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Pores size distribution and pores volume density of Mollisols and Vertisols under different cropping intensity managements with no-tillage

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ABSTRACT

In the Argentina Pampas, one of the most extensive agricultural areas in the temperate fringe of southern hemisphere, soil health is jeopardized mostly by the decline of physical and biological properties due to soil fragility and agricultural managements, even under No-tillage (NT). In this study, topsoil physical health of three Mollisols and one Vertisol under two agricultural managements with no-tillage (good and poor agricultural practices -GAP and PAP-, differing mostly in their cropping intensity -CI-) was evaluated by the indirect measurement of porosity features. Two types of pore features derived from soil water release curves (SWRC) of undisturbed samples at three depths (0.0–0.05, 0.05–0.010 and 0.010–0.20 m) were employed: a) pores size distribution (>1000, 300, 50 and < 50 μm) and b) pore volume density parameters: location (D_{mode}, D_{mean} and D_{median}) and shape (SD, Skewness and Kurtosis). Pore parameters were related to management variables, to clay mineralogy and to several soil physical and chemical properties allowing to i) evaluate the effects of cropping intensification on soil physical properties; ii) evaluate the effects of intrinsic and dynamics factors on the behaviour of pore variable; iii) build an optimal pore size frequency curve to assess soil health. Among all porosity features assessed, $P_{Mac>300\ \mu m}$ and D_{mode} showed close relationships with agricultural management variables and were positively related to a labile organic carbon fraction (POCc) and to the aggregates stability tests, regardless of the soil type. Thus, they both may be selected as sound indicators of physical health status of different pampean soils under NT cultivation. Particularly, in the PAP treatments and for the three depths evaluated, $P_{Mac>300\ \mu m}$ showed values below critical thresholds, highlighting the physical deterioration of soils subjected to this management. Cropping intensification expressed by the CI index was also strongly related with large pores and soil properties (i.e. organic carbon and aggregates stability). These results demonstrate that cropping intensification expressed by the CI index was effective to counteract compaction processes in a variety of soils of the Pampa region and must be seen as an important strategy to avoid porosity loss and to improve the benefits of NT.

1. Introduction

Agricultural management in the extensive Pampa and Chaco plains of Argentina, accounting for 25 million hectares, relies mostly (>78%) on no-till (NT) farming (Peiretti and Dumanski, 2014). Considering the low strength of abiotic mechanisms to regenerate soil structure (Taboada et al., 2004) and the common presence of heavy machinery on the field in this region (Botta et al., 2004), soil health is jeopardized, mostly by a decline of physical and biological soil properties (D'Acunto et al., 2018; Duval et al., 2016; Behrends Kraemer et al., 2021). NT in this region has been characterized by low crop diversification and low intensification –which implies a single crop per year for most of the years-, together with soybean predominance in the crop sequence (Caviglia and Andrade, 2010). Thus, several studies have reported low organic carbon contents, poor aggregates stability and high bulk density, among others physical constraints on water dynamics, even under NT

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Table 1

Crop sequences and management indexes for Good and Poor agricultural practices (GAP and PAP, respectively) for the different soil types in the six years previous to sampling. Adapted from Behrends Kraemer et al. (2019).

Soil treatment/	Entic Haplustoll (General Cabrera series)		Typic Argiudoll (Monte Buey series)		Typic Argiudoll (Pergamino series)		Typic Hapludert (Santiago series)	
	Mollisols						*Vertisol*	
	GAP	PAP	GAP	PAP	GAP	PAP	GAP	PAP
2004/2005	Wheat/Soybean	Peanut	Wheat/Sorghum	Soybean	Soybean	Soybean	Wheat/Soybean	Maize
2005/2006	Maize	Wheat/Soybean	Maize	Wheat/Soybean	Wheat/Soybean	Soybean	Sweet clover+Rye-Grass/Maize	Soybean
2006/2007	Wheat/Soybean	Soybean	Wheat/Soybean	Maize	Maize	Soybean	Soybean	Wheat/Soybean
2007/2008	Vetch/Maize	Wheat/Soybean	Vetch/Maize-Soybean	Soybean	Soybean	Soybean	Wheat/Soybean	Maize
2008/2009	Wheat/Soybean	Soybean	Maize	Soybean	Wheat/Soybean	Soybean	Maize	Soybean
2009/2010	Soybean	Soybean	Wheat/Soybean	Soybean	Maize	Soybean	Soybean	Soybean
CI_{agr}[a]	0.67	0.53	0.64	0.49	0.56	0.42	0.59	0.50
Years under No-Till	13	5	28	10	6	5	13	9
Soybean/Crops ratio[b]	0.40	0.62	0.28	0.75	0.50	1.00	0.44	0.57
Maize/Crops ratio[b]	0.20	0.00	0.30	0.14	0.25	0.00	0.22	0.28
Soybean/Maize[c]	4	5	1	5	2	6	2	2
Soybean as only crop (%)[d]	0.17	0.50	0.00	0.66	0.33	1.00	0.33	0.50

[a] CI_{agr}-Crop sequence intensification index: relationship between number of months occupied by crops and total number of months during the study period; [b]number of soybean or maize crops in relation to total crops during the study period; [c]number of soybean crops related to maize crops (soybean/maize), [d]years of soybean as the only crop in the year.

(Novelli et al., 2013; Behrends Kraemer et al., 2021). Also, morphologies resulting from compaction and increases of runoff are commonly described, leading to decreases on water availability and impacting on crop yields (Sasal et al., 2017; Imhoff et al., 2009).

NT systems can be managed with different cropping intensity, crop rotations, fertilization technologies and pest control. Thus, fields under NT can express contrasting health status. In the last decade, and with the aim to evaluate degradation processes and improve soil health, several studies have started to use indexes comprising the type and the intensity of land use and the effects of cropping on soil properties. Among them, the cropping intensity index (CI) (Caviglia and Andrade, 2010), which expresses the number of crops per year and thus reflects the presence of active roots in a given sequence, and the Soybean/Crops ratio (Novelli et al. 2011, Behrends Kraemer et al., 2017; Behrends Kraemer et al., 2019) have been proposed and reported in the literature. Different cropping intensities and fallow periods implies differences on volume, quality and temporal variations of crop residues, and root patterns, all of that in turn affecting soil structure (Novelli et al., 2017). For instance, the volume of crop residues is increased by double cropping or by crop rotations including maize or sorghum which adds to the soil twice the biomass produced by soybean.

As a consequence of soil degradation, farmers from the Pampa region (the most productive rainfed area of Argentina) have recognized the need to promote good agricultural practices, including rotations, cover crops and nutrient replacement, in parallel to monitoring soil health to ensure high long-term productivity (Wall, 2011). These good agricultural practices are partly related to crop intensification (double crops and crop diversification), among other technological improvements. In terms of productivity, intensified systems allowed to increase annual yields, with greater efficiency in the use of resources such as water and radiation throughout the year (Andrade et al., 2017; Caviglia and Andrade, 2010). Regarding soil health, more intensified systems under NT have shown improvements in some edaphic physical, chemical and biological properties (i.e. increases of aggregate stability, organic carbon content and of soil fauna) (Duval et al., 2016; Behrends Kraemer et al., 2017; Behrends Kraemer et al., 2021; D'Acunto et al., 2018).

However, in other cases cropping intensification have resulted on higher soil compaction as consequence of higher traffic intensity (Wilson et al., 2010; Álvarez et al., 2014; Behrends Kraemer, 2015). Development of soil compaction is directly related to changes in pore configuration in terms of size, distribution and connectivity of pores (Morrás et al., 2017), impacting on soils hydrological regime and finally on crop yields. Thus, the effects of cropping intensification are contradictory mostly because is soil dependent and also affected by management variables as tillage and agricultural history (Behrends Kraemer et al. 2017, 2021; Novelli et al., 2013; Soracco et al., 2018). Several methods and indicators are available to detect shifts in pore networks and water dynamics (Dexter et al., 2008). Among indirect methods, soil water retention curve (SWRC) produce accurate information about pores size distribution (Dexter, 2004). From these curves, it is possible to fit mathematical functions that allow the determination of different pore features to study structural degradation (Dexter et al., 2008; Imhoff et al., 2009). Water entry and movement is mainly regulated by macropores, even though these constitute a small proportion of the total porosity. In general, macropores are the first to be lost when soil is physically degraded due to machine traffic or animal trampling (Botta et al., 2004; Fernández et al., 2010), and it depends largely on both aggregates stability and organic carbon fractions (Álvarez et al., 2009). Different pore size diameters thresholds have been proposed to quantify macroporosity (from 3000 to 30 μm) being those delimited by 1000, 300, 50 and 30 μm the most used (Reynolds et al., 2002; Imhoff et al., 2009).

Besides, Reynolds et al. (2002) and Reynolds et al. (2008) also suggested the use of pore volume distribution to measure changes in the hydro-physical soil quality. In this sense, the comparison of a given pore pattern against the pattern in the same soil with the best physical status, or ideally against uncultivated soils, may be of interest to build sound physical quality indicators. Thus, several variables describing pore size frequency distribution such as modal pore (D_{mode}), median (D_{median}) and mean (D_{mean}), as well as pore curve variables such as standard dispersion (SD), skewness and kurtosis derived from SWRC have been tested. Castellini et al. (2013) and Shahab et al. (2013) achieved good results using this technique, adjusting optimal porosity thresholds for building soil quality indicators. However, there is limited research on these thresholds despite the fact that this method may provide useful information about impacts of soil cultivation, biological habitats and biogeochemical related processes.

Although there are studies that attempt to elucidate how tillage systems, crop rotations and fertilization modify soils pore configurations, often they only concern one type of soil, and the variables evaluated (*i.e.* soil management, organic carbon fractions) are sometimes insufficient to interpret adequately their effects on the pore system. In this sense, the development of new strategies for maintaining or improving the physical quality of cropped soils has been difficult and slow because of complex interactions among tillage practices, soil texture, organic carbon, crop types, temporal variation of physical properties and climate (Reichert et al., 2009; Lozano et al., 2014; Soracco et al., 2018).

A first step for the analysis is to recognize that soil quality depends on both inherent and dynamic properties and processes (Karlen et al., 2003). Inherent characteristics are those determined by basic soil forming factors that show little change over time, such as mineralogy and particle size distribution. On the other hand, dynamic soil properties refer to soil attributes, such as organic matter and aggregates stability, which can change considerably over relatively short time periods in response to human use and are strongly affected by agronomic activities.

In summary, there is a need of more integral approaches to evaluate the impact of agricultural intensification under no-tillage on the pores system of different soils.

The objective of this study was to evaluate the effect of good and poor agricultural practices on the porosity of the A horizon in different soils from the Pampean region of Argentina. Pore volume density functions and pores size distribution derived from soil water retention curves were used to achieve this objective.

2. Materials and methods

2.1. Soils and managements

Soil sites and management were selected by scientists and farmers of the BIOSPAS consortium, an interdisciplinary project with the long-term goal of defining ecological indicators of sustainability under NT farming (Wall, 2011). Four soils under **NT** cultivation (three Mollisols and one Vertisol), two different management practices (GAP: good agricultural practices; PAP: poor agricultural practices) and a reference system (NE: Natural environment), were studied (Table 1).

NE, consisted of natural grassland that had not been tilled for at least 30 years, located in areas close to the GAP and PAP sampling sites. GAP and PAP allocation followed the criteria of the AAPRESID program for Certification in Good Agricultural Practices (https://www.aapresid.org.ar/aapresid-certificaciones/buenas-practicas-agricolas/). Under this framework, the principal difference between both agricultural managements was the predominance of soybean in the crops succession in the PAP treatment (low cropping intensity), and a more balanced proportion of corn, wheat and soybean in the rotation in the GAP management (high cropping intensity). Also, GAP was characterized by targeted fertiliser placement and more efficient use of agrochemicals (herbicides, pest control) while PAP showed a broadcast fertiliser utilization, high use of agrochemicals, and lower yields. According to Derpsch et al. (2014), only GAP follows all of the NT system assumptions (diverse crop rotation, optimal use of fertilizers, integrated pest control, etc.). Both types of agricultural managements compared in this work were maintained at least for 5 years (Table 1). Further information is described in detail in Figuerola et al. (2012), including the farming practices and yields in each production site.

In production fields, the strict replication of management practices is rather difficult, so that the qualification of good or poor practices is actually a result of a combination of different practices related to agricultural activity. Thus, to overcome this restriction GAP and PAP management treatments were further quantitatively qualified including the following variables: years under no-till, number of soybean or maize crops in relation to total crops (soybean/crops; maize/crops), number of soybean crops in relation to maize crops (soybean/maize), years of soybean as the only crop in the year (soybean as only crop) and cropping intensification index in the agricultural sequence (CI_{agr}). This index was calculated as the relationship between number of months occupied by crops and the total number of months in the studied period (Table 1). When NE (cropping intensity = 1) was considered together with the agricultural treatments, the intensification index of the crop sequence was referred as to CI. Both CI_{agr} and CI reflect, among other features, the proportion of living roots throughout the year and the amount of stubble covering the soils surface.

The four sites, including three Mollisols and one Vertisol, are located along a west-east transect in the northern Argentine Pampas: Entic Haplustoll – General Cabrera series (33° 01′ 31″ S; 63° 37′ 53″ W), Typic Argiudoll – Monte Buey Series (32° 58′ 14″ S; 62° 27′ 06″ W), Typic Argiudoll - Pergamino series (33° 56′ 36″ S; 60° 33′ 57″ W) and Typic Hapludert –Santiago series (31° 52′ 59,6″ S; 59° 40′ 07″ W). Mean annual precipitation and mean annual temperature increase towards the east (from 795 mm to 1023 mm and from 16.3 °C to 18.0 °C, respectively, Servicio Meterológico Nacional, http://www.smn.gov.ar, November 2012). Rainfall varies with season and is concentrated during spring and summer. Landscape, drainage and other land characteristics can be found in Behrends Kraemer et al. (2017). Soil characterization is presented in Suppl. Table 1. Briefly, silt fraction is dominant in the A horizon of all soils; the mineralogy of the clay fraction is quite similar in Mollisols, 2:1 clays, mainly illites with a small proportion of irregular interstratified illite-smectite minerals and traces of kaolinite. By contrast, the Vertisol is characterized by a high proportion of smectite and lower proportions of the other above mentioned clay minerals (Behrends Kraemer et al., 2019). In all soil types, base saturation was higher than 80% and the pH was around 6. All determinations were done in winter at least two months after summer crop harvest and before the following seeding operation. All sites were sampled within a 20 day gap to minimize climatic (i.e. rainfalls occurrence and temperature) and management effects on all variables considered in the study. This procedure was necessary as Strudley et al. (2008), Soracco et al. (2018) and Algayer et al. (2014) showed a high seasonal variability of soil physical properties.

2.2. Soil water retention curve approach (SWRC)

In this study, pore size distribution and volume density parameters (location and curve shape) were derived from the SWRC of undisturbed soil samples. Undisturbed samples were obtained through steel cylinders (5.0 cm height × 5.9 cm diameter, volume = 136.7 cm^3) at three depths (0.0–0.05, 0.05–0.10 and 0.10–0.20 m). At 0.10–0.20 m depth, this determination was done by sampling at the middle section of this layer. For each combination of soil type (4), management (3), subplot (3) and depth (3), 4 replicates (n: 12 per management treatment) were used summarizing a total of 432 samples. Samples were subjected to 48 h of capillary re-wetting until saturation (distilled water). Suction was established at 0, 10, 30, 60, 90, 330, 2000 and 15000 cm water columns in pressure plate apparatus (Klute, 1986). To precisely set the lower suctions (10, 30 and 60 cm) a water hose in equilibrium with atmospheric pressure was attached to plate apparatus. Volumetric water moisture and matric suction pairs were fitted to van Genuchten (1980) water retention model, according to equation (1), considering the Mualem restriction m = 1–1/n (Mualem, 1986). This procedure was done with RETC software (van Genuchten et al., 1991), using nonlinear least squares optimization, reaching in all cases fittings above $R^2 > 0.96$. van Genutchen (1980) estimated parameters for soils, managements treatments and depths are presented in Supplementary Table 2.

$\theta_g = (\theta_{gs} - \theta_{gr})[1+(\alpha h)^n]^{-m} + \theta_{gr}$; $h \geq 0$ (1)where θ_g ($kg\ kg^{-1}$) is the gravimetric water content, θ_{gs} ($kg\ kg^{-1}$) is the saturated gravimetric water content, θ_{gr} ($kg\ kg^{-1}$) is the residual gravimetric water content (estimated), h is pore water suction head (cm) and α, n and m are empirical curve parameters estimations.

2.3. *Pore volume distribution functions*

For each sample, a pore volume distribution function was determined according to Reynolds et al. (2009) and Shahab et al. (2013) with a further normalization of this function to allow the comparison between different soil samples (equation (2)).

$$SWRC_n(h) = \frac{SWRC_v}{SWEC_{vi}} = \frac{m(ah)^n(1+m^{-1})^{(m+1)}}{[1+(ah)^n]^{(m+1)}}; 0 \leqslant SWRC_n \leqslant 1 \tag{2}$$

where $SWRC_n$ (h) is the normalized curve, $SWRC_v$ (h) is the volumetric soil water retention curve and $SWRC_{vi}$ is the slope of this curve in the inflection point.

The pore distribution function may be defined as the slope of the SWRC, at volumetric base vs Ln (h), and plotted with the equivalent pore diameter (D_{por}) in a Log10 scale (Jena and Gupta, 2002). D_{por} was determined using the capillary rise equation (Warrick, 2002) (equation 3); gravimetric SWRC measured at each depth was affected by bulk density to obtain volumetric SWRC.

$$D_{por} = \frac{4\gamma\ cos\omega}{\rho wgh};\ \mathrm{h} > 0\ (\mathrm{cm}) =; D_{por}\ (\mu\mathrm{m});\ 20\ ^\circ\mathrm{C} \tag{3}$$

where $\gamma = 72.8$ gm s^{-2} is pore water surface tension, $\rho_W = 0.998$ gm cm^{-3} is water density, g = 980 cm s^{-2} is gravitational acceleration, $\omega \approx 0$ is the water-pore contact angle; and h is pore water suction head (cm).

Equation (2) allowed to determine several pore distribution parameters using *Location* and *Shape* parameters (Reynolds et al., 2009), for the combination of soil type, management and depth. Location parameters include the mode (D_{mode}), median (D_{median}) and mean (D_{mean}) pore diameter values (equations (4)–(6)), and the shape parameters include standard deviation of porosity volume (SD), skewness –asymmetry- and kurtosis –peakdness- (Eq. (7)–(9)).

$$D_{\ mode} = \frac{2980\alpha}{m^{-1/n}} \tag{4}$$

$$D_{median-D0.5} = \frac{2980\alpha}{(0.5^{-1/m}-1)1/n}; \theta = 0.5 \tag{5}$$

$$D_{mean} = exp\left(\frac{inD0.16 + lnD0.50 + lnD0.84}{3}\right) \tag{6}$$

$$SD = exp\left(\frac{lnD0.84 - lnd0.16}{4} + \frac{lnD0.95 - lnD0.05}{6.6}\right); 1 \leqslant \mathrm{SD} < \propto \tag{7}$$

Skewness (8)

$$Kurtosis = \frac{InD0.05 - InD0.95}{2.44(InD0.25 - InD0.75)}; 0.41 \leqslant Kurtosis < \infty \tag{9}$$

where θ_n is the water content relative to saturated soil, while $D_{0.05}$, $D_{0.16}$, $D_{0.5}$, $D_{0.75}$, $D_{0.84}$ and $D_{0.95}$ were determined using equation (10).

$$D_\theta = \frac{2980\alpha}{(\theta^{-1/m}-1)^{1/n}}; 0 \leqslant \theta \leqslant 1 \tag{10}$$

D_{mode} is determined at the inflection point of the $SWRC_n$, corresponding to the most frequent pore diameter value. SD quantifies the size range of equivalent pore diameters, where SD = 1 indicates pore diameter homogeneity while high SD indicates an increase of equivalent pore diameters range. Skewness = 0 indicates a lognormal distribution. Negative values indicate high numbers of small pores, positive values indicate high number of large pores. Kurtosis = 1 corresponds to a lognormal distribution ("mesokurtic"); values > 1 indicate a "leptokurtic" distribution which is more peaked in the centre and more tailed in the extremes than the lognormal curve, while values < 1 indicate a "platykurtic" distribution which is less peaked in the center and less tailed in the extremes than the lognormal curve (Reynolds et al., 2009).

2.4. *Macroporosity > 1000 μm, >300 μm y > 50 μm, microporosity < 50 μm*

Different pore sizes were obtained with the fitted water retention curves (equations 1, 3). Pores>1000 μm ($P_{Mac>1000}$, Eq. 11) have been used by several authors to associate larger pores with fast drainage, and with pores of biological origin (fauna and roots) (Behrends Kraemer et al., 2018; Buczko et al., 2006; Imhoff, et al., 2009; Watson and Luxmoore, 1986). Also, macroporosity>300 μm ($P_{Mac>300,}$ Eq. 12) have been used, and thresholds related to this porosity size are available (Reynolds et al., 2009; Castellini et al., 2013). Optimum threshold would be $P_{Mac>300} \geq 0.05$–0.10 $M^3\ M^{-3}$ while values lower than ≤ 0.04 $M^3\ M^{-3}$ has been found in compacted soils (Carter, 1988; Drewry et al., 2001; Drewry and Paton, 2005). Reynolds et al. (2009) established $P_{Mac>300} \geq 0.07\ M^3\ M^{-3}$ and $P_{Mac>300} = 0.04\ M^3\ M^{-3}$ as optimum and critical values respectively. Macroporosity and Microporosity ($P_{Mac>50}$ and $P_{Mac<50}$ respectively) were calculated according to equation 13 and 14.

(11) $P_{Mac\ >1000} = \theta_s - \theta_{Mac \geq 1000\ \mu m}$ ($h_{Mac \geq 1000\ \mu m}$ = -0.03 m); $0 \leq P_{Mac\ >1000} \leq \theta_s$

(12) $P_{Mac\ >300} = \theta_s - \theta_{Mac \geq 300\ \mu m}$ ($h_{Mac \geq 300\ \mu m}$ = -0.1 m); $0 \leq P_{Mac\ >300} \leq \theta_s$

(13) $P_{Mac\ >50} = \theta_s - \theta_{Mac \geq 50\ \mu m}$ ($h_{Mac \geq 500\ \mu m}$ = -0.6 m); $0 \leq P_{Mac\ >50} \leq \theta_s$

(14) $P_{Mic<50} = \theta_{Mac \geq 50\ \mu m}$ ($h_{Mac \geq 50\ \mu m}$ = -0.6 m); $0 \leq P_{Mic<50} \leq \theta_s$

where, θ_s is saturation water content.

2.5. *Considerations on the use of SWRC for porosity estimation*

One of the most important assumptions for calculating pore functions from SWRC is that the physical behaviour of the soil is rigid or quasi rigid. Therefore, the Entic Haplustoll (Bengolea) is the ideal soil for this type of study, since its expansion potential does not exceed 18% (Behrends Kraemer, 2015). On the other hand, Typic Argiudolls from Monte Buey and Pergamino, and particularly NE treatments due to their higher content of organic matter, have a moderate degree of expansion (≈25%), which could add a small bias when SWRC is converted to porosity distribution. Finally, the Typic Hapludert, with an expansion rate of 44%, would not be *a priori* suitable for this type of analysis. Previous experiences have shown that SWRC is seriously affected in soils with clay contents greater than 570 g Kg^{-1} (Nagpal et al., 1972). In turn, Reynolds et al., (2002) and Reynolds et al. (2008) working with clay loam soils with clay contents of 370 g Kg^{-1}, were able to successfully use this methodology. Although the Hapludert samples did not show any fissures or cracks at the wilting point, and their maximum clay content was 489 g Kg^{-1} (soil average 430 g Kg^{-1}), for a better interpretation of the results, two datasets were selected: one considering all soils (complete data set = Mollisols + Vertisol) and the other without taking into account the results corresponding to the Hapludert (reduced dataset = Mollisols). Furthermore, as has been also shown for Pampean soils, the hydrophysical behaviour of Vertisols is different from that of Mollisols, due to their differences on clay mineralogy and aggregation mechanisms, among other factors (Novelli et al., 2013, 2020; Behrends Kraemer et al., 2019; Behrends Kraemer et al., 2021).

2.6. *Soil characteristics, organic carbon fractions and aggregates stability*

Pores size distribution and pores volume density variables were contrasted with soil characteristics, organic carbon fractions and aggregate stability tests. Soil characteristics presented in this manuscript are: Particle size distribution: clay (<2 μm), silt (2–50 μm) and sand (>50 μm); smectite and interestratified smectite/illite (S + S/I) content in the clay fraction, Atteberg limits: Ll (Liquid limit), Pl (Plastic limit)

Table 2

Mixed models analyses for pore size distribution and pore volume density variables showing fixed and random effects and AIC criteria. Contrast between *Complete* and *Reduced* models are also shown. $P_{\mathrm{Mac}\ >1000\ \mu m}$: macroporosity > 1000 μm, $P_{\mathrm{Mac}\ >300\ \mu m}$: macroporosity > 300 μm, $P_{\mathrm{Mac}\ >50\ \mu m}$: macroporosity > 50 μm, $P_{\mathrm{Mic}\ <50\ \mu m}$: microporosity < 50 μm, D_{mode}, D_{media} and D_{mean}: pore diameter for the more frequent, median and mean size, respectively, SD: standard deviation of pore size.

				Fixed effects†			Random effects SD‡	AIC[b]	Complete vs Reduced[a]
	Soil type	Management	Depth	P value Soil type * management.	Management.* depth.	Soil type*management* Depth	Subplot		Soil type
BD	<0.0001	<0.0001	<0.0001	<0.0001	ns	ns	ns	53.23	ns
$P_{\mathrm{Mac}\ >1000\ \mu m}$	<0.0001	<0.0001	0.0041	<0.0001	0.0003	0.0008	ns	144	0.01
$P_{\mathrm{Mac}\ >300\ \mu m}$	<0.0001	<0.0001	<0.0001	<0.0001	0.0001	0.0008	<0.0001	96	ns
$P_{\mathrm{Mac}\ >50\ \mu m}$	<0.0001	<0.0001	0.0001	0.0042	0.0079	ns	<0.0001	201	0.0009
$P_{\mathrm{Mic}\ <50\ \mu m}$	<0.0001	0.0002	0.0114	ns	0.0015	ns	<0.0001	215	0.0005
D_{mode}	ns	<0.0001	ns	0.0002	0.0011	ns	<0.0001	114	ns
D_{median}	<0.0001	ns	ns	0.0003	0.0162	0.005	<0.0001	281	0.0004
D_{mean}	<0.0001	ns	ns	0.0003	0.0182	0.0039	<0.0001	321	0.0001
SD	<0.0001	ns	ns	0.0003	0.0318	0.0038	<0.0001	322	0.0001
Skewness	<0.0001	ns	ns	0.0022	ns	0.1643	<0.0001	325	0.0005

† Fixed and random effect for the complete model.

‡ Standard deviation related to residual.

[a] Differences (Probability) between reduced and complete models with soil type factor as fixed effect.

[b] AIC: Akaike information criterion.

and Pi (Plasticity index). The following variables were determined in crushed 2 mm sieved soil samples: pH (1:2.5, soil:water), electric conductivity (EC), equivalent humidity (EH), exchangeable Ca^{2+} and soil organic carbon (SOC). Detailed information on procedures can be found in Rosa et al. (2014) and Behrends Kraemer et al. (2017). Organic carbons fractions were obtained from Duval et al. (2013) that worked in the same experiment. Three size organic carbon fractions are presented here: a coarse fraction (105–2000 μm) containing coarse particulate organic carbon (POCc), medium fraction (53–105 μm) with fine particulate organic carbon (POCf) and a fine fraction (<53 μm) containing silt clay and mineral-associated organic carbon (MOC). Aggregate stability tests were determined by Le Bissonnais (1996) method. The tests used here are five: i) fast wetting in distilled water (FW) –slacking effect-; ii) stir agitation in distilled water of samples previously immersed in ethanol (Stir) –cohesion effect-; iii) slow wetting in distilled water (SW) -microcracking effect; iv) Average of the previous tests (AS_{Mean}) and v) fast 10 s wetting (FW_{10s}) to assess early slaking processes (Behrends Kraemer et al., 2019). These values were extracted from Behrends Kraemer et al. (2019) and Behrends Kraemer et al. (2021). Mean values of all characteristics and soil properties for each management and soil type is presented in Suppl. Table 1. All determinations described here were done at 0–0.20 m depth and the contrast with pores size distribution and pore volume density variables were performed at this same depth.

2.7. Statistical analyses

Mixed models were constructed to study the effect of treatments as fixed factor (three levels): good agricultural practices (GAP), poor agricultural practices (PAP) and natural environment (NE); soil type as fix effect (three Mollisols and one Vertisol). In addition, this experimental design included, as random effects (random intercepts) the influences of subplots (n: 3) nested within plots and nested within soil types (Zuur et al., 2009). This model was denominated complete model. To evaluate the behaviour of pore variables regardless of the soil type a reduced model was built considering soil type as random effect. Later both models were compared to consider if some variable of soil porosity could be addressed in a wider scope. This procedure was performed for the three soil depths (0–0.05, 0.05–0.10 and 0.10–0.20 m). Also, variance heteroscedasticity was modelled for the effect of management treatment. All models were estimated in R with lmer function of the lme4 package (Bates et al., 2011). All location and shape of pore volume distribution curve variables and $P_{\mathrm{Mac}>300\ \mu m}$ and $P_{\mathrm{Mac}>300\ \mu m}$ were transformed (Log_{10}) as they did not attain normality (Shapiro Wilks, $P < 0.05$). Kurtosis could not be normalized with standard methods; therefore only descriptive data are presented. A variance components analysis

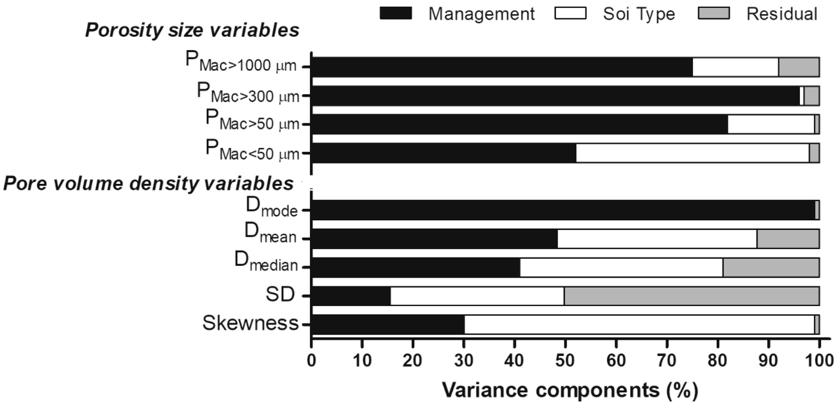

Fig. 1. Variance components (%) (management, soil type and residual) for mean (0.0–0.20 m) pore size distribution and pore volume density variables. $P_{\mathrm{Mac}>1000}$: macroporosity > 1000 μm, $P_{\mathrm{Mac}>300}$: macroporosity > 300 μm, $P_{\mathrm{Mac}>50\ \mu m}$: macroporosity > 50 μm, $P_{\mathrm{Mic}\ <50}$: microporosity < 50 μm, D_{mode}, D_{media} and D_{mean}: pore diameter for the more frequent, median and mean size, respectively, SD: standard deviation of pore size.

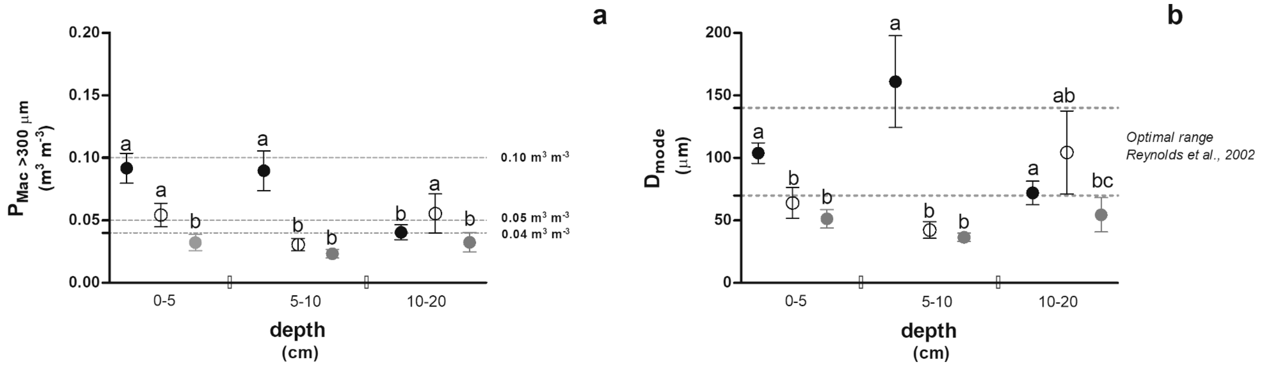

Fig. 2. a) Macroporosity > 300 µm ($P_{Mac\ >300\ \mu m}$) and b) D_{mode} (µm) for Natural environment (NE – black circle), good agriculture practices (GAP – white circle) and poor agricultural practices (grey circle) for 0–0.05, 0.05–0.10 and 0.10–0.20 m. Different letters correspond to statistical differences between management treatments for each depth ($p < 0.05$).

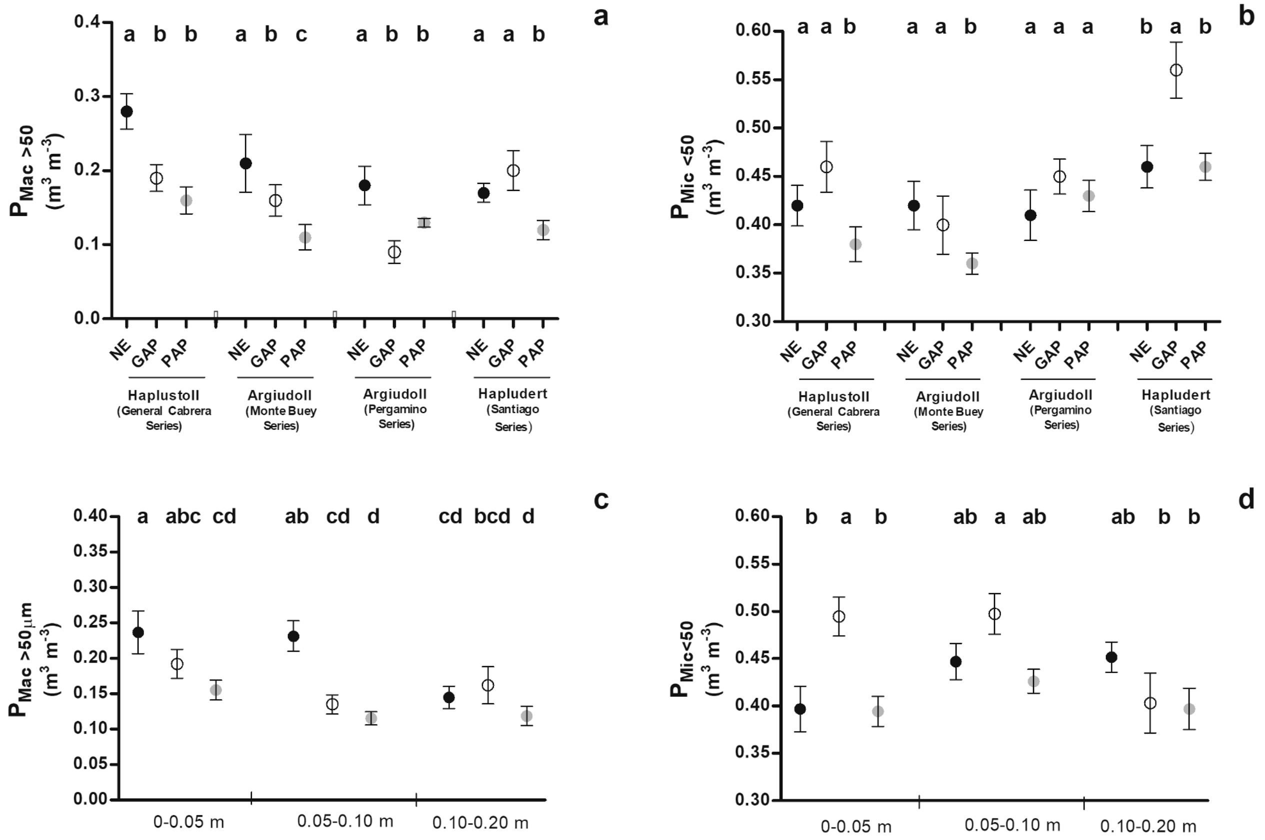

Fig. 3. Macroporosity > 50 µm ($P_{Mac\ >50}$) and microporosity < 50 µm ($P_{Mic<50}$) for Natural environment (NE – black circle), good agriculture practices (GAP – white circle) and poor agricultural practices (grey circle) for soil types (a) $P_{Mac>50\ \mu m}$ (b) $P_{Mic<50\ \mu m}$ and for different soil depths: 0–0.05, 0.05–0.10 and 0.10–0.20 m (c) $P_{Mac>50}$ (d) $P_{Mic<50\ \mu m}$. Different letters correspond to statistical differences between management treatments for the interaction management and soil or depth ($p < 0.05$).

was used to determine the variance proportions attributable to treatments and sites in soil properties as a proxy to discriminate the dynamic and inherent behaviour of each soil feature. Pearson correlations and linear regressions were performed in Infostat (Di Rienzo et al, 2011) to assess the relationship of pore variables with management variables, soil characteristics, organic carbon fractions and aggregate stability tests and to evaluate the effect of soil orders (Mollisols vs. Vertisol).

3. Results

3.1. Effects of management, soil type and depth factors on pores size distribution and pores volume density variables

According to mixed models most porosity variables showed significant differences between the complete (soil type as a fixed factor) and the reduced model (soil type as random factor) and thus analyses should take into account soil type factor (Table 2). However, no differences between models were detected for $P_{Mac>300\ \mu m}$ and D_{mode} allowing to consider both variables regardless of soil type. $P_{Mac>300\ \mu m}$ and D_{mode} showed the highest proportion variance for the management factor up to

Table 3

Location (Mode -D_{mode}-, Median -D_{median}-, Mean -D_{mean}-) and shape (Standard deviation -DE-, Skewness and Kurtosis Table 3) parameters for management treatments (NE: Natural Environment; GAP: good agricultural practices and PAP: poor agricultural practices) for each depth 0–0.05, 0.05–0.10 and 0.10–0.20 m and soil types. †Standard error. Green shaded values belong to the optimal category proposed by Reynolds et al. (2002).

Soil Type	Managements	Depth (m)	Location parameters						Shape parameters					
			Dmode (µm)		Dmedian (µm)		Dmean (µm)		SD (-)		Skewness (-)		Kurtosis (-)	
Haplustoll (General Cabrera Series)	NE	0-0.05	115,7	(27,5)†	12,6	(5,4)	4,6	(2,5)	162,5	(58,3)	-0,40	(0,01)	1,14	(0,003)
		0.05-0.1	227,8	(245,9)	35,0	(40,9)	14,5	(17,5)	96,1	(16,8)	-0,39	(0,01)	1,15	(0,001)
		0.1-0.2	44,1	(22,5)	5,4	(2,3)	2,0	(0,8)	117,0	(19,4)	-0,39	(0,00)	1,15	(0,001)
	GAP	0-0.05	31,2	(4,4)	3,9	(0,9)	1,5	(0,6)	129,0	(61,6)	-0,39	(0,02)	1,15	(0,004)
		0.05-0.1	31,5	(7,0)	3,3	(0,8)	1,2	(0,3)	163,2	(61,8)	-0,40	(0,01)	1,14	(0,003)
		0.1-0.2	145,5	(205,9)	19,2	(26,9)	7,4	(10,4)	102,2	(7,6)	-0,39	(0,00)	1,15	(0,001)
	PAP	0-0.05	42,4	(32,9)	6,4	(4,5)	2,7	(1,8)	95,0	(51,3)	-0,38	(0,02)	1,15	(0,004)
		0.05-0.1	29,8	(5,2)	3,9	(0,5)	1,5	(0,2)	109,7	(9,1)	-0,39	(0,00)	1,15	(0,001)
		0.1-0.2	79,1	(100,5)	11,8	(14,1)	4,8	(5,6)	75,8	(15,5)	-0,38	(0,01)	1,15	(0,001)
Argiudoll (Monte Buey Series)	NE	0-0.05	71,6	(12,5)	7,8	(12,7)	4,0	(6,9)	5779,7	(5707,1)	-0,41	(0,05)	1,13	(0,020)
		0.05-0.1	79,2	(15,6)	44,7	(9,5)	34,0	(7,9)	8,1	(1,4)	-0,26	(0,01)	1,15	(0,001)
		0.1-0.2	64,5	(15,6)	36,9	(34,8)	32,8	(32,3)	2583,5	(4467,7)	-0,27	(0,16)	1,13	(0,010)
	GAP	0-0.05	100,3	(39,1)	49,4	(56,0)	40,7	(50,8)	1625,9	(2800,4)	-0,31	(0,13)	1,14	(0,020)
		0.05-0.1	72,9	(1,9)	32,3	(19,7)	23,7	(17,9)	34,9	(47,2)	-0,30	(0,08)	1,15	(0,004)
		0.1-0.2	159,3	(101,0)	79,9	(50,5)	57,3	(36,1)	13,3	(0,2)	-0,25	(0,00)	1,15	(0,000)
	PAP	0-0.05	62,1	(26,9)	38,2	(26,1)	31,8	(23,9)	17,9	(23,1)	-0,25	(0,11)	1,15	(0,010)
		0.05-0.1	40,8	(10,8)	13,0	(11,7)	8,2	(9,5)	47,6	(33,0)	-0,34	(0,06)	1,15	(0,004)
		0.1-0.2	48,1	(24,4)	20,2	(13,1)	13,4	(9,4)	21,2	(12,4)	-0,31	(0,04)	1,16	(0,002)
Argiudoll (Pergamino Series)	NE	0-0.05	103,3	(13,6)	19,6	(31,0)	13,0	(21,9)	21181,9	(35967,8)	-0,39	(0,09)	1,13	(0,020)
		0.05-0.1	163,9	(44,2)	1,5	(1,6)	0,2	(0,3)	123743	(20459,1)	-0,45	(0,01)	1,12	(0,010)
		0.1-0.2	74,7	(32,9)	1,5	(1,2)	0,3	(0,3)	64489,3	(109570,8)	-0,44	(0,02)	1,13	(0,010)
	GAP	0-0.05	25,3	(17,1)	0,7	(0,8)	0,2	(0,2)	2839,6	(3699,4)	-0,43	(0,01)	1,13	(0,010)
		0.05-0.1	21,4	(17,8)	8,5	(14,2)	6,5	(11,2)	939,6	(1163,4)	-0,37	(0,10)	1,14	(0,010)
		0.1-0.2	27,0	(9,6)	9,6	(4,3)	5,9	(2,9)	20,6	(3,4)	-0,33	(0,01)	1,16	(0,000)
	PAP	0-0.05	33,4	(9,5)	11,9	(5,2)	8,0	(4,9)	38,6	(50,0)	-0,31	(0,07)	1,15	(0,005)
		0.05-0.1	28,9	(4,6)	10,7	(10,4)	7,9	(10,0)	54,5	(57,5)	-0,32	(0,10)	1,15	(0,004)
		0.1-0.2	53,9	(0,1)	15,6	(1,3)	8,6	(1,0)	28,8	(4,1)	-0,34	(0,01)	1,15	(0,001)
Hapludert (Santiago Series)	NE	0-0.05	125,0	(31,3	58,2	(28,2)	40,9	(24,1)	14,6	(8,8)	-0,30	(0,04)	1,16	(0,001)
		0.05-0.1	173,5	(97,1)	22,9	(26,7)	13,8	(19,0)	9024,4	(15525,8)	-0,38	(0,08)	1,14	(0,020)
		0.1-0.2	105,1	(31,0)	19,0	(25,2)	10,5	(15,4)	218233	(37799,4)	-0,40	(0,07)	1,13	(0,030)
	GAP	0-0.05	99,8	(22,6)	11,1	(11,9)	5,0	(6,6)	1058,0	(1629,1)	-0,40	(0,04)	1,14	(0,010)
		0.05-0.1	44,2	(15,4)	1,6	(2,6)	0,5	(0,9)	30937,4	(27020,3)	-0,44	(0,03)	1,13	(0,020)
		0.1-0.2	85,8	(58,3)	10,1	(9,2)	4,1	(3,6)	9891,8	(16981,3)	-0,40	(0,04)	1,14	(0,020)
	PAP	0-0.05	67,6	(21,8)	8,2	(9,5)	3,6	(4,6)	3353,1	(5624,2)	-0,41	(0,04)	1,14	(0,020)
		0.05-0.1	46,9	(15,9)	3,2	(5,0)	1,3	(2,1)	24730,8	(38014,6)	-0,43	(0,04)	1,13	(0,020)
		0.1-0.2	37,3	1(8,7)	0,0	(0,0)	0,0	(0,0)	138560	(1184274)	-0,46	(0,00)	1,11	(0,002)
Optimal range	Reynolds et al. 2002		60 -140		3-7		0,7 - 2		400 - 1000		- 0,43 to - 0,41		1,13 - 1,14	
	This paper (0-5 cm NE)		71 - 227		7.8 - 58		4.6 - 40.9		14.6 - 5779		-0.30 to -0.41		1.13-1.16	

98.1%, followed by $P_{Mac>50\ \mu m}$ and $P_{Mac>1000\ \mu m}$. On the contrary D_{median}, D_{mean} and Skewness showed a balanced proportion of management factor and soil type. In turn, SD showed an important variance attributable to residual factor (Fig. 1).

Regarding the pore sizes, $P_{Mac>1000\ \mu m}$ and the $P_{Mac>300\ \mu m}$ presented a very similar behaviour in the first two layers (0–0.05 and 0.05–0.10 m). For $P_{Mac>300\ \mu m}$ the observed trend was: NE > GAP > PAP with statistical differences between NE and GAP respect to PAP and NE and the agricultural treatments, respectively (Fig. 2a). However, it can be considered that $P_{Mac>300\ \mu m}$ was slightly more effective to discriminate between treatments, since it had a slightly lower AIC (Akaike information criterion) (26.2 and 19.3) for the first and second layer, respectively, compared to $P_{Mac>1000\ \mu m}$ (41.7, 44.3). The ranges found in the literature for $P_{Mac>\ 300\ \mu m}$ indicate that the NE values for the two most superficial depths strata are located within optimal ranges, while the rest of values for all treatments/depths, with the exception of GAP at 0–0.05 m, were in the range of compacted or degraded soil (Carter, 1988; Drewry et al., 2001; Drewry and Paton, 2005; Reynolds et al., 2009).

$P_{Mac>50\ \mu m}$ and $P_{Mic<50\ \mu m}$ showed an important effect of soil type and trends of both variables must be analysed for each one of them. For the case of Mollisols, the highest $P_{Mac>50\ \mu m}$ was shown by the NE treatment. For the Haplustoll and the Argiudoll (Monte Buey), GAP showed higher values than PAP with statistical significance in the latter. In the Argiudoll (Pergamino) no statistical differences were found. In the Vertisol NE showed similar values that GAP (Fig. 3a). Regardless of soil type, the values for the first two layers presented the following trend NE > GAP > PAP (Fig. 3c). As expected, $P_{Mic<50\ \mu m}$ was higher in the Vertisol, while in most soils GAP showed higher microporosity values compared to PAP (Fig. 3b).

Most frequent pore size (D_{mode}) could be modelled grouping all soils types. For the upper layers (0 to 0.10 m) the trend observed was NE > GAP > PAP. However statistical differences were only detected between NE and the agricultural treatments (Fig. 2b). Also, in agricultural treatments D_{mode} values tend to decrease from 0 to 0.5 to 0.5–0.10 m and raise again at 0.10–0.20 m depth. According to the optimum range proposed by Reynolds et al. (2002) (60–140 µm), PAP values fall below that range at all depths. GAP values in the surface layer are located in the lower threshold, falling below this threshold at 0.5–0.10 m depth. At the deepest layer, GAP presented optimum values although a high variability (Fig. 2b, Table 3).

For the rest of location and shape parameters the analysis considered

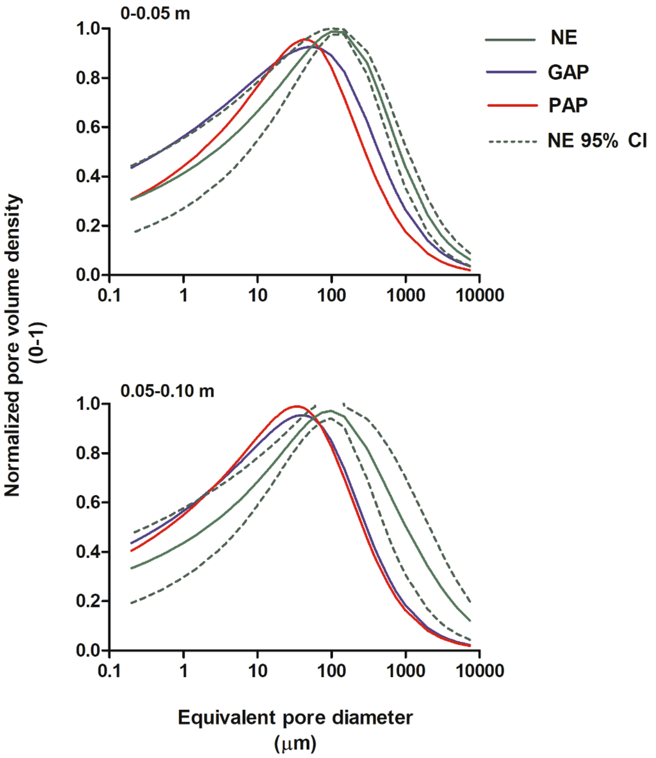

Fig. 4. Pore volume density distribution (normalized) according to equivalent pore diameter for Natural Environment (NE), Good Agricultural Practices (GAP) and Poor Agricultural Practices (PAP) for each depth (0–0.05 and 0.05–0.10 m). CI: Confidence interval for NE curve.

soil type factor (Table 2). Overall D_{median} and D_{mean} presented similar behaviour compared to D_{mode} (Table 3). Haplustoll and Argiudoll (Monte Buey Series) showed lower SD values compared to finer textured soils: Argiudoll (Pergamino Series) and Hapludert. SD in some treatments of these soils showed values that exceeded two folds the highest threshold proposed by Reynolds et al. (2002) (Table 3). No clear information regarding managements was provided by Skewness and Kurtosis.

As summary, from the values obtained it was possible to build a single pore volume density curve for each treatment and depth regardless of the soil type (Fig. 4). All curves discriminated by soil type and management can be found in Suppl. Fig. 1. Optimum range represented here by the NE treatment showed a small confidence interval at pore diameters higher that the D_{mode} and the inverse at smaller pores diameters. Even when, within NE curve, the only significant statistical parameter is D_{mode} (Table 2), this curve can be used as an ideal one allowing the comparison of pore sizes between the studied treatments. It must be noted that D_{mode} is higher in the uppermost layer of NE than in the agricultural treatments. Most of the curves presented a strong and negative skewness (<-0.30), Kurtosis ranged to lognormal distribution (Kurtosis close to 1) and therefore curves showed mesokurtic to slightly leptokurtic shapes. Compared to GAP, NE curve showed higher negative asymmetry values with less pore frequency in small pore sizes. At 0.05–0.10 m depth, in the curve region < D_{mode} kurtosis values were lower for GAP and PAP than for NE, thus evidencing a higher frequency of small pores in the agricultural treatments than in the reference plots (Fig. 4).

3.2. Relationship between pore size distribution and pore volume density variables with management variables, soil characteristics, aggregate stability and organic carbon fractions

3.2.1. Management variables

Overall, most significant correlations were found at 0–0.05 m depth followed by 0.05–0.10 and 0.10–0.20 m depths. Both $P_{Mac>300}$ μm, $P_{Mac>1000}$ μm showed numerous and strong correlations with managements variables mostly at the shallowest depths (Table 4). For instance, high and positive correlation coefficients were found between $P_{Mac>300}$ μm and $P_{Mac>1000}$ μm with CI_{all} (Fig. 5a, b). If NE is not considered (CI_{agr}), these coefficients decrease though it remains significant for large pores. These correlations increase their coefficient at 0.05–0.10 m depth. Also, the relationship between pore size distribution and cropping intensity is stronger when only Mollisols are evaluated (Table 4, Fig. 5c, d).

On the contrary, a negative relationship was found between large pore sizes and management variables reflecting the relative increment of soybean in the crops sequence or its exclusivity (Soybean/Crops; Soybean/Maize and Soybean as only crop). In this case, no large differences were found between the two data sets assessed (Mollisols and Mollisols + Vertisol). These relationships are mainly found at the topsoil with determination coefficients slightly higher for $P_{Mac>300}$ μm respect to $P_{Mac>1000}$ μm. Considering for instance the Soybean/Crops variable, in all soils the volume of these large pores decrease as the proportion of soybean in the crop sequence increase.

For curve location and shape parameters, strong correlations were found between CI_{all} and CI_{agr} and Years under NT (Table 4, Fig. 5e,f). Conversely, crop composition variables did not show important influence on volume density variables. Among all pore density variables, D_{mode} accounted for the greatest number of significant correlations (Table 4) with higher coefficients mainly at 0.05–0.10 m depth (Table 4). This variable showed a positive relationship with CI_{all}, CI_{agr} and Years under NT. The effect of CI_{all} could be modelled with both soil orders (Mollisols and Vertisol) (Fig. 5f). In turn the relationship between Years under NT and D_{mode} was affected by soil type differences. With higher number of years under no-tillage higher D_{mode} values were found, while no effects of this management variable were detected in the Vertisol (Fig. 5f). When the whole depth was considered (0.0–0.20 m), D_{median} and D_{mean} also showed positive correlations with Years under NT but weaker. The rest of the variables were little affected by management variables (Table 4).

3.2.2. Soil characteristics, aggregate stability and organic carbon fractions

Soil characteristics had less effect on all variables measured compared to managements practices. However, the direct relationship between clay content and microporosity ($P_{Mic<50\ \mu m}$) considering all soils, and the negative effect of silt in all pores larger than 50 μm (Table 5a) appears clearly. Calcium content presented a positive effect on all pore sizes (Table 5a). Location variables were poorly related with soil chemical and physical characteristics (Table 5b). On the contrary several correlations were detected between curves shape parameters and soil characteristics. SD for Mollisols + Vertisol was positively correlated with clay content, Atteberǵs limits and smectite + smectite/illite (Table 5b). Skewness and Kurtosis also showed numerous but weak correlations (Table 5b).

At variance with inherent soil characteristics, variables related with management such as organic carbon fractions and aggregates stability showed close relationship with pores properties (Table 5a,b). Pores larger than 50 μm presented high correlation coefficients with POC_c and POC_f. These coefficients were higher for $P_{Mac\ >300}$ and all correlations increase if only Mollisols dataset are considered (Table 5a). The relationships obtained between the porosity parameters and the organic carbon fractions were different according to the soil order. This is reflected in Fig. 6a were a positive relationship is detected between POCc and $P_{Mac>300\ \mu m}$ for the Mollisols but no relationship was found for the Vertisol. Total organic carbon only showed some influence on $P_{Mic<50\ \mu m}$ when all dataset was considered. In turn, aggregates stability tests showed high correlation coefficients with different pore sizes (Table 5a). The highest correlation coefficients were found between slaking tests (FW and FW_{10s}) and macroporosity (Table 5a). The stronger associations between both variables were evidenced for pores larger than 300 μm in

Table 4

Pearson correlations between pore size distribution and pore volume density variables and management variables. * $P < 0.05$; ** $P < 0.01$; *** $P < 0.001$. CI_{agr}: Crop sequence intensification index: relationship between number of months occupied by each crop and total number of months cropped during the study period; CI_{all}: CI_{agr} plus NE. Years under NT: number of years under no tillage; Soybean/Crops and Maize/Crops: number of soybean or maize crops in relation to total crops during the study period; Soybean/Maize: number of soybean crops related to maize crops (soybean/maize), Soybean as only crop: number of soybean crops as the only crop in the year. $P_{Mac>1000\ \mu m}$: macroporosity > 1000 µm, $P_{Mac>300\ \mu m}$: macroporosity > 300 µm, $P_{Mac>50\ \mu m}$: macroporosity > 50 µm, $P_{Mic<50\ \mu m}$: microporosity < 50 µm, D_{mode}, D_{media} and D_{mean}: pore diameter for the more frequent, median and mean size, respectively, SE: standard deviation of pore size, Skewness and Kurtosis.

	CI		**CI_{agr}**		**Years under no till**		**Soybean/Crops**		**Soybean/Maize**		**Maize/Crops**		**Soybean as only crop**	
	Mollisols + Vertisol	*Mollisols*	*Mollisols + Vertisol*	*Mollisols*	*Mollisols + Vertisol*	*Mollisols*	*Mollisols + Vertisol*	*Mollisols*	*Mollisols + Vertisol*	*Mollisols*	*Mollisols + Vertisol*	*Mollisols*	*Mollisols + Vertisol*	*Mollisols*
0–0.05 m														
$P_{Mac >1000\ \mu m}$	0.61 ***	0.80 ***	0.47 *	0.56 *			−0.58 **	−0.60 **	−0.62 **	−0.51 *	0.50 *		−0.51 *	−0.60 **
$P_{Mac >300\ \mu m}$	0.64 ***	0.81 ***	0.50 *	0.60 **		0.59 *	−0.61 **	−0.60 **	−0.64 ***	−0.55 *	0.46 *		−0.55 **	−0.60 **
$P_{Mac >50\ \mu m}$	0.41 *	0.52 **			0.45 *	0.53 *	−0.40 *							
$P_{Mic<50\ \mu m}$			0.43 *				−0.45 *		−0.55 **	−0.59 *	0.42 *	0.51 *	−0.41 *	
D_{mode}	0.55 ***	0.60 ***			0.47 *	0.63 ***								
D_{median}														
D_{mean}														
SD		0.42 *							−0.50 *					
Kurtosis									0.47 *	0.55 *	−0.50 *	−0.50 *		
Skewness		−0.40 *												
0.05–0.10 m														
$P_{Mac >1000\ \mu m}$	0.74 ***	0.74 ***	0.66 ***	0.50 *			−0.46 *						−0.41 *	
$P_{Mac >300\ \mu m}$	0.68 ***	0.79 ***	0.72 ***	0.55 *			−0.43 *							
$P_{Mac >50\ \mu m}$	0.73 ***	0.74 ***	0.50 *	0.50 *										
$P_{Mic<50\ \mu m}$														
D_{mode}	0.76 ***	0.75 ***			0.58 **	0.72 ***								
D_{median}						0.48 *								
D_{mean}														
SD														
Kurtosis														
Skewness														
0.10–0.20 m														
$P_{Mac >1000\ \mu m}$														
$P_{Mac >300\ \mu m}$														
$P_{Mac >50\ \mu m}$			0.43 *											
$P_{Mic<50\ \mu m}$						−0.48 *								
D_{mode}					0.51 *	0.50 *								
D_{median}		−0.40 *			0.46 *	0.58 *								
D_{mean}		−0.40 *			0.44 *	0.58 *								
SD		0.47 *												
Kurtosis		−0.70 ***		−0.50 *										
Skewness					0.55 **	0.60 **				−0.60 *		0.55 *		
0–0.20 m														
$P_{Mac >1000\ \mu m}$	0.48 ***	0.64 ***		0.57 *		0.52 *	−0.45 *	−0.50 *	−0.44 *					−0.50 *
$P_{Mac >300\ \mu m}$	0.58 ***	0.67 ***	0.51 *	0.57 *	0.41 *	0.55 *	−0.51 *	−0.50 *					−0.46 *	−0.50 *
$P_{Mac >50\ \mu m}$	0.55 ***	0.64 ***	0.50 *	0.50 *										
$P_{Mic<50\ \mu m}$														
D_{mode}	0.61 ***	0.59 **			0.56 ***	0.62 **								
D_{median}					0.58 ***	0.59 *								
D_{mean}					0.54 ***	0.55 *								
SD		0.52 **							−0.50 ***	−0.50 *	0.51 *			
Kurtosis		−0.60 **		−0.40 *					0.52 *		−0.50 *			
Skewness					0.41 *									

Mollisols (Fig. 6b).

Among location variables only D_{mode} showed strong relationship with organic carbon fractions, particularly with POCc (Table 5b). This relationship was stronger for Mollisols compared to complete dataset (Mollisols + Vertisol) (Fig. 6c). Curves shape parameters were also correlated with the more stable organic carbon fractions (i.e. TOC and MOC). Nevertheless, the relationships between shape parameters and organic carbon fractions were rather weak. For its part, aggregates stability tests presented strong and positive correlations only with D_{mode} and SD (Table 5b). All tests presented similar correlations coefficients with the exception of Stir test that presented lower values. These relationships were similar for Mollisols and Mollisols + Vertisol as it showed in Fig. 6d.

4. Discussion

In a first approximation, most of the porosity variables evaluated could be considered related to the type of soil. However, in the present study $P_{Mac>300\ \mu m}$ and D_{mode} did not show any interaction with soil types and thus they become interesting to evaluate health status of surface horizons regardless of soil type. Although, it must be considered that the absence of soil type * management interaction, did not underestimate the different climatic and soil water regime, among other factors expressed in each location. Nevertheless, for these variables, this approach is also supported by the high variance components attributable to management factor (96.1% and 98.7% for $P_{Mac>300\ \mu m}$ and D_{mode}, respectively) (Fig. 1) and by the close relationship among these variables with the labile organic carbon fraction (POCc) and with the aggregates stability tests (Table 4). These results coincide with other studies obtained in Pampean soils that have shown the high sensitivity of POCc and aggregates stability to account for fast changes of agricultural managements (Duval et al. 2013; Behrends Kraemer et al., 2021).

Furthermore, the comparison of the values here obtained for $P_{Mac>300\ \mu m}$ with the threshold values reported in the literature, highlights the interest of this variable. For instance, in this study and for all depths considered, PAP showed values below the critical threshold reported (0.04 $m^3\ m^{-3}$) (Carter, 1988; Drewry et al., 2001; Reynolds et al., 2002; Drewry and Paton, 2005). This pore size is large enough to be affected by management variables as crop sequence and machinery transit, and it would not have an erratic behaviour as can occur with larger pore sizes (*i.e.* $P_{Mac>1000\ \mu m}$) as a result of the formation of cracks or the fortuitous presence of fauna galleries. Moreover, the high variability detected for $P_{Mac>1000\ \mu m\text{-}}$, even with a good replication as used here (n: 12), suggest a need for a larger elementary volume (REV) to confidently include this porosity size.

In this study, and coincidentally with other works (Reynolds et al., 2002; Ferreras et al., 2007) agricultural treatments showed lower porosity compared to NE, mostly reflected in the values obtained for larger pores ($P_{Mac>300\ \mu m,\ >1000\ \mu m}$). Considering specifically agricultural treatments, GAP presented higher proportion of large pores ($P_{Mac>300\ \mu m}$) than PAP, which in turn is highly correlated with CI. Several authors have found better soil health under NT in treatments with higher CI (Caviglia and Andrade, 2010; Novelli et al., 2011, 2013). A higher number and diversity of crops along a crop sequence increases volume and diversity of roots, and hence organic carbon increases, promoting better soil structures and higher aggregate stability (Novelli et al., 2011; Behrends Kraemer et al., 2019; Sasal et al., 2017). Also, crop composition variables, particularly soybean/crops ratio could fairly predict porosity differences between evaluated plots.

However, a greater intensity of cultivation does not always result in beneficial effects for the soil (Wilson et al., 2010) and some examples can be found also in this study. The lack of generalized beneficial effects of CI may be explained here by the characteristics of the clay of one of the soils under study, and by the increased machinery traffic related to higher CI. Regarding the clay effect, in this study it was evident that strong relationship between pore sizes and CI was detected only in Mollisols (illitic clays). In contrast, in the Vertisol (smectite clays) aggregation and stabilizing mechanisms relies mostly on clay content and mineralogy type (Oades, 1993), thus reducing the effect of management and organic carbon fractions on pores features. Similar results were reported by Behrends Kraemer et al. (2019) and Novelli et al. (2011, 2013) on soils under NT in the same region. In those studies, the effects of organic carbon and soil hydrophobicity on aggregates stability were highly related to CI in Mollisols and low related with Vertisols.

As mentioned before, stronger effects of management treatments were found at the topsoil layer. For instance, at 0.05 m soil depth macroporosity expressed by $P_{Mac>300\ \mu m}$ shows the trend NE > GAP > PAP, thus allowing a clear discrimination between managements (Fig. 2a). At 0.05–0.10 depth, $P_{Mac>300\ \mu m}$ was similar in both agricultural treatments, falling below the optimum range proposed by Reynolds et al. (2009), a fact often described under NT. De Battista et al. (2005) found massive structures with low visible porosity at 0.03–0.10 m under this system. Similarly, Ferreras et al. (2007) reported densified layers at 0.07–0.14 m depth in Argiudolls under NT. Wander and Bollero (1999) describe structural and organic matter stratification under NT due to crop residue accumulation in the topsoil and absence of tillage. With increasing depth, organic carbon declines and lack of soil remotion can lead to porosity loss. This process is accentuated in silty soils, due to their lower expansion and contraction and lower ability to regenerate soil structure (Taboada et al., 2008).

In this study, the employment of pore volume density variables allowed to obtain porosity curves for different and representative soils of the Pampean Region. The optimum range for each curve parameter were similar to the ranges provided by Reynolds et al. (2002) and Castellini et al (2013), suggesting the existence of porosity ranges that favours most of soil physical processes (i.e. water dynamics, aeration). In this sense, by using this optimal curve methodology, Castellini et al. (2013) were able to discriminate between NT and conventional tillage treatments while Shahab et al. (2013) could relate D_{mode} with soil groups with contrasting soil quality. Similarly, in the present study, $P_{Mac>300\ \mu m}$ and D_{mode} have been found useful to detect changes in cropping intensity and years under no tillage (Table 4, Fig. 3). Both management variables are crucial in intensification schemes employed by farmers in the Pampean region and also seem adequate to evaluate the transition of traditional extractive agriculture to agroecological systems.

Porosity ranging from D_{mode} up to large equivalent pore diameters shows a narrow confidence interval, thus appearing suitable to predict favourable soil quality properties. On the contrary, the interval confidence below D_{mode} is wider, reflecting the effect of soil type (texture and clay mineralogy) and thus the use of D_{mean} and D_{median} appear less sound as descriptors of soil porosity.

In turn, SD values obtained in this study were several orders of magnitude higher than the optimal ranges found in the literature (Reynolds et al., 2009; Shahab et al., 2013; Castellini et al., 2013) (Table 4). Soil structural heterogeneity of plots under NT reported by several studies (Morrás et al., 2012, 2017; Behrends Kraemer and Morrás, 2018; Álvarez et al., 2014) may be responsible for these findings, as this heterogeneity is traduced in pore size scattering. Also, inadequate soil REV could enhance this variability. However, and adding to the heterogeneities resulting from cultivation, the four soils included in this work differ on their texture and Mollisols differ from the Vertisols on their mineralogy, both properties surely influencing the development of specific structural features in each soil. This is evidenced in this study by the high SD values obtained by the uncultivated reference plots (NE), where the intrinsic soil characteristics are freely expressed.

5. Summary and conclusions

The effects of good agricultural practices (GAP) and poor agricultural practices (PAP) on soil porosity features were evaluated in the topsoil of three Mollisols and one Vertisol from the Pampean region of Argentina.

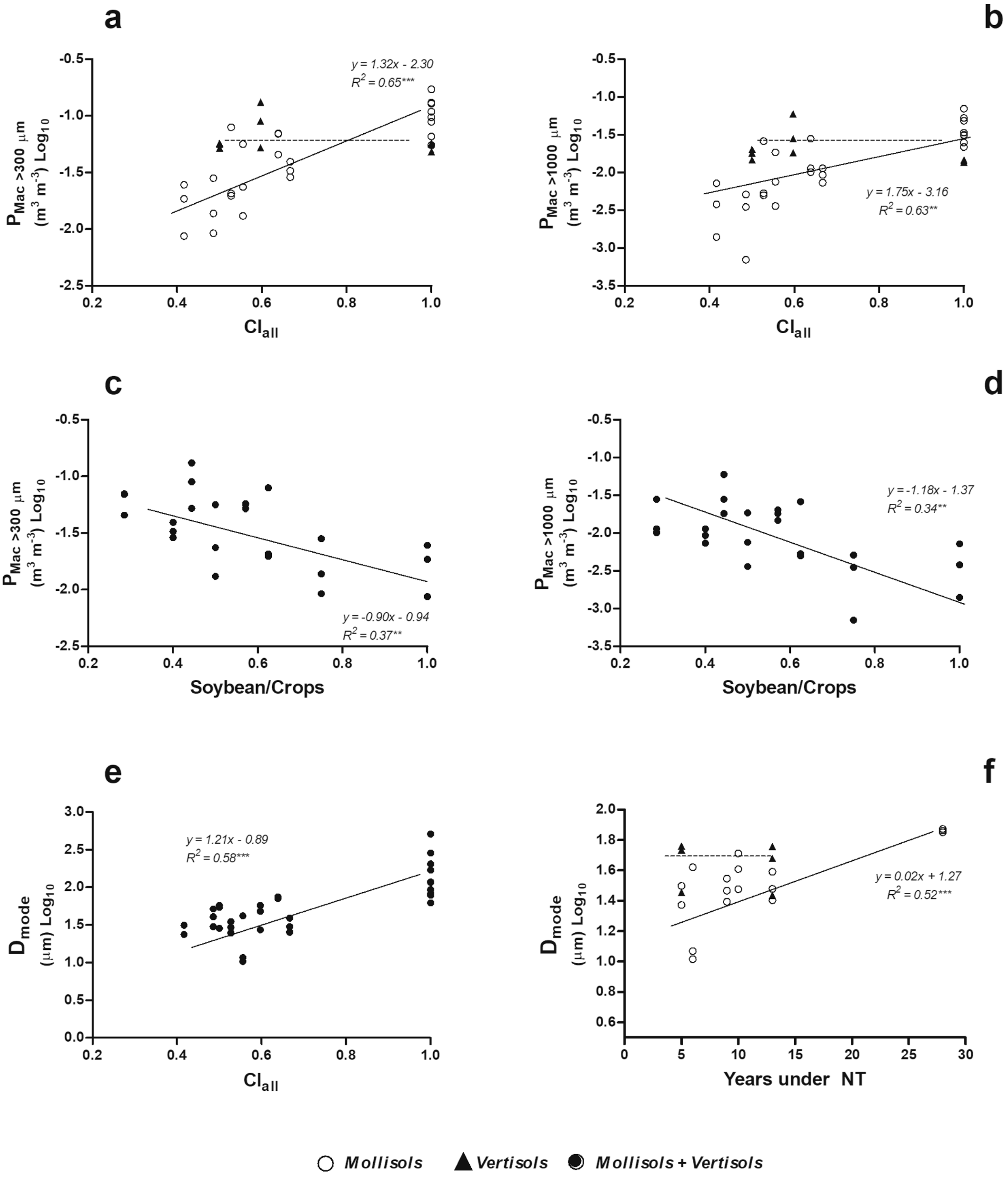

Fig. 5. Linear regressions between CI_{all} and $P_{Mac>300}$ (a) and $P_{Mac>1000}$ (b), Soybean/Crops and $P_{Mac>300}$ (c) and $P_{Mac>1000}$ (d) and D_{mode} and CI_{all} (e) and Years under NT (f). All regressions were performed considering 0–0.20 m depth. * $p < 0.05$, ** $p < 0.01$, ***$p < 0.001$. Full and dotted regression line correspond to Mollisols and Vertisol, respectively. $P_{Mac\ >1000}$: macroporosity > 1000 μm, $P_{Mac\ >300}$: macroporosity > 300 μm, D_{mode}: more frequent pore diameter size.

Pore volume density functions and pores size distribution derived from soil water retention curves were related to management variables and to soil properties allowing: i) evaluate the effects of cropping intensification on soil physical properties; ii) evaluate the effects of soils intrinsic and dynamics factors on the behaviour of pore variables; iii) build an optimal pores size frequency curve to assess the health of the soils here evaluated.

Among all porosity features assessed, $P_{Mac>300\ \mu m}$ and D_{mode} showed close relationships with agricultural management variables and were positively related to a labile organic carbon fraction (POCc) and to aggregates stability tests, regardless of the soil type (with low interaction with intrinsic variables). Thus, they both may be selected as sound indicators of health status for different pampean soils under NT cultivation. In this regard, pores represented by $P_{Mac>300\ \mu m}$ are large enough to be affected by the crop sequence employed and by the intensity of machinery transit, thus reflecting the type of agricultural management performed. Particularly, in the PAP treatments and for the three depths evaluated, $P_{Mac>300\ \mu m}$ showed values below the critical threshold reported in the literature (0.04 $m^3\ m^{-3}$) highlighting the physical deterioration of soils subjected to this management. Regarding the indexes

Table 5

Pearson correlations between pore size distribution (a) and pore volume density variables (b) at 0-0.20 m depth, with soil characteristics, organic carbon fractions and aggregate stability tests. Correlation coefficients are presented for all soils dataset (Mollisols + Vertisol) and for reduced dataset (Mollisols). * P<0.05; ** P<0.01; *** P<0.001. TOC: total organic carbon, POCc: Coarse particulate organic carbon, POCf: Fine particulate organic carbon, MOC: Mineralizable organic carbon, FW_{10s}: Fast wetting (10 s), FW: Fast wetting, Stir, SW: Slow wetting and AS_{mean} (FW, Stir and SW average). $P_{Mac >1000\ \mu m}$: macroporosity >1000 µm, $P_{Mac >300\ \mu m}$: macroporosity >300 µm, $P_{Mac >50\ \mu m}$: macroporosity >50 µm, $P_{Mac <50\ \mu m}$: microporosity <50 µm, D_{mode}, D_{media} and D_{mean}: pore diameter for the more frequent, median and mean size, respectively, SE: standard deviation of pore size, Skewness and Kurtosis.

a)

	$P_{Mac >1000\ \mu m}$		$P_{Mac >300\ \mu m}$		$P_{Mac >50\ \mu m}$		$P_{Mic<50\ \mu m}$	
	Mollisols + Vertisol	Mollisols	Mollisols + Vertisol	Mollisols	Mollisols + Vertisol	Mollisols	Mollisols + Vertisol	Mollisols
Soil characteristics								
Clay							0.62 ***	
Silt		-0.39 *	-0.34 *	-0.41 *	-0.52 **	-0.55 **		
Sand					0.38 *	0.52 *	-0.33 *	
EC						0.08	0.53 ***	
pH								
EH	0.46 **	0.40 *	0.46 **	0.41 *			0.61 ***	
Pl							0.52 **	
Ll	0.37 *						0.65 ***	
Pi	0.42 *		0.36 *				0.64 ***	
Ca^{+2}	0.60 ***	0.61 ***	0.59 ***	0.58 **	0.33 *	0.41 *	0.45 **	
S+S/I	0.41 *		0.35 *			0.51 *	0.58 ***	
Organic carbon fractions								
TOC							0.60 ***	
POCc	0.39 *	0.60 **	0.38 *	0.64 ***		0.62 ***	0.51 **	
POC_f	0.43 **	0.62 ***	0.47 **	0.63 ***		0.48 *	0.60 ***	
MOC							0.54 ***	
Aggregate stability								
SW10s	0.58 ***	0.75 ***	0.66 ***	0.77 ***	0.59 ***	0.69 ***		
FW	0.61 ***	0.75 ***	0.69 ***	0.76 ***	0.64 ***	0.73 ***		
Stir				0.39 *				
SW	0.49 **	0.71 ***	0.69 ***	0.75 ***	0.58 ***	0.69 ***		
ASmean	0.49 **	0.71 ***	0.60 ***	0.73 ***	0.54 ***	0.63 ***		

b)

	D_{mode}		D_{median}		D_{mean}		SD		Skewness		Kurtosis	
	Mollisols + Vertisol	Mollisols	Mollisols + Vertisol	Mollisols	Mollisols + Vertisol	Mollisols	Mollisols + Vertisol	Mollisols	Mollisols +Vertisol	Mollisols	Mollisols + Vertisol	Mollisols
Soil characteristics												
Clay							0.58 ***				-0.45 **	
Silt										0.44 *		
Sand							-0.50 *			-0.40 *	0.34 *	
EC							0.47 **					
pH												
EH	0.44 *	0.49 **					0.48 **				-0.33 *	
Pl							0.37 *					
Ll							0.58 ***	0.47 *			-0.45 *	-0.43 *
Pi							0.62 ***	0.57 **	-0.30 *		-0.48 **	-0.54 **
Ca^{+2}	0.42 *	0.39 *					0.51 **	0.42 *	-0.50 **	-0.50 *	-0.43 **	-0.42 *
S+S/I							0.46 *					
Organic carbon fractions												
TOC							0.43 **	0.43 *			-0.36 *	-0.40 *
TOCc	0.36 *	0.61 ***					0.38 *	0.46 *				-0.53 **
POC_f	0.39 *	0.59 **										
MOC							0.44 **			0.38 *	-0.37 *	
Aggregate stability												
SW10s	0.60 ***	0.63 ***						0.44 *		-0.40 *		-0.50 **
FW	0.60 ***	0.60 ***						0.41 *		-0.50 *		-0.46 *
Stir	0.34 *	0.55 **						0.46 *				-0.44 *
SW	0.60 ***	0.63 ***						0.42 *				-0.46 *
ASmean	0.61 ***	0.69 ***						0.49 **				-0.52 **

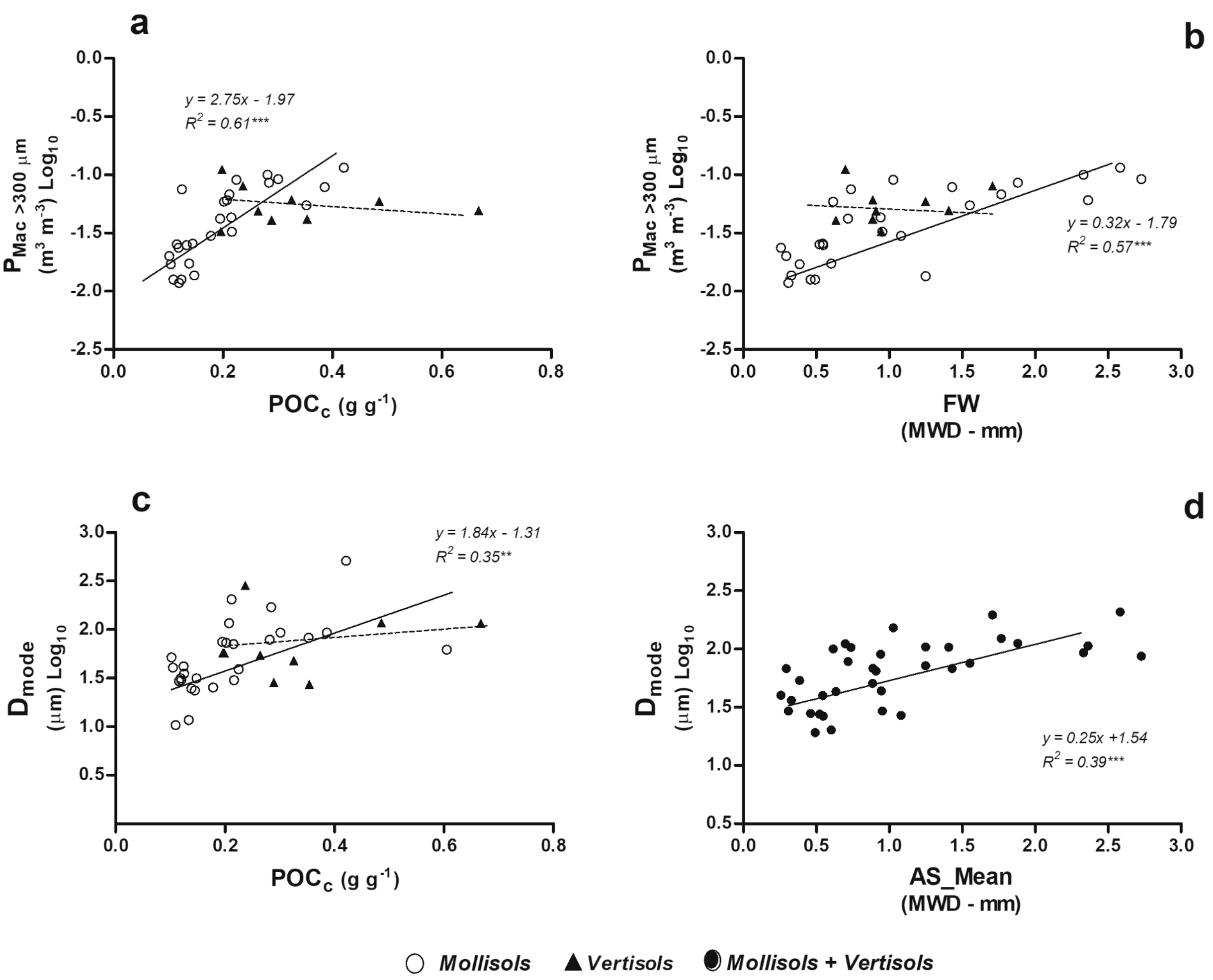

Fig. 6. Linear regressions between a) $P_{Mac>300}$ and POC_c, b) $P_{Mac>300}$ and FW, c) D_{mode} and POC_c and d) D_{mode} and $AS_{\_Mean}$. All regressions were performed considering 0–0.20 m depth. * $P < 0.05$, ** $P < 0.01$, *** $P < 0.001$. Full and dotted regression line correspond to Mollisols and Vertisol respectively. $P_{Mac\ >300}$: macroporosity > 300 µm, D_{mode}: more frequent pore diameter size, POCc: Coarse particulate organic carbon, FW: Fast wetting test and $AS_{\_Mean}$: Average of aggregate stability tests (FW, Stir and SW).

used to evaluate the effects of cropping intensification, CI_{all} and CI_{agr} obtained the highest coefficients and thus appeared as the more usefuls, revealing strong positive effects on porosity variables at the topsoil. These results demonstrate that crop intensification was effective to counteract compaction processes in a variety of soils of the Pampa region and must be seen as an important strategy to avoid porosity loss and to improve the benefits of no-tillage.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.geoderma.2021.115398.

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