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Organic carbon stored in soils under different land uses and soil textures in southeast Argentinean Mesopotamia

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ABSTRACT

Soil use affects soil organic carbon (OC) stocks by regulating the quantity and quality of incorporated organic matter. Understanding how soil texture and other factors control OC concentration and accumulation would be useful for designing sustainable soil management practices in order to promote and preserve OC storage. The aim of this work was to evaluate the effects of land use and soil texture on the vertical distribution and stock of OC in soils of the Argentinean Mesopotamia. In Entre Ríos Province, Argentina, the following sites were selected: native forest in a Typic Halacuept soil (fine to medium texture), agriculture and *Eucalyptus grandis* plantations of different ages (2–4 and 8–10 years) in Argic Peluderts soils (fine textures) and *E. grandis* plantations of different ages (2–4 and 8–10 years) in Oxic Udifluvents soils (coarse textures). OC concentration and stock were quantified up to 1 m depth, analysing distribution across the depth of the soil profile. The major differences in OC stock in equivalent mass were associated with texture; the average for coarse Oxic Udifluvents soils was 57.2 Mg OC ha^{-1} and 162.3 Mg OC ha^{-1} for Typic Halacuept and Argic Peluderts (fine to medium textures). Forest sites with fine textures stored three times more OC in equivalent mass than coarse textures under similar land use. No significant differences were observed between OC stock in equivalent mass in agricultural versus *Eucalyptus* plantations of similar texture. Sites with 8–10-year-old forest plantations in coarse soils were a special case, as they presented a great proportion of OC (60%) under 40 cm depth, due to a strong textural gradient with depth.

1. Introduction

Soil organic carbon (OC) is a key factor in soil quality and health, positively affecting crop production and biological edaphic activity (Schjønning et al., 2018). Global estimations have reported soil to be the principal OC reservoir, storing at least twice the carbon contained in the atmosphere and live vegetation together (Lal, 2004), thus, even a minor change in OC content could have a relevant impact on the global C balance (Schmidt et al., 2011). Soil can be a source or sink of atmospheric CO_2, according to how it is managed (Janzen, 2004), storing almost 1500 Pg of C as OC in the first meter depth, half of which is contained in the first 30 cm (Batjes, 1996).

Complex interactions between edaphic and climatic factors regulate the processes by which C enters and exits soil (Minasny et al., 2013; Cai et al., 2016). At a regional scale, the climatic factors precipitation and temperature regulate OC storage in the soil (Hobley et al., 2015; Gray et al., 2016; Cook et al., 2016). Considering a local scale, OC quantity is mainly determined by the soil parent material, topography, and texture (Schmidt et al., 2011; Gray et al., 2016; Cai et al., 2016; Cook et al., 2016). Soil use, in turn, through the type of vegetation and the quality and quantity of organic matter inputs, affects OC reserves, and OC stability depending on the management adopted in the area (Lal, 2018; Signor et al., 2018; Wiesmeier et al., 2019). OC levels fall rapidly when natural ecosystems such as forests or grasslands are converted into cultivated land (Fusaro et al., 2019; Andrade et al., 2020).

Soil texture is a key factor controlling C dynamics due to the physical protection of clay particles (Oades, 1988). When native grasslands are replaced by forest plantations, fine textured soils exhibit a high potential to accumulate C, whereas coarse textures might not show any effect (Laganière et al., 2010; Fialho and Zinn, 2014; Cook et al., 2016) or even

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a loss of C (Zinn et al., 2002). Understanding how texture and other factors control OC concentration and accumulation will be of help in designing sustainable soil management practices, with the objective of promoting and preserving OC storage, which is of particular relevance to mitigate the effects of global warming (IPCC, 2014). Changes in land use could produce, in turn, modifications in the quantity and composition of OC (Cramer et al., 2001; Berthelot et al., 2002; Schulp et al., 2008), highlighting the importance of monitoring the reserves of OC, since inventories at different scales are necessary information for decision making in the environmental and productive politicy areas (Lal, 2004; Paustian et al., 2016).

In the southeast (SE) sector of the Argentine Mesopotamia region, featuring soils with great textural variability, a variety of land uses can be observed. Forest plantations of *Eucalyptus grandis* have replaced native grasslands (Jobbágy et al., 2006), being barely characterised in terms of OC storage capacity. Despite the global recognition of forest systems in terms of C capture, it must be considered that a critical period exists during the stage of establishment of the plantation, from the harvest of the previous plantation to the closing of the canopy in the new one. During that period soil can undergo practices such as tillage or burning which could generate important losses in OC (Powers et al., 2009; Sandoval López et al., 2018), that might not be reverted with the growth of the forest stand (Eclesia et al., 2012). Therefore, examining the role and potential of these ecosystems for OC capture capacity is essential for decisions concerning soil use and management, aiming at the mitigation of climatic change. The objective of this work was to evaluate the effect of soil use and texture on OC distribution and stock in soils of the Mesopotamia region of Argentina, under the following scenarios: native forest and agriculture in fine textured soils, forest plantations of different ages (2–4 years and 8–10 years) in coarse and fine textured soils.

2. Materials and methods

2.1. Study area

The study was carried out in Gualeguaychú, located in the SE of Entre Ríos Province, in the Mesopotamia Region of Argentina (33°1′17S; 58°13′37W). The predominant climate is humid temperate. Mean annual temperature is 18 °C, with an average of 11 °C in the coldest month (July) and 26 °C in the warmest (January). Average annual rainfall in the region is 1136 mm, concentrated in spring and summer (Forte Lay et al., 2008). The predominant landscape of this region is the rolling Peniplanicies, which originated from Pampean secondary sediments. It is covered by materials of aeolian origin of moderate to thin thickness. The Peniplanices present moderately (2–4%) and less intense (0.5–1%) slopes. Another typic landscape is constituted by the sedimentary deposits of the streams and ancient alluvial plains, poorly drained and interspersed with alkaline soils.

For the study soils with contrasting textures were selected, under the following land uses: native forest vegetation with minimum anthropic disturbance, agriculture (15–50 years of agriculture, oats or wheat/soybean-maize rotation, with regular inorganic NP fertilization) and forest plantations of `E. grandis` with two age ranges, 2 to 4 years and 8 to 10 years. From the combination of texture and land use the following scenarios were obtained: 1) THNF: Typic Halacuept (Soil Survey Staff, 2014) soil (fine to medium textures) under native forest vegetation, 2) APAgri: Argic Peludert soil with fine to medium texture under agriculture, 3) APEu 2-4y: Argic Peludert soil (fine to medium textures) under forest plantations of `E. grandis` of 2 to 4 years, 4) APEu 8-10y: Argic Peludert soil (fine to medium textures) under forest plantations of `E. grandis` of 8 to 10 years, 5) OUEu 2-4y: Oxic Udifluvent soil (coarse texture) under forest plantations of `E. grandis` of 2 to 4 years, and 6) OUEu 8-10y: Oxic Udifluvent soil (coarse-textured) under forest plantations of `E. grandis` of 8 to 10 years. These combinations of soils and land uses are the most common in the region. Fine to medium textured soils had more than 300 g kg^{-1} of clay in the 0–60 cm layer, whereas coarse-textured ones belonging to Oxic Udifluvents had lower clay contents. Argic Peluderts are well-developed, deep, and moderately well-drained soils, Typic Halacuepts are alluvial, alkaline poorly drained soils, and Oxic Udifluvents evolved from sandy sediments lying on sandy clay loam to sandy clay materials of varying depth, usually greater than 80 cm (Tasi, 2009). For each scenario (treatment) three randomly selected replicates were collected, locations are shown in the map (Fig. 1).

2.2. Characterization of the forest treatments

Most of the forests were converted after native grasslands except for treatment OUEu 2-4y, which was preceded by a forest cycle of *Pinus elliottii.* The plantation density at the time of sampling was 560 to 1150 plants ha^{-1}. In each field lot of *E. grandis,* 3 temporary sampling plots were installed. In each plot, the following parameters were recorded: plant density, diameter at breast height (DBH) of all individuals, and medium height of 6 to 10 plants at each replicate (Table 1).

In the study area, the average biomass productions measured were 25 m^3. ha^{-1} y^{-1}, and 35 m^3. ha^{-1} y^{-1} for fine and coarse soils, respectively (personal communication).

2.3. Soil sampling and analysis

Soil samples were taken at each site at the following depths: 0–20, 20–40, 40–60, 60–80, 80–100 cm, which were oven-dried at 40 °C for 48 h, ground to pass a 2 mm sieve. The following analyses were carried out: pH (potentiometry, soil/water ratio 1:2.5: Thomas, 1996), OC concentration (Nelson and Sommers, 1996), and texture (Bouyoucos, Ashworth et al., 2001). Undisturbed soil samples were taken for bulk density determination (cylinder method with a volume of 100 cm^3, Burke et al., 1986). OC mass (OCM) in each soil layer was calculated from the OC concentration values and bulk density in each depth level, as shown in eq. 1:

$$OCM = BD{*}z{*}OC\left(g\ kg^{-1}\right){*}10 \tag{1}$$

where:

OCM: OC mass content (Mg ha^{-1}); z = thickness of the layer sampled (m); BD: Bulk density (Mg m^{-3}).

In order to quantify OC stocks, soil profiles were referred to a mass equivalent of the deepest layer, 80–100 cm, using the equation presented by Sisti et al. (2004):

$$\mathrm{OCequm} = \sum\nolimits_{i=1}^{n-1}\mathrm{OCMi} + \left[\mathrm{MTn} - \left(\sum\nolimits_{i=1}^{n}\mathrm{MTi} - \sum\nolimits_{i=1}^{n}\mathrm{MSi}\right)\right]\mathrm{OCn} \tag{2}$$

where:

OCequm is the OC stock (Mg ha^{-1}) at the depth where soil mass is equal to that of the reference profile; $\sum$ OCMi (from i to n-1) is the sum of OCM (Mg ha^{-1}) from the first soil layer to the penultimate layer n-1 of the profile; MTn is the mass of soil in the deepest layer in the treatment profile (80–100 cm); MTi is the sum of the soil mass of layer 1 (surface) to “n” (greatest depth) in the treatment soil profile; MSi is the sum of the soil mass from the surface layer to “n” (greatest depth) in the reference profile; OC$_n$ is the C concentration (Mg C Mg^{-1} soil) in the deepest layer in the treatment profile. The profile reference with the lowest soil mass was one of the replicates of APAgri (12,513 Mg C Mg^{-1} soil).

The same criterion as that applied for OCequm was used to quantify clay content at equivalent soil mass, clayequm, to detect relationships among clay and OC contents in soils with different masses up to a meter depth.

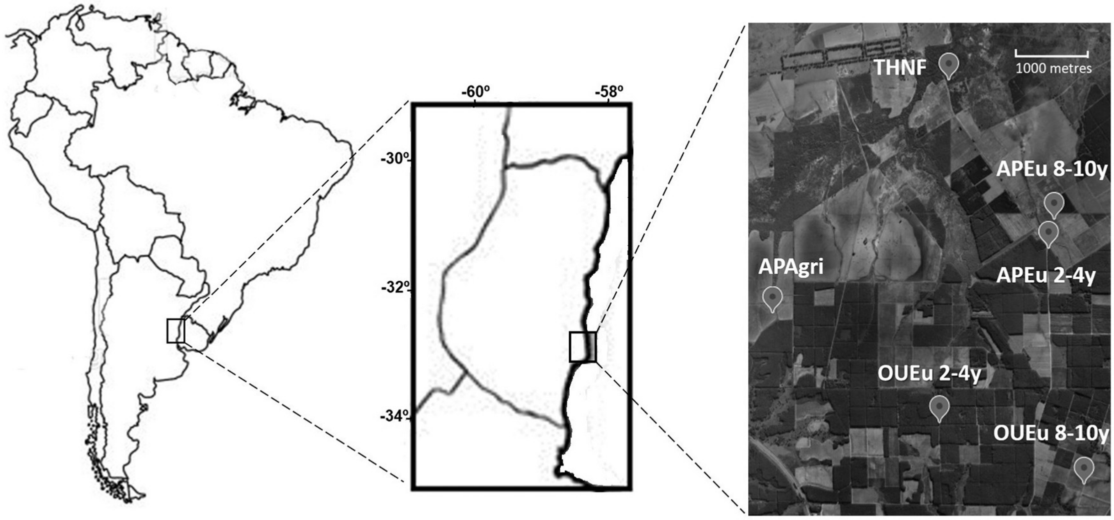

Fig. 1. Study area of Argentina and location of sampled sites.

Table 1
Main characteristics of forest plantations in soils with different textures.

Age (years)	Density (pl. ha^{-1})	DBH (cm)	Height (m)
Fine - medium texture: Argic Peludert			
	619 ± 77	13.6 ± 0.44	12.5 ± 0.28
2–4	811 ± 51	12.4 ± 0.79	13.3 ± 0.28
	1144 ± 51	8.1 ± 0.06	4.1 ± 0.012
	796 ± 44	16.7 ± 1.70	20.9 ± 1.22
8–10	568 ± 113	18.8 ± 1.39	23.7 ± 1.20
	715 ± 135	19.1 ± 1.91	20.8 ± 0.54
Coarse texture: Oxic Udifluvent			
	855 ± 61	4.2 ± 0.51	4.3 ± 0.32
2–4	815 ± 206	4.5 ± 0.14	4.8 ± 0.10
	922 ± 132	7.5 ± 1.08	7.7 ± 0.62
	980 ± 34	20.0 ± 0.91	21.8 ± 0.53
8–10	877 ± 34	18.1 ± 0.10	23.5 ± 0.06
	737 ± 13	18.9 ± 0.84	22.4 ± 0.71

DBH: diameter at breast height**.** Values of density, DBH and height are expressed as mean ± 1 SD.

2.4. *Statistical analyses*

The mean soil properties (clay content, pH, BD, OC concentration OCequm and clayequm) differences among treatments were analysed at each depth by ANOVA and Tukey tests with a significance level of 0.05. Simple regression analyses were performed between OCS and clay content, both expressed at mass equivalent at 0–100 cm, OCequm and clayequm, respectively.

3. Results

3.1. *General site characteristics*

In sites THNF, APAgri and both APEu, similar clay contents were observed in the whole profile. For OUEu 8-10y, clay contents up to 80 cm depth were significantly lower compared to most of the other situations (Fig. 2), but not significantly different in the last layer. In the medium layers, 40–60 and 60–80 cm OUEu 2-4y presented similar clay contents to APEu.

The highest pH was found in the site with native vegetation (THNF) ($p < 0.05$), throughout the whole profile (Fig. 2). In the layer 0–20 cm, THNF had a pH of 7.3, 1.18 units greater than that of APAgri, 1.48 units higher compared to APEu 2-4y, and 1.77 units higher than the average of OUEu sites. In the 20–40 cm layer, the pH of THNF was 8.4, significantly higher than the rest, with a difference of 2.27 pH units; in 40–60 cm, the pH of the THNF was 8.93, 2.49 pH units greater than the average of the rest sites.

For the 0–20 cm and 20–40 cm layers, no significant differences in pH were found among forest plantations and agricultural sites. For depths 60–80 cm and 80–100 cm the OUEu 8-10y site presented significantly lower pH values (Fig. 2).

Bulk density (BD) up to 60 cm (Fig. 2) did not differ among treatments. For layer 60-80 cm the main difference was found between OUEu 2-4 y and OUEu 8-10, having BD values of 1.55 Mg m^{-3} and 1.36 Mg m^{-3} respectively. For layer 80-100 cm, BD in OUEu 2-4 y was 1,61 Mg m^{-3}, significantly higher than the other treatments.

3.2. *OC concentration and stock in soil*

In general terms, significant variability was observed in OC concentrations in the evaluated sites. The lowest values were observed in OUEu 2-4y and OUEu 8-10y in the whole profile, and the highest in APEu 8-10y. Except in OUEu 8-10y, where an increase of OC was found below 60 cm, for the rest of the sites OC concentration tended to decrease with depth (Fig. 3), although in THNF, this decrease was greater. Despite varying texture and soil use, THNF, OUEu 2-4y, and OUEu 8-10y sites did not present significant differences in OC concentrations for 20 to 80 cm depth. For depth 80–100 cm OC concentration in OUEu 2-4y and OUEu 8-10y did not differ compared to the other treatments. OUEu sites did not show significant differences for different plantation ages at any depth (Fig. 3). In APEu sites, OC concentration was similar for both ages. Below 60 cm depth, the APAgri and APEu 8-10y sites presented a significantly higher OC concentration than in THNF. In APAgri OC concentrations below 20 cm were similar to those of APEu.

A similar trend was observed when OC data were expressed as stock (Mg C ha^{-1}) (Fig. 3). OC stocks per layer were similar in THNF and OUEu 2-4y below 20 cm depth. Most land uses showed a decrease in OC (Mg C ha^{-1}) with depth, except for OUEu 8-10y that increased in depth. In the sites OUEu or APEu with *Eucalyptus* plantations, no differences were observed ($p > 0.05$) in OC (Mg C ha^{-1}) between different plantation ages.

The OC stock distribution expressed as a proportion (OC content in a layer/OC content in 0–100 cm) varied with sites (Fig. 4A). Significant differences between the proportional OC contributions of each depth were only observed between the THNF and OUEu 8-10y situations in almost the entire profile (Fig. 4A). In THNF the proportion of OC

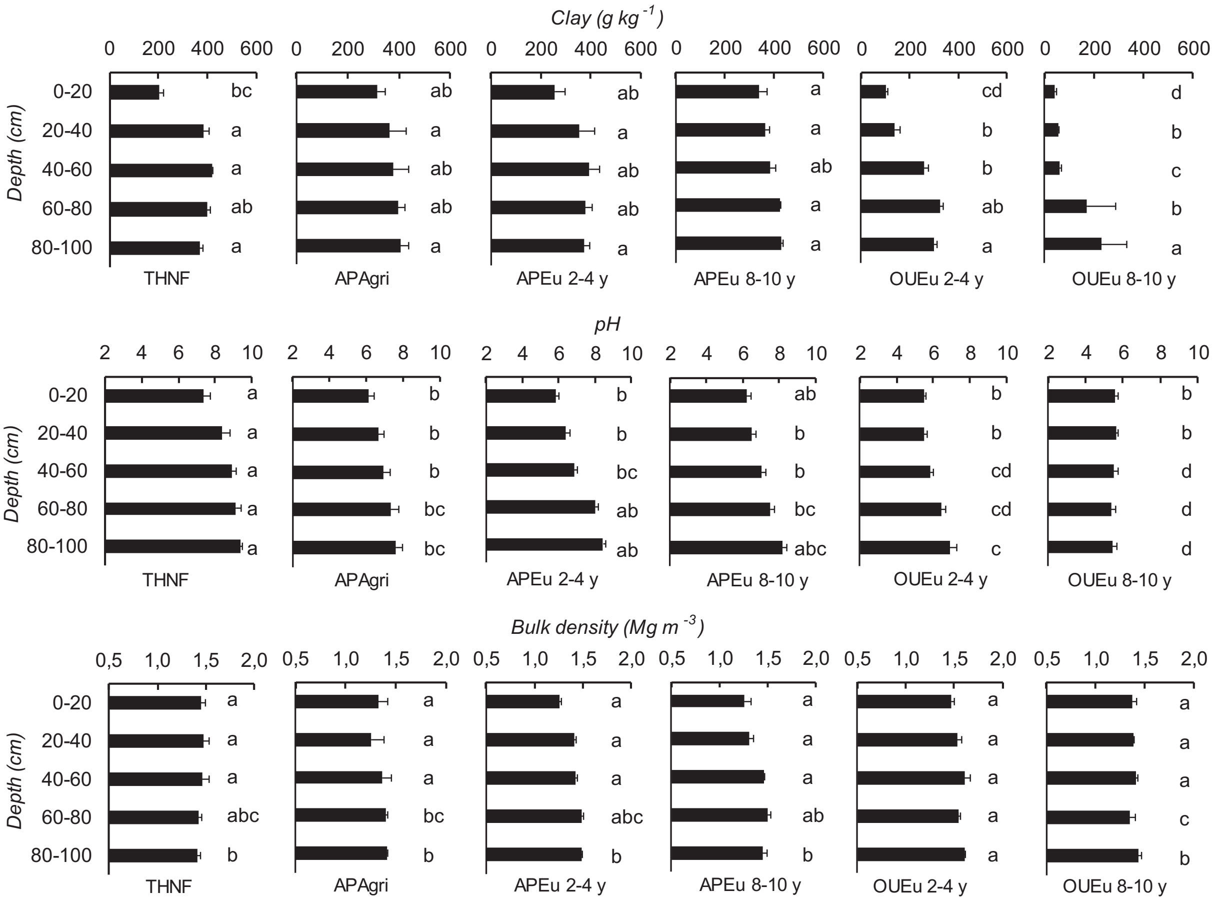

Fig. 2. Clay content, pH and bulk density in each soil layer for treatments: THNF: Typic Halacuept, native forest; APAgri: Argic Peludert under agriculture; APEu 2-4y: Argic Peludert under forest plantations of *E. grandis* 2 to 4 years; APEu 8-10y: Argic Peludert under forest plantations of *E. grandis* 8 to 10 years; OUEu 2-4y: Oxic Udifluvent under forest plantations of *E. grandis* 2 to 4 years and OUEu 8-10y: Oxic Udifluvent under forest plantations of *E. grandis* 8 to 10 years. Fine lines over horizontal bars indicate standard error. Different letters indicate significant differences among treatments within each soil layer ($p < 0.05$).

decreased drastically with depth, registering a proportion of OC of 48% in the 0–20 cm layer and a proportion of OC of 3.2% at 80–100 cm. On the contrary, in OUEu 8-10y a slight decrease was observed in the proportion of OC from surface to 60 cm, and the contribution of OC below 60 cm increased; the proportion at 0-20 cm was 24%, while in the deeper layer it was 28%. For APAgri, APEu 2–4 y, APEu 8–10 y and OUEu 2–4 y, the proportion of OC also decreased in depth without statistical differences between the different sites, neither with THNF or OUEu 8-10y. All the sites presented similar OC proportions in the 40–60 cm layer. Considering the curve of OC accumulation with depth (Fig. 4B) significant differences were found between OUEu 8-10y and THNF for all layers. From surface to 40 cm of depth, OC accumulation was 40% in OUEu 8-10y and 76% in THNF. Considering a soil depth of 60 or 80 cm, OC accumulation in OUEu 8–10 was 54% and 73%, and in THNF was 90 and 97%, respectively. The OC cumulative proportion in depth for APAgri, APEu 2-4y, APEu 8-10y, and OUEu 2-4y did not differ significantly among them ($p > 0.05$) or with OUEu 8–10 and THNF.

Changes in BD for different soil uses could affect OC reserves when comparing fixed soil depths, thus OC stocks at 100 cm were calculated in equivalent soil mass (Ellert et al., 2002). OC expressed as equivalent mass (OCequm) was significantly ($p < 0.05$) higher in APEu 8-10y compared to coarse textures and THNF, but not significantly different in APEu 2-4y and APAgri (Fig. 5A). Clay content, expressed in equivalent mass (clayequm), was similar in APEu 2-4y, APEu 8-10y, APAgri, and THNF and significantly higher than OUEu 2-4y and OUEu 8-10y. Clay content at equivalent soil mass, clayequm, at 0–100 cm explained 46% ($p < 0.05$) of the variability of OCequm in a linear adjustment (Fig. 5B), whereas when THNF was excluded from the analysis, that relationship was even stronger ($p < 0.05$, $r^2 = 0.66$).

4. Discussion

4.1. Soil properties and OC

According to the American classification system Soil Taxonomy (Soil Survey Staff, 2014), the textural classes of the fine-medium textured sites APAgri and APEu were similar, varying from loamy at the surface to clay loam in depth, whereas THNF has a lighter surface granulometric composition (Fig. 2, clay 0-20 cm). For OUEu 2-4y, the textural class varied from sandy loam to sandy clay loam and in OUEu 8-10y texture was sandy at the surface and sandy clay in depth. Within similar textures, (APAgri, THNF, and APEu) pH was significantly different in THNF due to alkalinity. Soil pH, a chemical property controlling other attributes, can be affected by climate, vegetation, topography, among others (Hong et al., 2019). Halacuepts soils at THNF exhibited pH higher than 8.5 below 20 cm, probably associated with the increase in exchangeable sodium percentage (ESP), due to its lower position in the landscape. Analysing pH variations with depth for the sampled sites, lower pH values were observed in the first layer, which increased with depth. Lower values at the surface are often associated with the production of organic acids, generated by OC enrichment from plant materials and organic matter decomposition (Zhou et al., 2020). Furthermore, in the coarse textured soils (OUEu), greater acidity could be a consequence of lixiviation of bases from the surface sandy layers (Kalbitz et al., 2000)

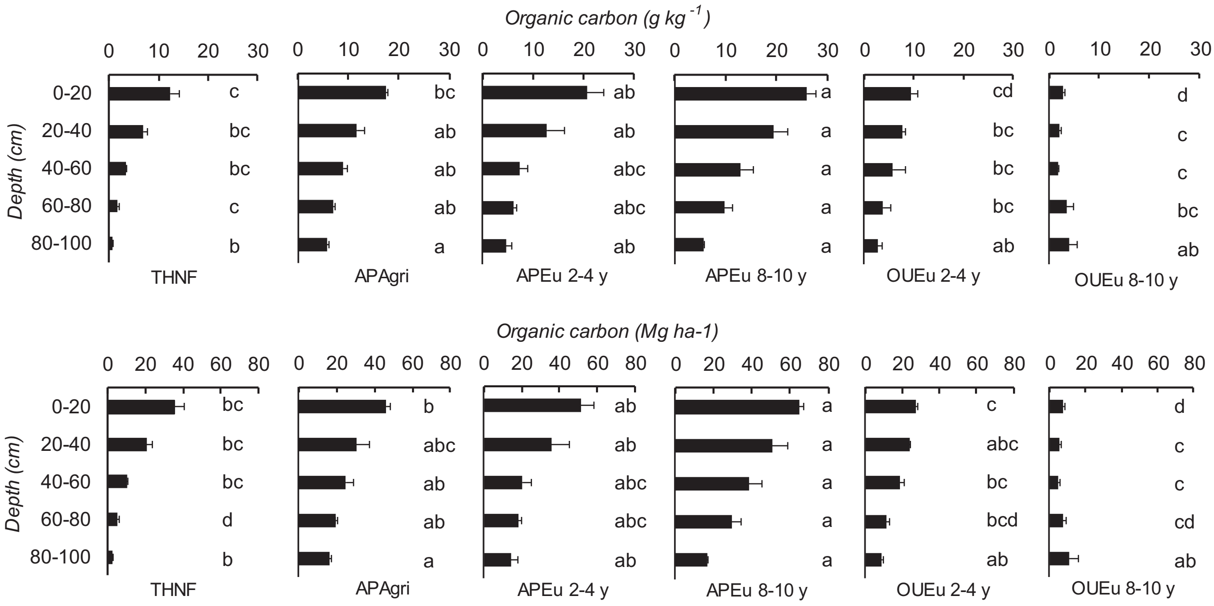

Fig. 3. Vertical distribution of soil organic carbon concentration (top panel) and soil organic carbon stock (bottom panel) in different layers per treatment. THNF: Typic Halacuept native forest; APAgri: Argic Peludert under agriculture; APEu 2-4y: Argic Peludert under forest plantations of *E. grandis* 2 to 4 years; APEu 8-10y: Argic Peludert under forest plantations of *E. grandis* 8 to 10 years; OUEu 2-4y: Oxic Udifluvent under forest plantations with *E. grandis* 2 to 4 years and OUEu 8-10y: Oxic Udifluvent under forest plantations of *E. grandis* 8 to 10 years. Fine lines over horizontal bars indicate standard error. Different letters indicate significant differences among treatments within each soil layer ($p < 0.05$).

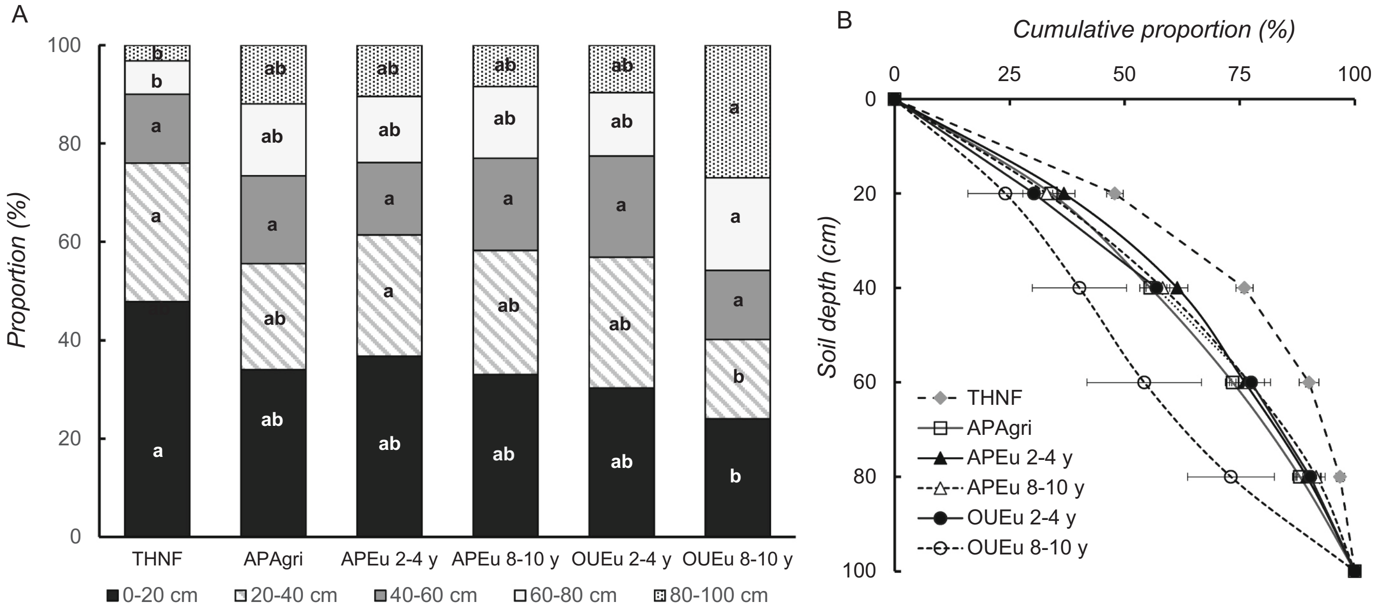

Fig. 4. A) Vertical distribution of OC in proportion (quantity of OC per layer/ quantity of OC 0–100 cm) per layer for each treatment. B) Cumulative proportion of OC per layer up to 1 m depth. THNF: Typic Halacuept, native forest; APAgri: Argic Peludert under agriculture; APEu 2-4y: Argic Peludert under forest plantations of *E. grandis* 2 to 4 years; APEu 8-10y: Argic Peludert under forest plantations of *E. grandis* 8 to 10 years; OUEu 2-4y: Oxic Udifluvent under forest plantations of *E. grandis* 2 to 4 years and OUEu 8-10y: Oxic Udifluvent under forest plantations of *E. grandis* 8 to 10 years. Fine lines over horizontal bars indicate standard error. Different letters indicate significant differences ($p < 0.05$).

and forest nutrient uptake (Jobbágy and Jackson, 2003) and the later replacement of basic cations by protons in exchange sites. BD was similar in all fine-medium textured sites (APAgri, THNF, and APEu), so apparently, there were no differences in this soil property due to management. Takele et al. (2015) and Amanuel et al. (2018) reported opposite results, namely lower bulk densities in forests compared to annual crops, due to organic matter losses in annual crop soils and compaction in the surface layer caused by continuous machinery traffic. In our data, the effects of land use on OC content were weak, and probably for this reason there were no differences in bulk density. In addition, the predominance of smectite clays, which have the capacity for contraction and expansion, could be one of the causes of natural structuring and less susceptibility to compaction of these soils.

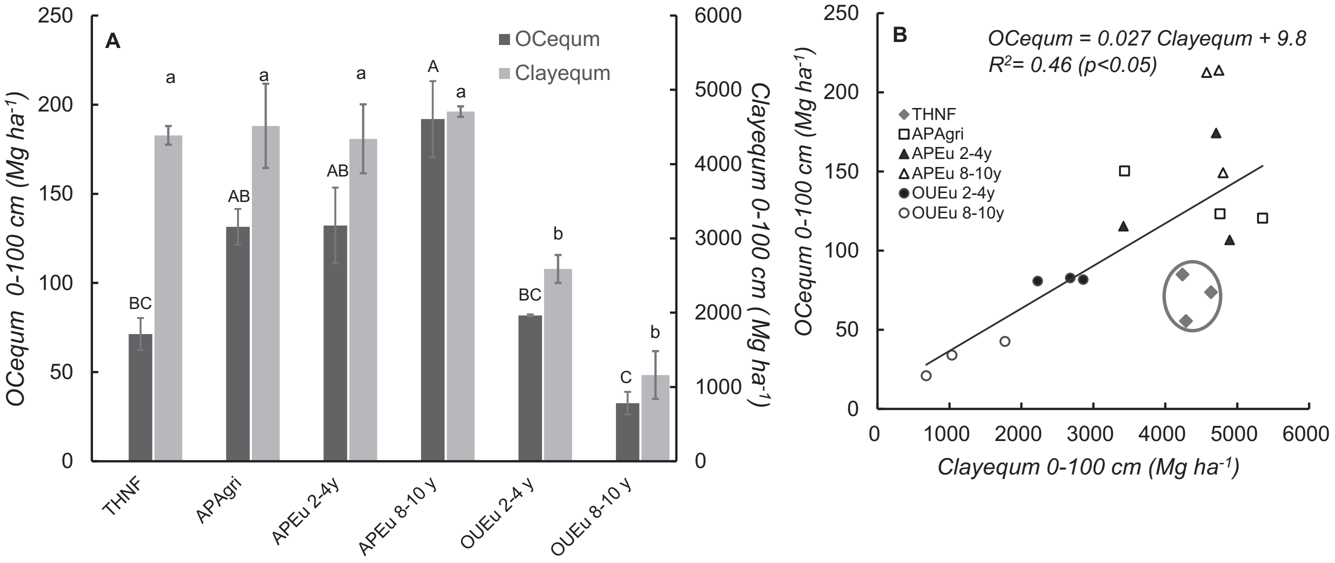

Fig. 5. a). Organic carbon stock and clay from 0 to 100 cm depth, expressed as equivalent soil mass (soil mass at 100 cm of 12,513 Mg ha^{-1}) for the treatments: THNF: Typic Halacuept, native forest; APAgri: Argic Peludert under agriculture; APEu 2-4y: Argic Peludert under forest plantations of *E. grandis* 2 to 4 years; APEu 8-10y: Argic Peludert under forest plantations of *E. grandis* 8 to 10 years; OUEu 2-4y: Oxic Udifluvent under forest plantations of *E. grandis* 2 to 4 years and OUEu 8-10y: Oxic Udifluvent under forest plantations of *E. grandis* 8 to 10 years. Fine lines over thick bars indicate standard error. Different lower-case letters indicate significant differences between treatments in clay content, upper-case letters indicate significant differences between treatments in SOC in ($p < 0.05$) in equivalent soil mass. b) Relationship between organic carbon stock and clay content at 0–100 cm. The circle inside the Figure indicates the data from THNF site, if these are excluded from the regression, R^2 value would be 0.66.

4.2. Organic carbon vertical distribution

Regardless of texture and land use, the greatest OC quantity and concentration were located in the first 20 cm, decreasing with soil profile depth. These results agree with various studies (Seely et al., 2010; Zhao et al., 2014; Zhao et al., 2016). One exception was site OUEu 8-10y, where OC quantity and concentration decreased up to 40–60 cm, followed by an increase in deeper layers. This increase was associated with the rise in clay content, which almost doubled in the two bottom layers (60–80 cm vs 40–60 and 80–100 cm vs 60–80 cm). As described by Tasi (2009), one of the particular features of these Entisols (Oxic Udifluvents) is the presence of a layer of sandy alluvial material deposited over lacustrine clay sediments. This lithological discontinuity, which can appear at varying depths below 70 cm, has finer materials ranging from sandy-clay-loam to clay. Consequently, evaluations at depths greater than 100 cm would be justified in soils presenting such textural discontinuity in the profile.

THNF site had the greatest proportion of OC in the first 20 cm of the profile, which therefore decreases in concentration and mass with depth, representing 48% of the carbon accumulated to 1-m depth (OC accumulation being 15 times more in the 0–20 layer than in the 80–100 layer). A similar pattern was reported by Du et al. (2013) in a study of OC, root distribution, and activity in a 27-year-old mixed plantation of *Robinia pseudoacacia* L. and *Fraxinus velutina* Torr. According to these authors root distribution of both species suggests a strategy of salinity avoidance. The high sub-surface alkalinity of THNF is likely to have conditioned net primary productivity and vertical root distribution (Yang et al., 2016), the main source of OC in depth.

As reported by Heiderer (2009), there would also be differences in the distribution of OC mass between surface soil and subsoil, depending on land use. In our work, most sampled sites exhibited a decrease in OC proportion with depth. This distribution pattern is the norm in most soils, as the first layer generally includes most OC derived from aboveground residues and main roots. Nevertheless, as opposed to the results of Heiderer (2009), no clear differences were observed in the distribution of OC mass in soils with similar textures and different land uses, such as APAgri and APEu, as could have been expected for forest plantations with deeper root systems that could have supplied higher OC quantities to the subsoil (Jobbágy and Jackson, 2000).

Due to the higher OC concentration in the surface soil layer, C storage monitoring studies have focused on the first 20–30 cm. Nonetheless, as we have observed, limiting analyses to the surface layers and ignoring subsoil could underestimate OC storing capacity in sites such as OUEu 8-10y. In this case, a relevant proportion of OC was found (60%) under 40 cm, as a consequence of the higher proportion of clay and OC concentration. Moreover, it is possible that in the environmental and sandy textural conditions of these sites, the surface soil could facilitate processes of organic matter migration or dissolved OC transport through macropores, up to the lithological discontinuity with high clay content, lower BD, and fewer macropores (Paul, 1984; Rumpel and Kogel-Knabner, 2011). These observations provide useful information for decision making when estimating C reserves of coarse textured forest soils at a regional scale, that significantly impact the effectiveness of C storage.

4.3. Organic carbon stock and land use

Forest soils represent a major proportion of the carbon reserve of the earth, so changes in the OC cycle are relevant worldwide not only for OC capture but also for maintaining the productive capacity of forests including all the ecosystemic services they offer (James and Harrison, 2016). The capacity for storage of OC in soils depends on mineralogical composition, texture, climate, land use, and management (Jandl et al., 2007; Wang et al., 2013). In the present study, most differences in OC stock were associated with texture. OCequm at 100 cm was on average for coarse textured soils 57.2 Mg OC ha^{-1} and 162.3 Mg OC ha^{-1} for medium-fine textures (Fig. 5). APEu sites stored three times more OC than OUEu sites (+ 105.1 Mg OC ha^{-1}). In fine textured soils, the effect of the clay fraction, or silt plus clay, on OC accumulation is reported and related to the protection these particles exert on the organic fraction comprising processes of adsorption, occlusion and, aggregation (Jenkinson, 1977; Anderson and Paul, 1984; Burke et al., 1989). Thus, soil types exhibit differential OC capture capacity due to their inherent potential to retain it (Gibson et al., 2002).

In sites with medium-fine texture (THNF, APAgri, APEu), OC values were similar to that observed by Du et al. (2015) that reported values from 87 to 165 Mg OC ha^{-1} for lateritic soils with plantations of *Eucalyptus* 1–8 years old. On the other hand, the values of OCequm found in our study are also similar compared to those in Garcia (2010) for the same region, in plantations of *E. Grandis* 1–9 years old. The latter study reports that in the Vertisols sampled at a depth of 0–50 cm the stock varied between 57.9 Mg ha^{-1} and 163.5 Mg ha^{-1} in plantations without thinning and between 112.8 and 160.6 Mg ha^{-1} in thinned ones.

The OC content in APAgri was significantly higher than in THNF below 60 cm, whereas OCequm at APAgri was higher but not significantly different from THNF, as opposed to previous studies showing higher OC stocks under native vegetation areas compared to annual crop soils (Deng et al., 2014). In sites without disturbances, OC quantity is controlled by climate, vegetation, original soil material, topographic position and texture (Sims and Nielsen, 1986), whereas in agricultural sites, the input of plant residues to the soil is much lower (Deng et al., 2014). In THNF alkalinity could have affected OC input and vertical distribution pattern. Another factor contributing to this difference is the fact that in APAgri soil conservation practices were applied, such as crop rotation, no-tillage, and balanced inorganic fertilization, which minimize C losses and/or increase inputs (Wang et al., 2016; Alvarez et al., 2014).

E. grandis is the main tree species cultivated in the Mesopotamia region of Argentina. Forest plantations have been proposed as an effective strategy for reducing global warming, however, factors determining the rate of OC capture are being widely discussed in the literature. According to Chen et al. (2020), OC capture in soils after a forest plantation varies with climatic zones, and previous land use, while forest species have a lower effect. Plantation age is another factor likely to modify OC soil stocks, although reported results are contradictory. Some studies indicate a significant increase in OC content with plantation age (Paul et al., 2002; Peichl and Arain, 2006), others have found the increase in OC content in the first decade after plantation (Hooker and Compton, 2003), whereas others have detected increases in the first years, and a later decrease (Garcia, 2010; Du et al., 2015). Chen et al. (2020) state that during the first 10 years or less, these ecosystems are generally weak or neutral C sources. In our study, plantations of *Eucalyptus* did not exhibit differences in OC stocks stored at 0–100 cm depth, according to plantation age. This could probably be explained by the fact that in both cases plantations were 10 years old maximum and could have been in the stage Chen et al. (2020) indicated as weak or neutral C sources. Breeding advances have reduced plantation cutting age to maximize economic return to 10–12 years in the region of our study. It is possible, however, that a delayed cutting age should be considered to allow recovery of the OC levels or maximizing OC storage. It would be of interest in the future to consider not only the economic value of the harvestable product but also the environmental value of a higher OC storage in the soil-plant system, in order to minimize greenhouse gases emissions.

5. Conclusions

The aim of this study was to evaluate the effect of land use and texture on the distribution and OC stock in soils of the Mesopotamia region of Argentina under the following scenarios: native forest in a Typic Halacuept soil, agriculture and forest plantations of different ages (2–4 years and 8–10 years) in Argic Peluderts soils (fine textured soils) and forest plantations of different ages (2–4 years and 8–10 years) in Oxic Udifluvents soils (coarse textured soils). OC concentration and quantity were affected mainly by soil texture, being greater in fine textures and lower in coarse ones. Intrinsic soil characteristics, such as alkalinity or the presence of a lithological textural discontinuity in-depth, generated changes in OC quantity and vertical distribution. OCequm up to 100 cm was roughly triple in fine textured sites, independently of management. Contrary to what we expected, no great differences were found in OC stock in soils with *E. grandis* plantations of differing ages, at any texture studied. Besides, no differences were found, for similar texture soils, between forests and agricultural land use. These results contribute to the understanding the variation in OC for different land uses particularly forests, for which information is scarce in the region. Implementation of monitoring systems requires consideration of soil type, as the capacity of OC storage could be underestimated.

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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