W, C and T) showed such tendencies, while other two RS did not show differences between management systems.

C/N increased only in both management systems of the sandiest soils (GA and SL) between 1996 and 2005. In RS sites with soils of medium and finest textures, C/N remained unchanged, while it decreased in three CS sites with medium textured soils (C, LV and T). Summarizing, increases between 1996 and 2005 in CS were detected mostly in sandy soils, decreases in medium textured soils and there were no changes in the finest.

The C/CHt ratio did not show definite tendencies between CS and RS in 1996, as it was similar between management systems in three sites (GA, W, and LP) and higher in CS than in RS in the other three. In 2005, the C/CHt ratio was lower in most CS than in RS cases, remaining unchanged only in one (SL). C/CHt tended to decrease from sandy to fine textured soils, with 17.3 the average of both sampling dates and management conditions of the sandiest soils GA and SL, and 13.3 the same average of the finest T and LP soils.

Between 1996 and 2005 C/CHt remained mostly unchanged in RS, only increasing in GA and decreasing in W and LP. In CS, large decreases

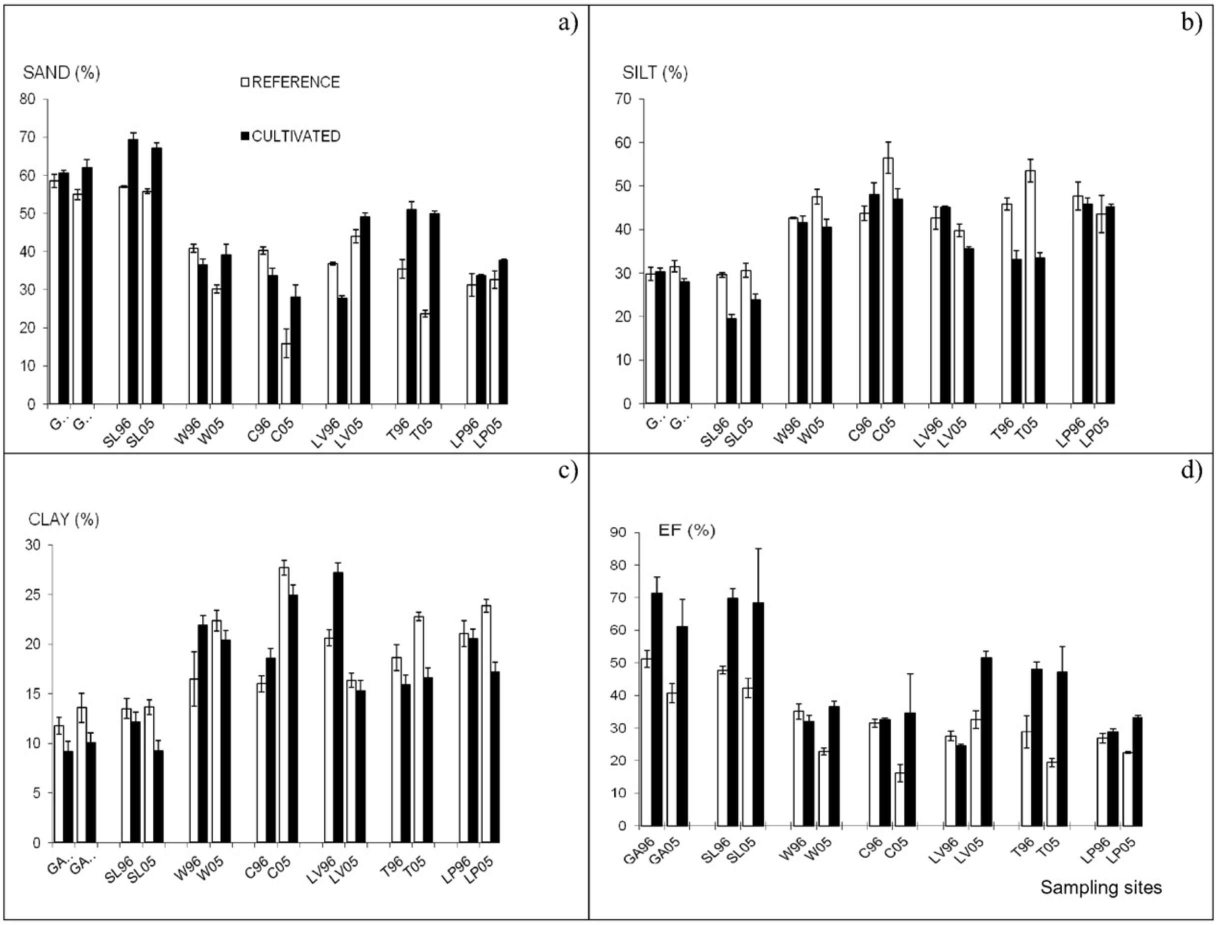

Fig. 2. Contents of a) sand, b) silt, c) clay and d) the erodible fraction (EF) in the first 20 cm of reference and cultivated soils of seven sites, sampled in 1996 (xx96) and 2005 (xx05). Error bars indicate significant differences at $p < 0.05$.

were found in medium and fine textured soils of sites W, C, LV T and LP, while no changes were detected in sandy soils of GA and SL.

C/CHt variability did not show definite tendencies, being alternatively higher or lower in different management systems and sampling dates.

Fig. 3 shows that pH values were mostly lower in RS (5.9 in average of all sites) than in CS (7.0) for both sampling dates ($p < 0.05$), with 1996, on average, 5.9 in RS and 7.0 in CS. In 2005, averaged pH values were 4.9 in RS and 6.8 in CS. In most cases, differences between RS and CS were higher in 2005 than in 1996.

pH variability was higher in RS than in CS in both sampling dates. In 1996 the CV of RS varied between 2.2 and 23%, and between 7.3% and 10.3% in 2005. In CS the CV varied between 0.7 and 3% and between 0.4 and 3% in 2005.

Between 1996 and 2005 pH values decreased in most RS sites, while it remained unchanged in CS in two sites (SL and LV), decreased in four (GA, C, T and LP) and increased in one (W).

3.2. "Corrected" comparison of reference and cultivated soils

Fig. 4a shows the variation of each textural fraction in cultivated soils in the period 1996–2005. Such data were obtained by considering the contents of reference soils as a comparison basis, and after subtracting the variations between both management systems that occurred prior to 1996. Results show that most CS soils had sand increases, mainly in the medium textured soils (W, C and LV), reaching a maximum of 17%. In agreement with these variations, clay and silt contents mostly decreased. Only in two soils (SL and LP), CS conditions showed slight silt increases and in one case (SL) small sand decreases.

Fig. 4b shows that EF was higher in CS than in RS in all sites mainly in those with medium textured soils (W, C and LV). In these cases EF contents were between 17 and 23% higher in CS than in RS. EF increases in the sandiest soil (GA) were the lowest (less than 1%), while increases averaged 8% in the finest textured soils T and LP.

Fig. 5 shows that OC, CHt and N decreased in the period 1996–2005 in CS in relation to RS in all studied soils. Such decreases tended to be higher in fine textured soils than in sandy soils. OC decreases reached more than 56,000 kg/ha in one of the finest soils (T), and averaged almost 30,000 kg/ha in the RS soils. Only one sandy soil (SL) showed slight OC losses of approximately 10,000 kg/ha.

Losses of CHt and N from CS had similar magnitudes, varying from an average of 600 kg/ha in sandy soils (GA and SL) to 3250 kg/ha in the finest textured soils (T and LP). Losses of CHt and N were similar in sandy soils but losses of N were higher than those of CHt in fine textured soils.

Fig. 6 shows that C/CHt- and C/N ratios showed similar trends, being lower in most CS cases than in RS after the nine year period. Differences between management systems were higher in medium textured soils than in sandy or fine textured ones. C/CHt variations were higher than those of C/N in all studied soils, varying those of C/CHt between 2.1 and 12 and those of C/N between 3.7 and 8.0.

pH values (Fig. 7) showed no definite trends in CS in relation to RS after nine years. It remained unchanged in four soils of variable textures (GA, C, LV and LP), and increased in other three (SL, W and T). The

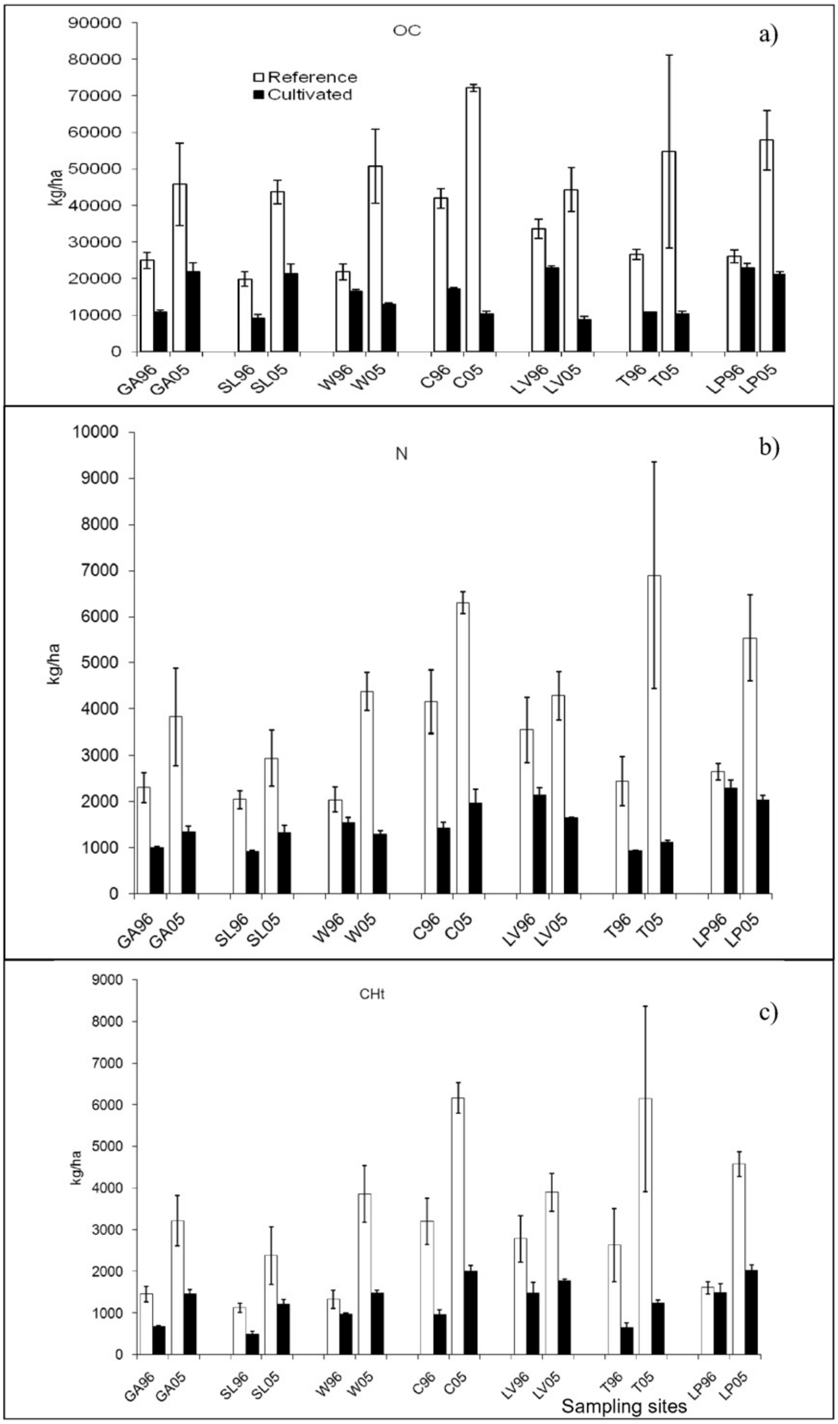

Fig. 3. Contents of a) organic carbon (OC), b) total nitrogen (N) and c) total carbohydrates (CHt), in the first 20 cm of reference and cultivated soils of seven sites, sampled in 1996 (xx96) and 2005 (xx05). Confidence intervals calculated for $p < 0.05$.

largest variation occurred in site W, where pH increased 2.5 points (Fig. 8).

4. Discussion

Differences in sand and clay contents between management systems did not show definite tendencies in 1996, as they increased in some CS cases and decreased in others in relation to RS. On the other hand, silt contents were mostly similar between both management conditions in this sampling date. None of the expected changes in soil texture produced by wind erosion were detected, like a decrease of the finest fractions (clay and silt) by deflation from CS eroded soils, as it is known that these fractions are the most susceptible to be transported by wind in the studied soils (Aimar, 2002; Buschiazzo et al., 2007, Colazo and Buschiazzo, 2015). Also, a residual accumulation of sand as a product of the lower contents of the finest textural fractions by deflation was also not evident. The lack of changes does not necessarily indicate that management conditions have not affected soil texture in the period between forest clearing (occurred by middle of 1900s after Dussart et al., 2011) and 1996. Opposite tendencies were expected in RS, where the forest ecosystem should have trapped the finest particles transported by wind that were produced by wind erosion in neighbor

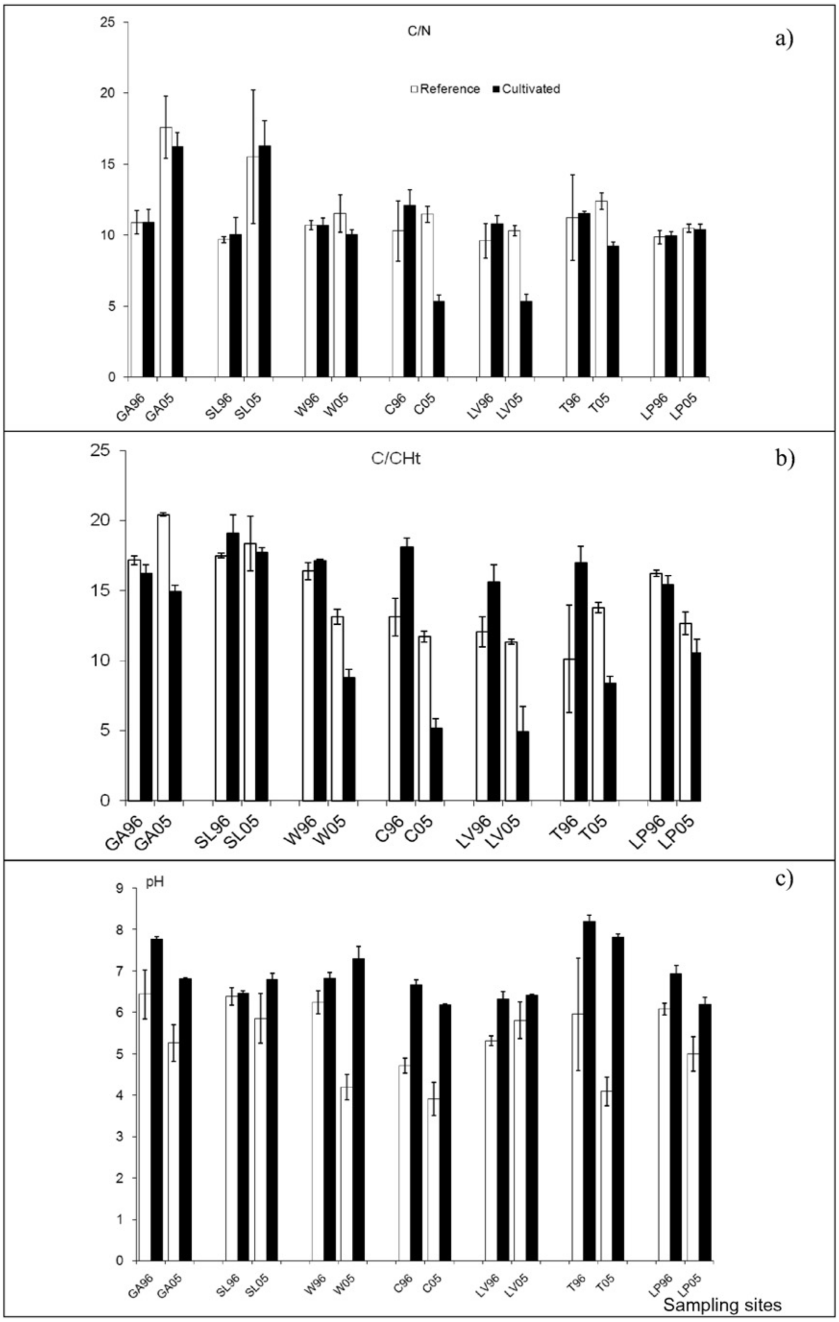

Fig. 4. Values of a) C/N, b) CHt/OC and c) pH in the first 20 cm of reference and cultivated soils of seven sites, sampled in 1996 (xx96) and 2005 (xx05). Error bars indicate significant differences at $p < 0.05$.

soils. In this case a dilution of sand contents was expected. The lack of definite changes in soil texture may be the product of variable management and climatic conditions given prior to 1996, when frequent and successive deflation and sedimentation processes may have occur. These conditions may have produced changes in the soil texture in different ways, mainly in CS: during dry periods, when the soil coverage with plant residues was low, wind erosion may have produced a decrease in the proportion of the finest particles, while during moister conditions and with plant coverage, an increase of these particles may have occurred. As a matter of fact no-tilled soils of the semiarid Argentina highly covered with plant residues, accumulated 500 kg/ha of wind transported sediments coming from neighboring eroded areas during a time-period of few months (Buschiazzo et al., 2007). It is known that since middle 1900s several alternating dry and wet periods existed, during which wind erosion events alternatively occurred in this region (Casagrande and Vergara, 1996). The abovementioned hypothesis cannot be demonstrated here, as no precise records of the management practices carried out in that period, like crops rotations or tillage practices, are given. Such conditions can determine the soil coverage and the magnitude of wind erosion of the soil (Buschiazzo et al., 2007).

Between 1996 and 2005 sand contents mostly increased in CS and decreased in RS, while the finest particles, clay and silt, showed mostly opposite tendencies. Such trends reflect the expected effect of wind erosion, which removed the finest particles by deflation in CS, increasing sands by residual accumulation, and increased the finest particles in RS due to the sedimentation of the blown out material coming from neighbor wind eroded soils. The largest changes in the textural fractions occurred in medium textured CS soils which showed the largest sand

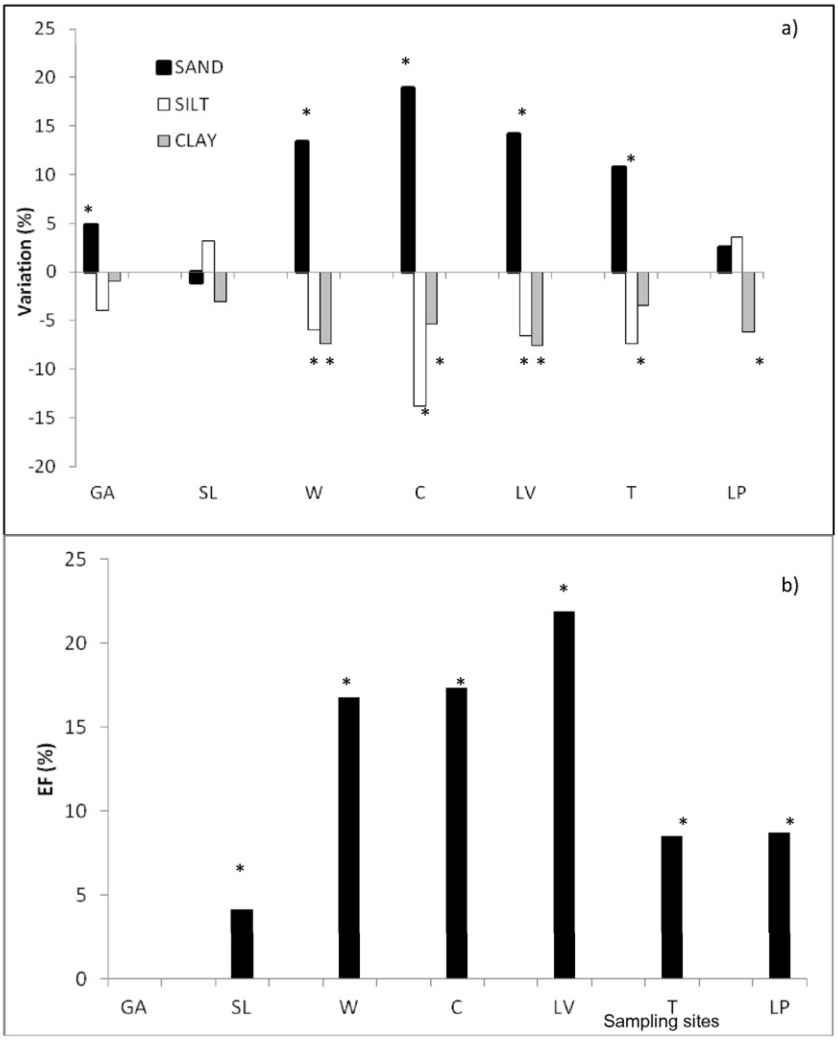

Fig. 5. Variations of a) sand, silt and clay contents, and b) the erodible fraction (EF), between reference- and cultivated pedons in 7 different textured soils. Positive values indicate increases and negative decreases in cultivated — in relation to reference soils in the period 1996–2005. Asterisks indicate significant differences between management systems ($p < 0.05$).

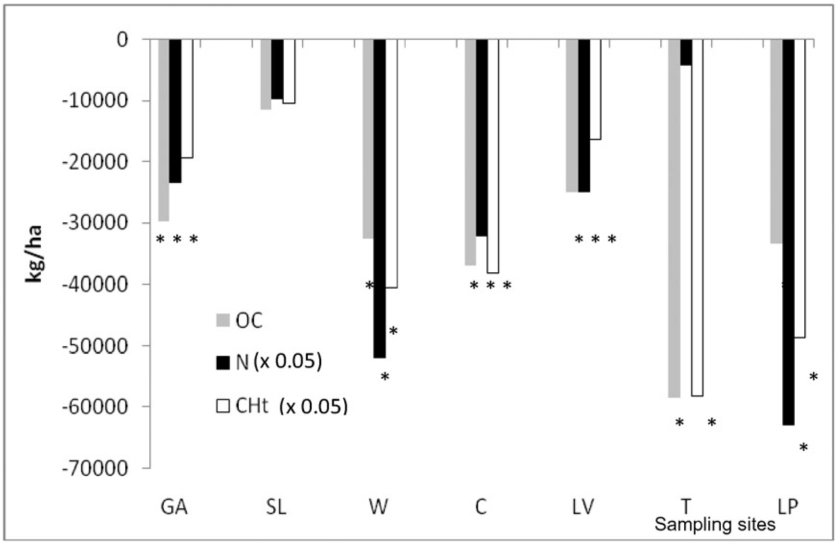

Fig. 6. Variations of organic carbon (OC), total carbohydrates (CHt), and total nitrogen (N), between reference- and cultivated pedons in 7 different textured soils. Positive values indicate increases and negative decreases in cultivated — in relation to reference soils in the period 1996–2005. Asterisks indicate significant differences between management systems ($p < 0.05$).

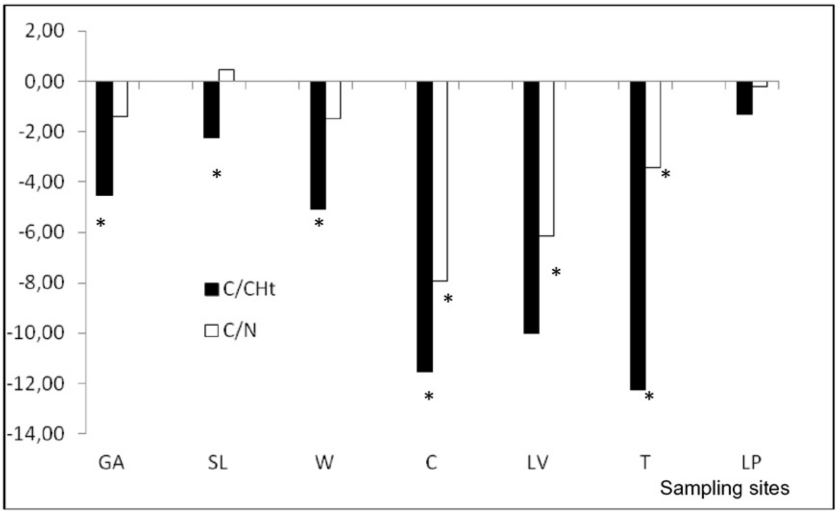

Fig. 7. Variations of the ratios C/CHt and C/N, between reference- and cultivated pedons in 7 different textured soils. Positive values indicate increases and negative decreases in cultivated — in relation to reference soils in the period 1996–2005. Asterisks indicate significant differences between management systems ($p < 0.05$).

increases. This agrees with results of Colazo and Buschiazzo (2015) who found largest textural changes in sandy loam soils, and lowest in sandy and loamy soils of the semiarid Pampas of Argentina, when comparing reference forest soils with adjacent cultivated soils. These authors attributed such changes to the largest effect of wind erosion on cultivated soils, but present results indicate that such conclusion may be partially correct, as larger textural changes occurred in RS rather than in CS. Therefore, in the nine year period, the accumulation of eolian material coming from external sources was more determining in changing the textural composition of RS than wind erosion in CS.

Changes in soil texture occurred in most CS and RS soils between 1996 and 2005, but with higher magnitudes in the medium textured ones (W, C and LV). This indicates not only a higher impact of wind erosion but also a prevailing local movement of wind transported materials within these sites, as the material seems to be lost from CS soils and mostly gained by their neighbor RS soils.

EF contents were higher in sandy- than in fine textured soils, which is in agreement with the lower aggregation and the formation of smaller aggregates in sandier soils. López et al. (2007) demonstrated that the amount of fine and easily erodible aggregates in soils of Argentina and Spain increased with sand contents.

EF contents were higher in RS than in CS in all sites in both sampling dates. Nevertheless, after nine years of accumulated effects, EF decreased in RS in most cases and remained mostly similar in CS. This indicates that differences between RS and CS were mostly produced by a decrease of EF in RS rather than by an increase in CS. These results indicate that soil aggregation under natural conditions within the *Caldenal* ecosystem has been relatively more important than aggregate destruction produced by tillage in cultivated soils in a relatively short period of time (nine years). It can be also deduced that if EF is compared between RS and CS considering EF of RS as constant, overestimations of the negative effects of cultivation on EF can be deduced.

EF decreases in RS agree with increases in the contents of organic compounds observed in the same soils, which promoted soil aggregation. The binding effect of organic compounds is a largely known process (Chepil, 1950; Toogood, 1978; Kay and Munkholm, 2004).

OC, N and CHt contents increased between 1996 and 2005 in all RS soils but they did not show definite tendencies in CS soils. OC and N showed similar tendencies, as they increased more than 100% in all RS soils and in two sandy CS soils in the nine year period. These increases are probably a product of pedogenesis, mainly humification in the A horizons. The pedogenetic evolution of RS may be linked to the increase in

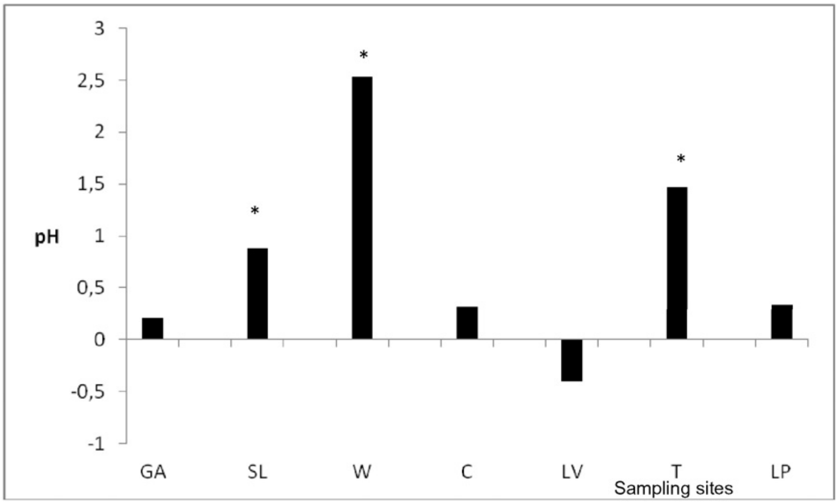

Fig. 8. Variations of pH values between reference- and cultivated pedons in 7 different textured soils. Positive values indicate increases and negative decreases in cultivated — in relation to reference soils in the period 1996–2005. Asterisks indicate significant differences between management systems ($p < 0.05$).

the amount of fine textural fractions which are known to improve the water holding capacity and, consequently, the accumulation of organic matter in the studied region (Buschiazzo et al., 1991; Buschiazzo, 2006) and of other parts of the world (Munn et al., 1978; Burke et al., 1989). The period of time within which this process occurred was relatively short (nine years), indicating that humification in this semiarid region has been very fast.

Between 1996 and 2005, OC and N showed increases in the sandiest CS soils, losses in the medium textured, and no changes in the finest textured soils. Increases in the sandiest CS soils are probably related to the conservative management systems carried out during the analyzed nine year period, as these soils were covered with permanent pastures or crops used for extensive cattle grazing during that time. Such management conditions are known to increase the amount of organic residues incorporated yearly in the soil and to improve the accumulation of organic matter (Buschiazzo et al., 1991). The medium textured soils were submitted to a more intensive management practices than sandy soils. In this case alternating permanent pastures and annual crops like wheat, oats, corn and sunflower were grown under conventional tillage practices that included the soil preparation for crop seeding or planting with diskers. Under these conditions, the breakdown of aggregates and the destruction of the soil organic matter probably occurred, due not only to tillage operations but also to wind erosion, as the soil remained bare and smooth during some periods of time (Mendez and Buschiazzo, 2010). The finest CS soils did not show changes in their OC and N contents between 1996 and 2005, though they were the most intensively used. This should be attributed to their higher resistance against degradation processes produced by tillage operations or wind erosion. Colazo and Buschiazzo (2015) also found that the finest textured soils of this region were the most resistant to be degraded by wind erosion.

OC contents of all RS soils increased by 32,000 kg/ha on average of the nine year period. This is equivalent to a rise of 1.3% of the original OC contents. OC increases of sandy CS soils submitted to conservative management practices reached more than 12,200 kg/ha, equivalent to a rise of approximately 0.5% of the original OC contents.

OC increases in RS could have originated either by humification, deposition of wind transported material enriched in OC, or both processes. It remains uncertain which of each process contributed to these increases but, assuming an OC concentration of 3% in the wind transported material (Aimar, 2002) and a medium deposition rate of 3 Mg ha^{-1} $year^{-1}$ (Buschiazzo et al., 2007), the OC coming from eolian sources during the nine year period was approximately 1 Mg ha^{-1}. Similar results are obtained if this calculation is made considering the theoretical OC contribution of the 30 cm-thick eolian sediment that covers today the volcanic ash layer accumulated in many sites of the *Caldenal* ecosystem, which was accumulated by the eruption of the Chilean Quizapu volcano in 1932 (Hevia et al., 2007). Assuming an initial OC content of 3% (Aimar, 2002) and a constant sedimentation rate during the 73 years, the eolian deposition of OC should be slightly higher than 1 Mg ha^{-1}. This value is much lower than the registered increases during the nine year period, which indicates that humification should be the prevailing factor for OC increases. If these calculations are right, a high capacity of the studied soils to sequester C is possible in a very short period of time.

All studied soils showed increases in the CHt contents between 1996 and 2005; nevertheless, such changes were higher in RS (above 120%) than in CS (83%). This is probably linked with the larger amount of organic residues produced in RS than in CS, where a relative large amount of biomass is exported from the system with harvests or cattle grazing. It has been demonstrated that the formation of total carbohydrates is directly related with the presence of plant debris (Tisdall and Oades, 1982; Gregorich et al., 1994).

CHt differences between CS and RS after the nine year period tended to increase from sandy to fine textured soils. Such differences were due to the larger increases in fine than in coarse textured RS soils. This must be linked with the higher biomass production in fine textured than in sandy soils.

In the period 1996–2006, C/N ratios remained unchanged in most RS soils, indicating that the quality of the soil organic matter did not change in the *Caldenal* soils. This agrees with results of Kirkby et al. (2011) who demonstrated that the variability of C/N between different soil types and management systems is very low. C/N increases were detected only in sandy CS and RS soils and decreases in medium CS textured soils. C/N increases are normally linked to increases in the amount of residues containing mainly recalcitrant organic compounds like cellulose and lignin (Martín Jiménez, 1996). This may be the case for sandy CS soils, where conservation management practices allowed a positive C balance. This explanation cannot be applied to RS, in which management practices did not change in this period. C/N decreases can be attributed in this case to a relative enrichment of N in relation to C, due mainly to OC losses from the soil due to tillage and wind erosion. It is known that the remaining organic matter compounds that predominate in highly degraded soils are mainly composed of very stable substances with relatively low C/N ratios (Burke et al., 1989).

C/CHt ratios showed similar tendencies as C/N ratios. As a matter of fact, differences between management systems of both ratios correlated linearly and positively between them ($R^2 = 0.75$, $p < 0.05$). Differences between management systems are related to decreases in CS between 1996 and 2005, as both quotients remained rather constant in RS in the same period. These decreases indicate a relative enrichment of the labile organic compounds in CS which may have been produced by the accumulation of C but mainly N in the more stable organic matter remaining after the soil degradation, linked to the mineral fractions. Burke et al. (1989) found that C contents increased five to nine times while N increased 13 to 26 times in the recalcitrant organic matter fraction of soils, after 12 years of cultivation.

Variations of C/CHt between management systems in the period 1996–2005 were higher than for C/N, particularly in medium textured soils. It can be deduced that the labile carbonaceous organic compounds have been more affected by management than the labile nitrogenous forms in these soils.

pH values of CS were mostly higher in CS than in RS after the nine year period. Such differences are associated with larger decreases of pH values in most RS than in CS, and with pH increases or no pH changes in CS. The lower pH values of RS is associated with the higher OC contents of these soils after the nine year period, which is known to lower pH values of the studied soils. Buschiazzo and Panigatti (1996); Buschiazzo et al. (1999) indicate that, in neutral or light alkaline soils as those of the semiarid Argentina, an increase in organic matter contents produces a lowering of pH values in the A horizons.

The variability of the organic compounds (OC, N, and CHt, and the C/N ratio) was in all cases higher in RS than in CS in both sampling dates. This must be attributed to the highest spatial variability of plant residues within the *Caldenal* ecosystem, where a high diversity of plant species coexists, producing a high space-variable accumulation of organic compounds in the soil. Buschiazzo et al. (1999) also found that the low variability existing in agriculture soils must be attributed to the continuous incorporation of plant residues of uniform chemical composition into the soil as they have been occupied by crops since many years. Another space-homogenizing effect of these compounds in CS must be tillage operations, which repeatedly mixed the topsoil (Urioste et al., 2006; Kabiri et al., 2015).

OC, N, CHt and C/N variability remained mostly unchanged between 1996 and 2005 in CS but it increased in the same period in RS. Results of CS were expected as management practices and the incorporation of organic materials into each cultivated soil remained almost unchanged during the nine year period. The origin of the variations detected in RS is not clear. It can only be hypothesized that such changes are linked with the moistest climatic conditions as rains of this nine year period (812 mm) were 32% higher than the historic records (550 mm). Under these moister conditions, higher amounts of biomass produced by a higher variety of plant species were available in the *Caldenal* ecosystem which may have led to the formation of organic compounds of variable quality in the soils.

The variability of the textural fractions was much lower than those of the organic compounds in all studied cases. This was probably due to the higher homogeneity of the materials removed or deposited by wind erosion than of the organic compounds accumulated in the soil. Aimar (2002) demonstrated that wind erosion removes mostly the silt fraction from the studied soils making the textural composition of the wind transported material rather homogeneous, while the composition of the vegetation, mainly in the *Caldenal* ecosystem, is highly variable (INTA, 1980) making the humification process also highly variable. These results also support the hypothesis of a low contribution of eolian processes to OC accumulation in the soil and speak more for a pedogenetic formation of organic compounds in the nine year period.

If soil degradation is assessed considering the variations between CS and RS existing in 2005 and differences attributed to changes produced only in CS, decreases of N (98% as average of all sites, CV = 82), CHt (82%, CV = 57) and OC (43%, CV = 29) will be overestimated in all studied sites; decreases of C/N (5%, CV = 40) and C/CHt (20%, CV = 36) will be underestimated in most sites and decreases of pH (205%, CV = 327), and EF (123%, CV = 215) will be mostly overestimated.

5. Conclusions

Soil properties of cultivated- but also of their neighbor reference "virgin" soils of a semiarid environment changed along a nine year study period. One of the main driving factors of these changes was wind erosion, which mainly decreased the proportion of fine particles (silt and clay) in cultivated soils due to deflation processes, and increased them in reference soils due to the sedimentation of wind transported material produced mainly by erosion of neighbor cultivated soils.

The medium textured soils (loamy sand) suffered the largest textural changes, apparently because they were submitted to management practices that promoted wind erosion. The coarsest- (sandy) and finest textured soils (sandy loam) did not show remarkable textural changes, apparently because they were, respectively, managed with more conservative practices or they were more resistant to erosion processes than medium textured soils.

The accumulation of fine materials, and the probable higher deposition of plant residues under moister conditions of the studied period, increased by 50% the contents of total carbon (OC), total carbohydrates (CHt) and nitrogen (N) in most reference soils, apparently produced to a large extent by humification. After the nine year period, cultivated soils presented, in average, 64% less OC, CHt and N than reference soils, but these differences were produced mainly by increases in reference soils rather than by decreases in the cultivated soils.

The C/N and C/CHt ratios decreased in medium textured cultivated soils. Such decreases were the main origin of the differences with reference soils, which showed mostly no changes of these ratios in the nine year period.

The wind erodible fraction showed increases mainly in medium textured cultivated soils and decreases in all reference soils, in association with losses of the fine fractions and OC in cultivated soils and their increase in reference soils.

pH values were higher only in some cultivated than their reference pairs after nine years, but such differences were produced mainly by pH decreases in reference soils (in association with higher OC contents) rather than by increases in the cultivated soils.

We concluded that the simple comparison of cultivated and reference soils can lead to errors in measuring soil degradation in semiarid environments. If soil properties have changed in both, reference and cultivated soils, changes of some soil properties can be overestimated but also underestimated.

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