MR. EMMANUEL ADRIAN GABIOUD (Orcid ID : 0000-0003-0591-1447)
PROF. MARIELA SOLEDAD SEEHAUS (Orcid ID : 0000-0001-5642-2155)

Article type : Special Issue Paper

# Addition of organic and inorganic amendments to regenerate the surface structure of silty soils

E.A. GABIOUD[a]*, M.C. SASAL[a], M.G. WILSON[a], M.S. SEEHAUS[a], N.V. VAN OPSTAL[a], S. BEGHETTO[b] & A. WINGEYER[a].

[a]*Instituto Nacional de Tecnología Agropecuaria. EEA Paraná. Ruta 11 km 12.5. Oro Verde 3101, Entre Ríos, Argentina.*
[b]*Facultad de Ciencias de la Educación, Universidad Nacional de Entre Ríos. Alameda de la Federación 106, Paraná, Entre Ríos.*

* gabioud.emmanuel@inta.gob.ar

Running Tittle: Amendments to regenerate soil surface structure

# Abstract

The widespread degradation of the structure of silty soils under no till systems (NT) that has been observed in recent years is characterized by the presence of a platy structure (P) near the soil surface. Under these conditions, addition of organic and inorganic amendments could have beneficial effects on soil physical properties. We assessed structural regeneration following addition of amendments in an Argiudoll of Paraná, Argentina. Poultry litter (PL) and gypsum (G) were applied, providing an organic and inorganic amendment, respectively. Four treatments were tested: PL (7.5 Mg ha$^{-1}$), G (3 Mg ha$^{-1}$), the combination of PL+G (7.5+3 Mg ha$^{-1}$), and control (T) with no amendment. Description and quantification of the structural state of the soil profile was made using a Visual Soil Evaluation method: "Le profil cultural". Aggregate stability, bulk density, total porosity, pore size distribution and soil shear strength for each soil structure and soil organic carbon (SOC) were determined at two depths. Twenty months after the amendment applications, both PL and PL+G treatments led to a significant increase of SOC in the upper 5 cm of soil. The proportion of Gamma (Γ) structure increased and P declined under PL and PL+G compared with G and T inn the A horizon. Treatments G and PL+G contributed to an increase in average diameter of aggregates in Γ only. The use of PL amendment alone or in combination with G could be a promising strategy to regenerate, in the short-term, the degraded soil structure under NT.

**Keywords:** regeneration; soil structure; poultry litter; gypsum; platy structure.

## Introduction

Silty soils of the Argentinian Humid Pampas region are predominantly cultivated using no till system (NT). This practice is adequate to mitigate erosion processes associated with tillage. However, when combined with the simplification of crop sequences and soybean (*Glycine max,* L.) monoculture, NT can generate some physical degradation processes of soil surface structure such as compaction, reduction of infiltration rate and structure stability, causing an increase in water loss through surface runoff (Sasal *et al*., 2017a,b). Many authors have reported that under NT, silty soil structure in the region systematically showed a vertical ordering of different structure types, characterized by the development of a platy soil structure (P), having thin and flat aggregates oriented in parallel to the soil surface in the upper soil layer (Sasal *et al.,* 2006; Sasal 2012; Lozano *et al.,* 2013; Álvarez *et al.,* 2014). In this context, the study of structure regeneration of degraded soils under NT, without disturbing the soil by tillage, is important.

Several authors reported the evolution from compact structures (massive) to fragmented ones over the long-term under NT (Boizard *et al.,* 2013; Sasal *et al.,* 2017a). Such evolution of soil structure depends on natural factors, including soil shrinkage and swelling during wet-dry cycles, development of root systems, digging and tunneling by soil fauna and other biological mechanisms of aggregation and cracking (Dexter, 1988; Drewry, 2006; Taboada *et al.,* 2008; Sasal *et al.,* 2017b).

The application of organic amendments as a source of macro and micronutrients for plants is a traditional practice in agriculture. However, in addition to supplying nutrients in the short-term, the application of organic amendments has beneficial effects on soil physical properties, reducing runoff and nutrient loss, and overall plant growth (Piccolo and Mbagwu, 1990; Tester, 1990; Unc and Goss, 2006; Bastida *et al.,* 2008). Literature reports of improvement in different indicators of soil physical quality suggest that organic amendments can be a promising approach to regenerating soil structure under NT. The use of inorganic amendments for the improvement of soil physical properties was generally aimed at the formation and stabilization of soil aggregates (Norton *et al.,* 1998), as well as improvements in soil penetration resistance and macroporosity (Orellana and Pilatti, 1990). Calcium, the most important component in these amendments, helps to stabilize the structure of aggregates in some soils (Wallace, 1994; Fisher, 2011; Walworth, 2012). The beneficial effects of soil incorporation of gypsum are attributed to its ability to release electrolytes that improve clay aggregation in sodic and non-sodic soils (Flanagan *et al.*, 1997a; Flanagan *et al.*, 1997b; Dontsova, 1998; Tirado- Corbalá *et al.*, 2013). Nonetheless, information about the value of the surface application of gypsum for the regeneration of soil structure under NT is scarce and even less for its combination with organic amendments.

In this study we assessed the short-term evolution of soil structure in the surface horizon of an Aquic argiudoll under NT after addition of "poultry litter" (PL) as organic amendment and gypsum (G) as inorganic amendment. A Visual Soil Evaluation (VSE) method: “Le profil cultural” (CP) (Gautronneau and Manichon, 1987) was carried out to describe the proportion and distribution of different structural units, and physical properties of these structures were determined to identify short-term strategies for structural regeneration of silty soils.

## Materials and methods

### *Study site and soil description*

The study was carried out at the Paraná Experimental Station of the Instituto Nacional de Tecnología Agropecuaria (INTA) in Entre Ríos province, Argentina (31° 51′ S and 60° 31′ W). The region has a subhumid (annual rainfall ≈ 1000 mm) and temperate climate (annual temperature ≈ 18.3 °C). Winter temperatures are rarely below 0 °C. During the study period (June 2014 to April 2016), the annual average precipitation was 1145 mm. The area is covered by a fine, illitic, thermic Aquic Argiudoll (Soil Survey Staff, 2010) of the Tezanos Pinto Series. The texture of the A horizon is silty loam with 270 and 660 g kg$^{-1}$ of clay and silt, respectively (Plan Mapa de Suelos, 1998). This series is representative of the Molisolls that cover the Humid Pampas of Argentina.

### *Field Experiment*

In June 2014, a field experiment was initiated in a production plot with a Soybean (*Glycine max* Merr.)-Corn (*Zea mays* L.) rotation under NT for at least 15 years (Figure 1). The experimental design was randomized complete blocks with three replicates. The four treatments tested included surface applications of:

- poultry litter (PL) as organic amendment. PL is a mixture of feces, wasted feeds, feathers and rice husks from bedding material. Entre Rios province produces the most chicken (*Gallus gallus domesticus*) in Argentina and PL is treated as a residue. The bedding material was stabilized in a pile for 5 months before application to the soil surface (Table 1). The amendment was applied at 7.5 Mg ha$^{-1}$ of dry PL (corresponding to approximately 3.5 Mg ha$^{-1}$ of carbon).
- gypsum (G) as inorganic amendment. The product used was agricultural gypsum YESOER85 granulated from 1-5 mm, from Piedras Blancas S.A Company (http://www.yesoer.com.ar/caracteristicas-del-producto/) (Table 1). The application was 3.0 Mg ha$^{-1}$ according with Wilson & Cerana (2004) who observed significant changes in physical conditions of soils under rice cultivation with additions between 1.5 and 3.0 Mg ha$^{-1}$ of G, without causing phytotoxicity effects in crops.

- combination of both poultry litter and gypsum (PL+G) at the same rates as in the individual treatments,
- control (T) with no amendment applied but receiving triple calcium phosphate (600 kg ha$^{-1}$) and granulated urea (400 kg ha$^{-1}$); this application provided the same N and P additions as PL.

Amendments were manually applied in August 2014 to achieve a uniform and accurate distribution of materials.

Four samplings were carried out over a two-year period: the first before applying amendments in June, 2014; the second after amendment application but before sowing soybean in October, 2014; the third after soybean harvest and before sowing corn in August 2015; the fourth after corn harvest in April 2016.

*Field and laboratory measurements*

The soil structure was described using a Visual Soil Evaluation (VSE) (Ball and Munkholm, 2015) method: "Le profil cultural" (CP) (Gautronneau and Manichon, 1987) modified by Boizard *et al.,* (2017) for improving the assessment of soil structure under NT. Profile methods allow for a more detailed structure assessment (Emmet-Booth *et al*., 2016). Soil pits, 1 m wide and 0.3 m deep (to include the whole A horizon), were dug perpendicularly to the direction of sowing. As traffic was not controlled and crop residues covered the soil surface, wheel tracks could not be identified in advance. This VSE method is based on distinguishing different morphological units, each corresponding to a given soil structure: Gamma structure (Γ) with high structural porosity, visible aggregates and a rough surface; Platy structure (P) characterized by a network of horrizontally-oriented cracks; Delta structure (Δ) with high cohesion, no visible macropores and smooth surface on breaking; Phi structure (Φ) composed of fragments with sharp edges, separated by flat cracks oriented in all spatial directions.

After labeling the different morphological units with pins of different colors, each soil profile was photographed as specified by Sasal *et al.,* (2017a). The relative proportion of each structural type was calculated as the ratio of the area of each structural type to the total area of the A horizon within a single soil pit. The depth of the A horizon corresponded to the upper limit of the argillic B horizon. Mapping of the morphological units and the quantification of the relative proportion of each structural type using image analysis provided a semi-quantitative *in situ* characterization of soil structure, which did not depend on the soil water content at the time of observation (Boizard *et al*., 2002).

On the first sampling date, 3 pits were randomly prepared and CP described (perpendicular to the sowing lines) over the studied field to analyze the structural state before application of treatments. In addition, two random composite soil samples (0-5 and 5-15 cm depth) were collected to determine SOC at the first and the last sampling dates. One CP was described for each treatment and replicate on other sampling dates.

At 20 months after amendment application, soil shear strength (Ss) was measured horizontally *in situ* with a vane tester (Eijkelkamp, The Netherlands) 19 mm in diameter and 35 mm height on the exposed soil profile (Sasal *et al*., 2017a) and undisturbed soil cores (0.03 m high and 0.05 m in diameter) were taken to determine the bulk density (Bd) (Burke *et al*., 1986) of each type of soil structure (three replicates per treatment) in all the pits. The main axis of the cylinders was horizontal. Cores in their sampling cylinders were saturated under vacuum over 24 hours, and subsequently brought to -1, -6 and -23 kPa matric potential using a tension table with a hanging water column (Klute, 1986). Pore size distribution was calculated using the relationship between soil water content and matric potential (Hillel, 1980). Soil pores were classified as: micropores (< 12.5 μm diameter), mesopores (12.5-50 μm) and macropores (> 300 μm).

Disturbed soil samples were taken from each type of soil structure. The bulk density of sieved 2–3-mm diameter aggregates was determined, at field soil moisture, using the kerosene impregnation and hydrostatic weight method which is based on Archimedes' principle (Monnier *et al*., 1973; Fiès *et al*., 1981). These small aggregates were chosen to avoid the presence of cracks caused by tillage and weathering and thereby describing the pore space caused by the particle arrangements only (soil textural density: DTb). Then, soil structural porosity (SP) was obtained from Bd and DTb according to: $SP = (1 - (Bd/DTb)) \times 100$. Aggregate stability (AS) was also measured using the Le Bissonnais (1996) method. This method involves three pretreatments (fast wetting, stirring after prewetting and slow wetting), which distinguishes three breakdown mechanisms: slaking, mechanical breakdown and microcracking (Cosentino *et al*., 2006, Novelli *et al*., 2013). The sum of the mass fraction remaining on each sieve after sieving, multiplied by the mean aperture of the adjacent sieves was used to calculate the mean weight diameter (MWD) of the soil aggregates for each pretreatment and the means of the three pre-treatments were calculated (MWDmean).

### *Statistical Analyses*

The effect of the treatments on the parameters measured was assessed by means of analysis of variance by using mixed general linear models (previous check of the ANOVA assumptions), Fisher LSD test for means comparison and linear regressions, using the InfoStat 2017 software (Di

Rienzo *et al.*, 2017). To fit the mixed-effects models, two combinations of model parameters were tested considering heteroscedasticity (sub-populations that have different variabilities from others). The best model was selected by Akaike's information criterion (AIC) and Bayesian information criterion (BIC) (Di Rienzo 2011).

## Results and discussion

### *Evolution of soil structure as a result of the application of amendments*

Figure 2 shows a CP for the initial situation. The selected site had no Γ structure, but a continuous 10 cm thick P structure from soil surface. Below the P structure, there was a Φ structure with high presence of cracks, fissures and root channels. The presence of a Δ structure was localized and only occupied 10 to 15% of the profile. De Battista *et al*. (1994) and Sasal (2012) observed the presence of Δ structure in similar percentages for agricultural silty soils under NT in other sites of the Pampas plain.

The evolution of soil structure types over the 20-months of assessment varied among treatments (Figure 3). Visual changes registered over time were the generation of a Γ structure in the soil surface and modification of the proportion, thickness and continuity of the other structures.

For Γ structure, there was a significant interaction between treatments and time after application ($p<0.05$). At 2-months after application of the amendments, there was no presence of a Γ structure, but this increased noticeably after 12-months of application under the PL treatment (Figure 4). At 20-months after application the effect of adding either PL or PL+G resulted in the highest Γ proportion (26.1 and 25.4%, respectively). Thus, PL applications significantly increased Γ structure by approximately 2.2 times compared to T and G. The application of G did not increase Γ compared with T treatment. The 8% Γ structure proportion at 20-months sampling time for G and T are consistent with the findings of Boizard *et al.,* (2017) in an Argiudoll of the same series for an agricultural rotation under NT.

Figure 5a shows a significant decrease in P structure proportion over time ($p<0.05$), registering an average decrease of 36% at 20-months after application. Treatment effect was also significant ($p<0.05$) on P structure (Figure 5b). Averaged across times, PL treatment resulted in 27% reduction relative to the proportion in T and G. Boizard *et al.,* (2017) in Argiudolls of Paraná with a long-term corn-wheat/soybean rotation under NT found a reduction in P values of 37%, more than in our results. This difference may be related to increased biological activity and root growth from the winter crop (wheat) that was not present in our study.

Finally, for Φ and Δ structures found below 10 cm soil depth, neither the interaction between treatments and time after application, nor treatments and time effects were statistically significant. Sasal *et al.,* (2017a) surveyed the CP of Argiudolls of the Pampean core zone. They reported that the proportions of Φ and Δ structures in the soil profile showed the lowest variations across the region. At 2- and 20-months after application of treatments, average Φ structure was 41.7% and 39.3%, respectively, while average Δ structure was 7.1 and 9.3%, respectively. Similar values were reported by De Battista *et al.,* (1994) and Boizard *et al.,* (2017) for agricultural soils under NT. Probably, the surface application of amendments cannot modify soil structures below 10 cm depth, at least in the short-term. Over a 2 year period under NT, Peigné *et al*., (2013) also found that main changes in the proportions of different soil structures took place in the first 10 cm soil.

Consistent with results of Sasal *et al.,* (2017a), a significant negative correlation was observed ($y=-0.8895x+48.695$, $r = 0.74$; $p <0.05$) between the proportions of Γ and P structure. The negative sign suggests that Γ structure develops from P structure. This reduction in the P proportion constitutes a structural regeneration indicator as it was found that an increment in Γ structure may improve water infiltration into the soil, soil aeration and biological activity (Sasal *et al.,* 2006).

*Physical properties of structure types after 20 months since application of amendments*

There was no significant effect of treatment by structure type interaction on Db, Ss, and TP (Table 2), pore size distribution (Figure 6) and SP values. However, significant differences were observed among structure types (p< 0.05) for the following physical properties:

*Bulk density*

The Γ and Δ structures had the smallest and the greatest Bd, respectively, while P and Φ structures had intermediate Bd values (Table 2). The P, Δ and Φ structures had Bd values close to the Bd of 1.44 Mg $m^{-3}$ obtained by Wilson *et al.,* (2013) for Mollisols of this region.

*Shear strength*

The largest Ss value corresponded to the Δ structure, twice as big as that of Γ (Table 2). The Ss value for Γ was similar to that found by Wilson *et al.,* (2013), who reported Ss values close to 30 kPa in the surface of a Molisol with a Bd of 1.1 Mg $m^{-3}$. The Ss value for P was significantly smaller than those found in Φ and Δ, which agrees with reduced Ss reported when horizontal cracking introduces weakness planes in highly compacted structures (Boizard *et al.,* 2013).

*Total porosity and Pore size distribution*

In agreement with the smaller Bd and Ss, Γ had significantly larger TP value (56.5%) (Table 2). The smallest TP corresponded to Δ, which was 21% less than the value reported for Γ. Both, P and Φ had similar intermediate values of TP (~ 46%).

Confirming visual observation, pore size distribution was characteristic for each soil structure (Figure 6). These characteristic differences in pore size distribution between various types of structures were also found by Neves *et al.,* (2003) in Brazilian soils. In our study, remarkably greater macro and mesopore diameters were found for Γ, with 5.3%, 11.7% and 18.2% corresponding to pore sizes of > 300, 300-50 and 50-12.5 μm, respectively. In addition, the micropores amount (<12.5 μm) was significantly smaller than that for other structures. Similar macro and micropores amounts were found by Sasal (2012). The remaining structures had similar pore size distribution assemblages with average values of 1.1%, 3.7%, 8.1% and 32.8% for pores > 300, 300-50, 50-12.5 and < 12.5 μm, respectively.

### *Soil Structural porosity (SP)*

The SP of Γ (8.5%) was significantly greater than that of the rest of the structures, 2.5 times greater than for P (4.3%) (data not shown). The SP of P did not differ from that of Φ and Δ (3.5 and 2.7% respectively). The SP values obtained for P, Φ and Δ were in agreement with those reported for Argiudolls of the Argentine Pampas by Sasal (2012) and De Battista *et al.,* (1994).

The findings on TP, pore size distribution and SP emphasize the need to promote agricultural practices that could change patterns of structure distribution into the soil profile as a way to improve certain global soil physical properties, such as soil porosity.

### *Aggregate stability (AS)*

In contrast to the rest of the soil physical properties presented above, a significant interaction treatments x type of soil structure was observed in AS (Table 3). The MWDmean showed that Γ (found in the first 10 cm depth) presented greater AS under the G and PL+G treatments, indicating that this stability effect was due to the inorganic amendment ($p < 0.05$) (average MWDmean 1.5 vs 1.1 mm for treatments with and without G, respectively). For P (also found on the first 10 cm depth), the AS under T was smaller than under G and PL, but comparable with PL+G. Gabioud *et al.,* (2011) for the first 10 cm soil of similar soil type reported MWDmean values of >2 mm under pristine situations, and between 1.0 – 1.5 mm for agriculture soils under NT. For Φ y Δ, no significant differences due to treatments have been detected. These results were expected since these structures were found below 10 cm depth, and as mentioned before, the amendments were surface applied.

*Modifications of soil organic carbon (SOC) by application of amendments*

Local studies have reported increases in SOC due to the addition of organic amendments in Argiudolls. After poultry litter additions, Andreau *et al.,* (2012) reported increases in total soil carbon in horticultural productions, and De Battista & Arias (2016) reported increases 0.9 % in the organic matter of agricultural Vertisols.

Accordingly, a significant increase (0.42%) at 20-months after application of amendments relative to initial SOC (Table 4) was observed under PL and PL+G treatments. Although 20-months after application of treatments, T had a similar SOC to value at the start of the experiment, treatment G also showed a significant increase in SOC. The significant increases in SOC took place in the first 5 cm of soil. In the subsurface 5-15 cm layer, no significant differences were observed.

The combination of CP method with the study of the physical properties of each soil structure type allowed us to distinguish the specific effects of the addition of organic and inorganic amendments on soil structure dynamics. Specially, important evidence was gathered for the understanding the fate of the P structure, its dynamics and the regeneration of Γ structure from P in silty soils, especially in the upper centimeters where water infiltration and soil water erosion occur. Based on this evidence, it is possible to propose agricultural practices that are compatible with NT to improve soil quality in the short-term. In this sense, the combination of PL+G adds the benefits of the C inputs from PL and the increased soil stability (AS) from G, which could improve the infiltration of water into the soil.

## Conclusions

Short-term soil structure regeneration of silty soils affected by continued agricultural use requires screening and evaluation of potential strategies, like the use of organic and inorganic amendments.. In our study, Γ structure showed improved physical conditions, Bd, Ss, TP, SP and pore size distribution (with an increase in >300µm pores), compared to the rest of the structures. After 20-months, poultry litter amendment improved soil surface SOC, the proportion of Γ structure and decline of P, and soil stability (when combined with gypsum). The application of the two amendments had a complementary effect, since PL increased the Γ percentage and G strengthened soil aggregates against water action. If the changes induced by PL persisted over time, the increased Γ structure could promote improvements in other processes, determining soil productivity through water infiltration, percolation rates and water distribution in the soil profile. We showed that it is possible to regenerate soil structure of NT soils in the short-term with the addition of amendments.

## Acknowledgements

This study was supported by three projects: PNNAT 1128042, PNSUELO 1134023 and PRET ERIO 102. We thank the technical and support staff of the Natural Resources Group of the EEA Paraná INTA.

References

Álvarez, C. R., Taboada, M. A., Perelman, S. & Morras, H. J. M. (2014). Topsoil structure in no-tilled soils in the Rolling Pampa, Argentina. *Soil Research*, 52(6): 533 - 542.

Andreau, R., Gelati, P., Provaza, M., Bennardi, D., Fernández, D. & Vázquez, M. (2012). Degradación física y química de dos suelos del cordón hortícola platense. Alternativas de tratamiento. *Ciencia del Suelo*, 30(2): 107 – 117.

Ball, B. C., Munkholm, L. J. (Eds.). (2015). Visual Soil Evaluation: Realising Potential Crop Production with Minimum Environmental Impact. *CABI*, Wallingford.

Bastida, F., Zsolnay, A., Hernández, T. & García, C. (2008). Past, present and future of soil quality indices: A biological perspective. Review. *Geoderma*, 147: 159 – 171.

Boizard, H., Peigné, J., Sasal, M. C., Guimaraes, F., Piron, D., Tomis, V., Vian, J. F., Cadoux, S., Ralisch R., Tavares Filho, J., Heddadj, D., De Battista J., Duparque, A. & Roger-Estrade J. (2017). Developments in the "profil cultural" method for an improved assessment of soil structure under no-till. *Soil and Tillage Research*, 173: 92 – 103.

Boizard, H., Yoon, S.W., Leonard, J., Lheureux, S., Cousin, I., Roger-Estrade, J. & Richard, G. (2013). Using a morphological approach to evaluate the effect of traffic and weather conditions on the structure of a loamy soil in reduced till-age. *Soil and Tillage Research*, 127: 34 – 44.

Boizard, H., Richard, G., Roger-Estrade, J., Durr, C. & Boiffin, J. (2002). Cumulative effects of cropping systems on the structure of the tilled layer in northern France. *Soil and Tillage Research*, 64: 149 – 164.

Burke, W., Gabriels, D. & Bouma, J., eds. (1986). *Soil Structure Assessment*. Rotterdam, A.A Balkema, 92p.

Cosentino, D., Chenu, C. & Le Bissonnais, Y. (2006). Aggregate stability and microbial community dynamics under drying-wetting cycles in a silt loam soil. *Soil Biology and Biochemistry* 38: 2053 – 2062.

De Battista, J. J., Andriulo, A., Ferrari, M. & Pecorari, C. (1994). Evaluation of the soils structural condition under various tillage systems in the Pampa Humeda (Argentina). In: *Proceedings of the 13th ISTRO Conference*, Alborg, Denmark, pp. 99 – 103.

De Battista, J. J. & Arias, N. M. (2016). Utilización de la cama de pollo como fertilizante en cultivos anuales, en suelos Vertisoles de Entre Ríos. En Almada, N. S., Araujo, S. R., Arias,

N. M., Bernigaud, I. C., Bueno, D. J., De Battista, J. J., Duarte, S. L, Federico, F. J., Ferrer, J. L., Gallinger, C. I., Gange, J. M., García, A. L., Genta, G., Procura, F., Pulido, D. G., Ré, A. E., Rodriguez, F. I. & Soria, M. A; Editores. Cama de pollo en Entre Ríos: aportes para un mejor uso y manejo. 1ª Edición. Ediciones INTA. 85 pp.

Dexter, A. R. (1988). Advances in characterization of soil structure. *Soil and Tillage Research*, 11: 199 - 238.

Di Rienzo, J. A., Casanoves, F., Balzarini, M. G., Gonzalez, L., Tablada, M. & Robledo, C. W. (2017). InfoStat versión 2017. Grupo InfoStat, FCA, Universidad Nacional de Córdoba, Argentina. URL: http://www.infostat.com.ar

Di Rienzo, J. (2011). Modelos lineales mixtos: aplicaciones en InfoStat / Julio Alejandro Di Rienzo Raúl Edgardo Macchiavelli., Fernando Casanoves - 1a. ed. - Córdoba: Grupo Infostat, 2011. 193 p.

Dontsova, K. M. (1998). Soil structure and infiltration as affected by exchangeable Ca and Mg, and soil amendment. MS thesis. West Lafayette, Ind.: Purdue University, Department of Agronomy.

Drewry, J. J. (2006). Natural recovery of soil physical properties from treading damage of pastoral. *Agriculture Ecosystems and Environment*, 114: 159 - 169.

Emmet-Booth, J. P., Forristal, P. D., Fenton, O. , Ball, B. C. & Holden, N. M. (2016), A review of visual soil evaluation techniques for soil structure. *Soil Use Management*, 32: 623-634. doi:10.1111/sum.12300.

Fies, J. C., Stengel, P., Bourlet, M., Horoyan, J., & Jeandet, C. (1981). Densité texturale de sols naturels. I.-Méthode de mesure. *Agronomie*, 1(8), 651-658.

Fisher, M. (2011). Amending soils with gypsum. Crops & Soils Magazine, November - December 2011. URL: http://landstewards.com/wp-content/uploads/2016/02/amending-soils-with-gypsum.pdf. May 2019.

Flanagan, D. C., Norton, L. D. & Shainberg, I. (1997a). Effect of water chemistry and soil amendments on a silt loam soil: part 1: infiltration and runoff. Transactions of the ASAE, 40(6), 1549-1554.

Flanagan, D. C., Norton, L. D. & Shainberg, I., (1997b). Effect of water chemistry and soil amendments on a silt loam soil: part 2: infiltration and runoff. Transactions of the ASAE, 40(6), 1555-1561.

Gabioud, E. A., Wilson, M. G. & Sasal, M. C. (2011). Análisis de la estabilidad de agregados por el método de Le Bissonnais en tres órdenes de suelos. *Ciencia del Suelo*, 29(2) 129 - 139.

Gautronneau, Y., & Manichon, H. (1987). Guide méthodique du profil cultural (p. 71). Groupe d'études d'application et de recherche en agriculture. Lyon, France.

Hillel, D. (1980). Applications of soil Physics. *Academic Press*. US.p.425.

Klute, A. (1986). Water retention: laboratory methods. pp 635- 660. En Klute, A. (ed). *Methods of soil analysis*. Part 1: Physical and mineralogical methods. *Agronomy* 9, ASA, ASA, Inc., Publisher, 1188p., Madison, Wisconsin, USA.

Le Bissonnais, Y. 1996. Aggregate stability and assessment of soil crustability and erodability. I. Theory and methodology. *European Journal of Soil Science* 51(5), 1314-1320.

Lozano, L. A., Soracco, C. G., Cornelis, W. M., Gabriels, D., Sarli, G. O. & Villarreal, R. (2013). Anisotropy of Pore Size Classes' Connectivity Related to Soil Structure Under No Tillage. *Soil Science*, 178(11): 612 - 617.

Monnier, G., Stengel, P. & Fies, J. C. (1973). Une méthode de mesure de la densité apparente de petits agglomérats terreux: application a l'analyse des systèmes de porosité du sol. *Annales agronomiques*, 24(5), 533 - 545.

Neves, C. S. V. J., Feller, C., Guimarães, M. F., Medina, C. C., Tavares Filho, J. & Fortier, M. (2003). Soil bulk density and porosity of homogeneous morphological units identified by the cropping profile method in clayey Oxisols in Brazil. *Soil and Tillage Research*, 71: 109 - 119.

Norton, L. D. & Dontsova, K .M. (1998). Use of soil amendments to prevent soil surface sealing and control erosion. *Advances in GeoEcology*, 31, 581-588.

Novelli, L. E., Caviglia, O. P., Wilson, M. G. & Sasal, M. C. (2013). Land use intensity and cropping sequence effects on aggregate stability and C storage in a Vertisol and a Mollisol. *Geoderma* 195-196: 260 - 267.

Orellana, de J. & Pilatti M. (1990). Aplicación de enmiendas cálcicas en un horizonte B2t. *Ciencia del Suelo*, 8 (2):127-139.

Peigné, J., Vian, J.F., Cannavaciuolo, M., Lefevre, V., Gautronneau, Y & Boizard, H. (2013). Assessment of soil structure in the transition layer between topsoil and subsoil using the profil cultural method. *Soil and Tillage Research,* 127: 13–25.

Piccolo, A. & Mbagwu, J. S. C. (1990). Effects of different organic waste amendments on soil microaggregates stability and molecular sizes of humic substances. *Plant and Soil*, 123: 27 - 37.

Plan Mapa de Suelos (1998). Carta de Suelos de la República Argentina. Departamento Paraná, Provincia de Entre Ríos, Serie Relevamiento de Recursos Naturales Nº 17, 114 pp.

Sasal, M. C., Boizard, H., Andriulo, A., Wilson, M. & Léonard, J. (2017a). Platy structure development under no-tillage in the northern humid Pampas of Argentina and its impact on runoff. *Soil and Tillage Research*, 173: 33 - 41.

Sasal, M. C., Léonard J., Andriulo, A. & Boizard, H. (2017b). A contribution to under-standing the origin of platy structure in silty soils under no tillage. *Soil and Tillage Research*, 173: 42 – 48.

Sasal, M. C. (2012). Factores condicionantes de la evolución estructural de suelos limosos bajo siembra directa. Efecto sobre el balance de agua. Tesis Doctoral. Escuela para Graduados Alberto soriano, Facultad Agronomía UBA. 126p.

Sasal, M. C., Andriulo, A. E. & Taboada, M. A. (2006). Soil porosity characteristics and water movement under zero tillage in silty soils in Argentinian Pampas. *Soil and Tillage Research*, 87: 9-18.

Soil Survey Staff. (2010). Keys to Soil Taxonomy, 11th ed. United States Departament of Agriculture. Natural Resources Conservation Service, 346 pp.

Taboada, M. A., Barbosa, O. A. & Cosentino, D. J. (2008). Null creation of air-filled structural pores by soil cracking and shrinkage in silty loamy soils. *Soil Science*, 173(2): 130 -142.

Tester, C. G. (1990). Organic amendment effects on physical and chemical properties of a sandy soil. *Soil Science Society of America Journal,* 54(3): 827 - 831.

*Tirado-Corbalá, R., Slater, B. K., Dick, W. A.,* Bigham, J., & McCoy, E. (2013). Hydrologic properties and leachate nutrient responses of soil columns *collected fro*m gypsum-treated fields. *Soil and Tillage Research*, 134: 232 - 240.

Unc, A. & Goss, M. J. (2006). Impact of organic waste amendments on soil hydraulic properties and on water partitioning. *Journal of Environmental Engineering and Science,* 5(3): 243 - 251.

Wallace, A. (1994). Use of Gypsum on soil where needed can make agriculture more sustainable. *Communications in soil science and plant analysis,* 25(1-2), 109-116.

Walworth, J. (2012). Using Gypsum and Other Calcium Amendments in Southwestern Soils. College of Agriculture and Life Sciences, University of Arizona (Tucson, AZ). URL: https://extension.arizona.edu/sites/extension.%20arizona.edu/files/pubs/az1413.pdf. May 20119.

Wilson, M. G., Sasal, M. C. & Caviglia, O. (2013).Critical bulk density for a Mollisol and a Vertisol using least limiting water range: Effect on early wheat growth. *Geoderma*, 192: 354 - 361.

Wilson, M. G. & Cerana, J. (2004). Mediciones físicas en suelos con características vérticas. *Revista Científica Agropecuaria*, 8(1): 11 - 22.

**Table 1** Physical and chemical characterization of the poultry litter and gypsum amendments used.

| Poultry litter | |
|---|---|
| pH | 7.9 |
| Electrical conductivity (mS cm$^{-1}$) | 7.7 |
| Moisture (%) | 47.5 |
| Organic matter (%) | 59.8 |
| Dry matter (%) | 52.5 |
| Total Organic Carbon (% dry) | 47.2 |
| Kjeldahl Nitrogen (%) | 2.5 |
| Total Phosphorus (mg g$^{-1}$) | 16.9 |
| C/N ratio | 18.9 |
| Density (g L$^{-1}$) | 309.8 |
| Magnesium (mg 100g$^{-1}$) | 1080 |
| Calcium (%) | 2.87 |
| Potassium (%) | 1.5 |
| Sodium (%) | 0.138 |
| Sulfate sulfur (mg kg$^{-1}$) | 312.1 |
| **Gypsum** | |
| Calcium (%) | 20.7 |
| Sulfate sulfur (%) | 16.6 |
| Moisture (%) | 0.3 |

**Table 2** Bulk density (Bd), Shear strength (Ss) and Total Porosity (TP) values and standard errors of each soil structure types after 20-months of amendment application. Different letters within a column indicate significant difference (LSD Fisher $p<0.05$).

| Structure | Bd (Mg $m^{-3}$) | | Ss (kPa) | | TP (%) | |
|---|---|---|---|---|---|---|
| Γ | 1.08a | ±*0,01* | 32.3a | ±*1.69* | 56.6a | ±*0.33* |
| Ρ | 1.37b | ±*0.02* | 45.8b | ±*1.35* | 46.1b | ±*0.78* |
| Φ | 1.43c | ±*0.01* | 56.4c | ±*1.54* | 46.3b | ±*0.40* |
| Δ | 1.47d | ±*0.01* | 70.2d | ±*2.57* | 44.4b | ±*0.88* |

**Table 3** Mean weight diameter mean (mm): values and standard errors of the structure–treatment interaction after 20 months of application amendment. Structures: Gamma (Γ), Platy (P), Phi (Φ) and Delta (Δ). Treatment, T: Control; G: gypsum; PL+G: poultry litter and gypsum; PL: poultry litter). Different letters indicate significant difference among structure by treatment combinations (LSD Fisher p<0.05).

| | Treatment | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| Structure | T | | G | | PL+G | | PL | |
| Γ | 1.16 bc | ±*0.08* | 1.46 a | ±*0.03* | 1.51 a | ±*0.21* | 1.12 bc | ±*0.05* |
| P | 1.05 c | ±*0.01* | 1.41 ab | ±*0.09* | 1.16 abc | ±*0.20* | 1.34 ab | ±*0.05* |
| Φ | 1.17 abc | ±*0.10* | 1.09 c | ±*0.06* | 1.32 abc | ±*0.05* | 1.23 abc | ±*0.10* |
| Δ | 1.21 abc | ±*0.07* | 1.28 abc | ±*0.03* | 1.10 bc | ±*0.05* | 1.30 abc | ±*0.02* |

**Table 4** Soil organic carbon (%) and standard errors for two depths (0-5 and 5-15 cm) at initial conditions (before amendment treatments application) and after 20-months of amendment applications (T: control, G: gypsum; PL+G: poultry litter and gypsum; PL: poultry litter). Different letters within each depth indicate significant differences (LSD Fisher p<0.05).

| | Depth (cm) | | | |
|---|---|---|---|---|
| | 0-5 | | 5-15 | |
| Initial Condition | 2.05c | ±*0.06* | 1.47a | ±*0.05* |
| T | 2.08bc | ±*0.14* | 1.38a | ±*0.03* |
| G | 2.33ab | ±*0.09* | 1.47a | ±*0.05* |
| PL+G | 2.48a | ±*0.05* | 1.37a | ±*0.08* |
| PL | 2.47a | ±*0.07* | 1.47a | ±*0.06* |

**Figure 1** Location of the study site and the experimental design in the field in Argentina.

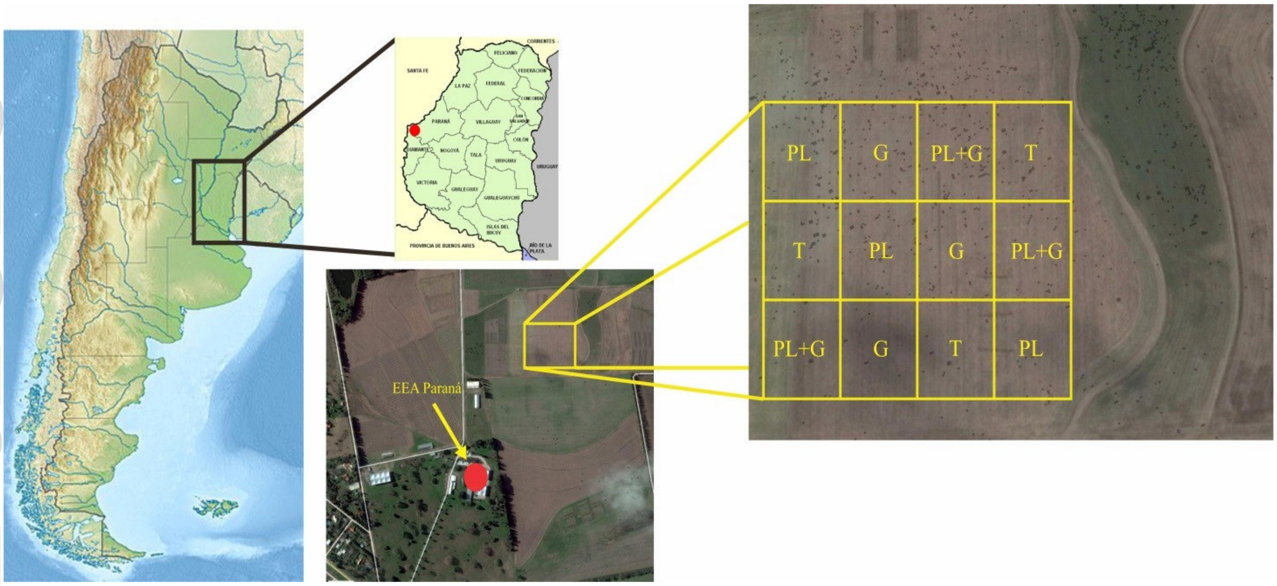
**Figure 2** Soil structures present in a cultural profile of the initial situation (before amendments application). Colors indicate different structures: orange P, brown Φ and red Δ.

**Figure 3** Visual Soil Evaluation by "Le profil cultural" (CP) method. Columns represent the post amendment application time and the rows represent the amendment treatments (T: control; G: gypsum; PL + G: poultry litter and gypsum; PL: poultry litter). Different colors represent soil structures found: green Gamma (Γ), orange Platy (P), brown Phi (Φ) and red Delta (Δ). Each image corresponds to an example of the three profiles per treatment.

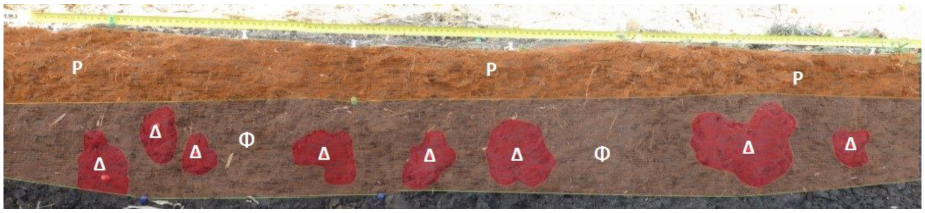
**Figure 4** Gamma (Γ) structure percentage (%) and standard errors for post amendment application time-amendment treatment interaction. Months after amendment application: 2-, 10- and 12-months. Amendment treatments: T: control; G: gypsum; PL+G: poultry litter and gypsum; PL: poultry litter. Different letters indicate significant difference among treatments by post amendment application time combinations (LSD Fisher $p<0.05$).

**Figure 5** Platy (P) structure percentage (%) and standard errors for (a) post amendment application time, and (b) amendment treatment . Months after amendment application: 2-, 10- and 12-months. Amendment treatments: T: control; G: gypsum; PL+G: poultry litter and gypsum; PL: poultry litter). For each graph, different letters indicate significant difference (LSD Fisher $p<0.05$).

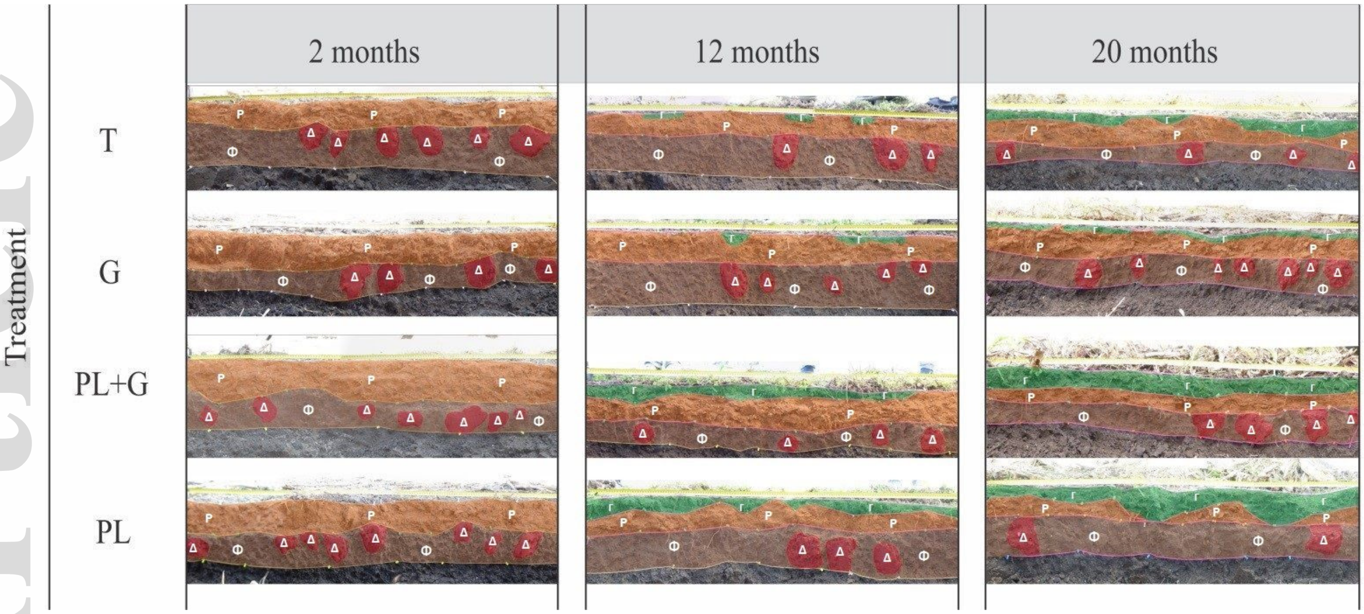
**Figure 6** Pore size distribution (>300 µm, 300-50 µm, 50-12.5 µm and >12.5 µm) for the different structures (Gamma (Γ), Platy (P), Phi (Φ) and Delta (Δ)) found in Cultural Profile after 20-months of amendment treatments application. Different letters indicate significant difference (LSD Fisher $p<0.05$) among soil structures for the same pore size.



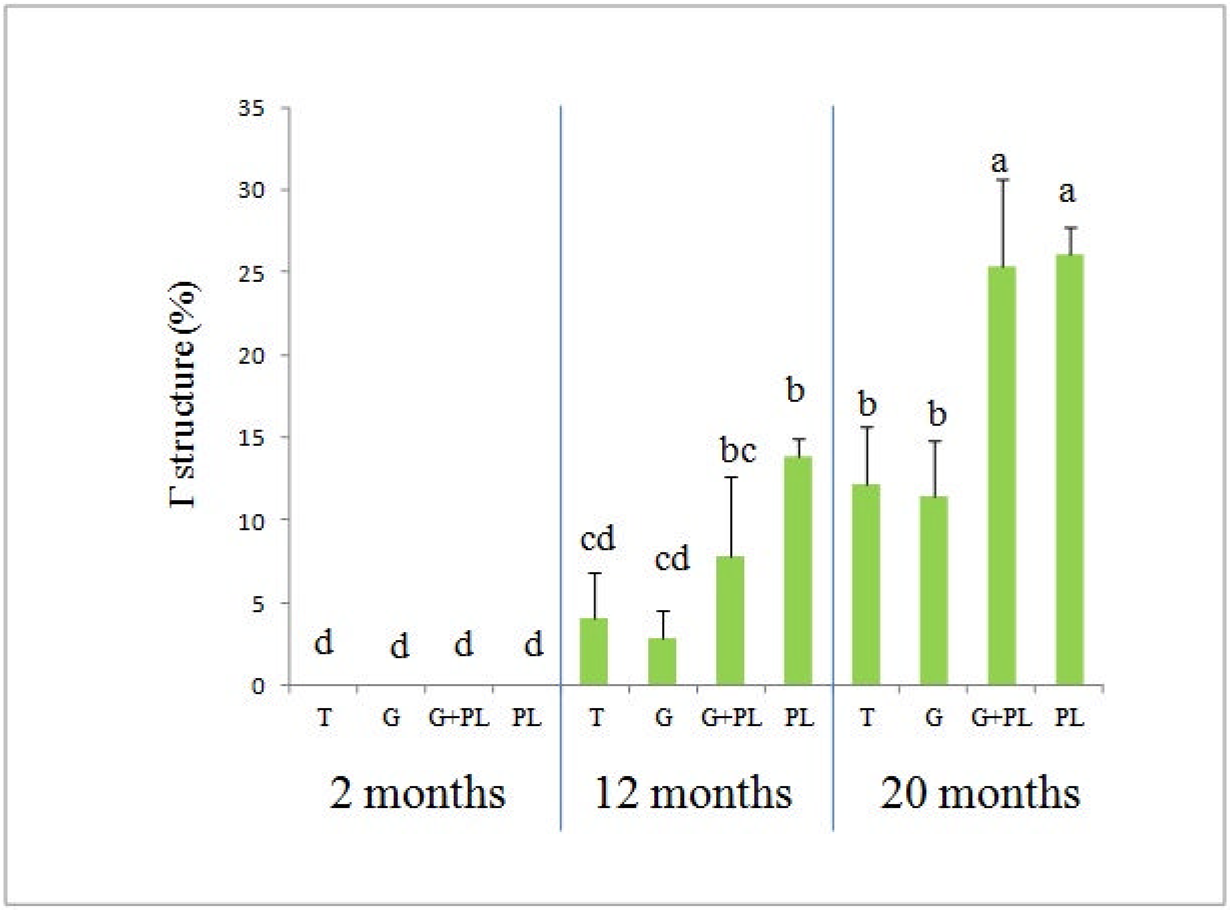
sum_12567-2019-037_f1.tif



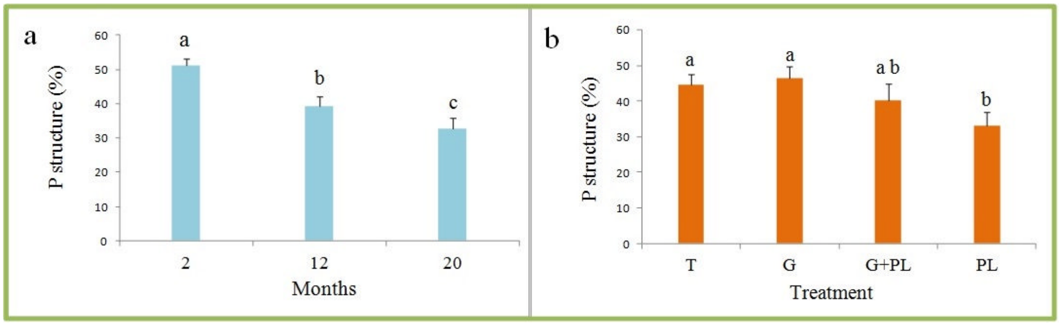
sum_12567-2019-037_f2.tif



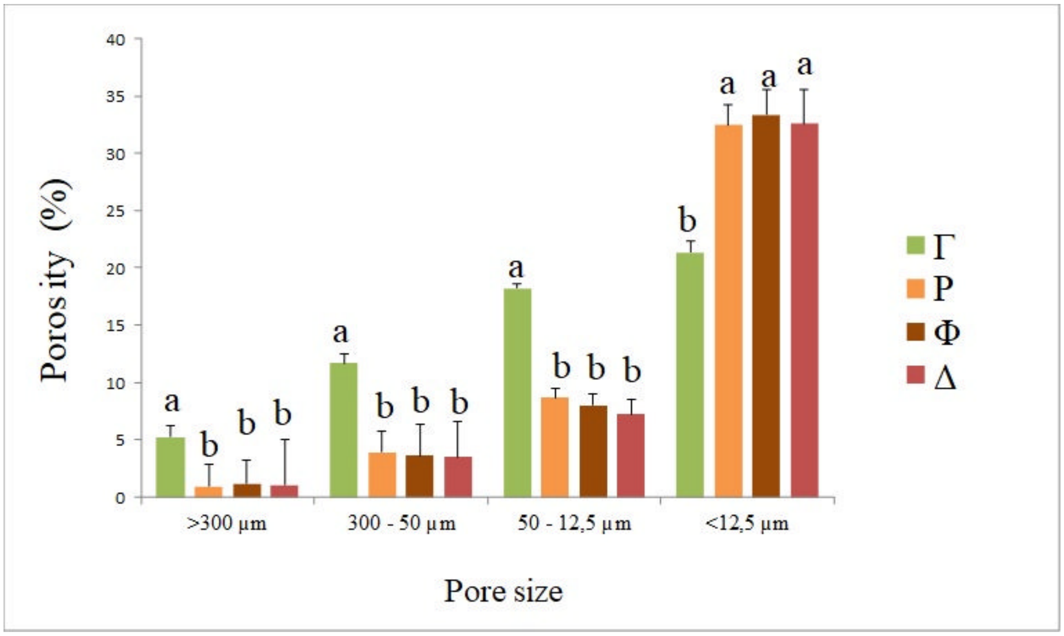
sum_12567-2019-037_f3.tif



sum_12567-2019-037_f4.tif



sum_12567-2019-037_f5.tif



sum_12567-2019-037_f6.tif