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# Addition of amendments to restore a compacted soil under no-tillage system

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**ABSTRACT.** The addition of organic and inorganic amendments can improve soil structure and reduce soil compaction. In this context, this study aimed to evaluate whether the application of amendments reduces penetration resistance (PR) in the short term and describe the spatial variability of PR in the surface horizon of an Aquic Argiudoll under no-tillage in northeast Argentina. Four treatments, consisting of surface applications of 7.5 Mg ha$^{-1}$ poultry litter (PL), 3.0 Mg ha$^{-1}$ gypsum (G), the combination of PL+G, and untreated control (T), were arranged in a complete randomized block design with three replications. Two more treatments were added to the experiment 12 months later, consisting of PL reapplications on half of the surface of the PL+G and PL treatments (PL+G+PL and PL+PL, respectively) in a split-plot design with three replications in 4×20-m plots. PR was determined in the field with an Eijkelkamp penetrologger following a 2-m long transect perpendicular to the sowing direction at 10 different spots separated 0.2 m from each other. The spatial variability was quantified for each treatment using semivariograms. The highest PR was observed in the T treatment (1.96 MPa) and the lowest PR in PL+G+PL (0.21 MPa). All treatments showed a high spatial dependence (94.9 to 99.9%). Treatments with PL reapplication (PL+PL and PL+G+PL) showed profiles with lower PR and more homogeneous kriging maps. PL reapplication on PL treatments showed no effects on PR values. However, PL reapplication on the PL+G treatment led to positive effects in all PR ranges. Thus, the PL+G+PL treatment, which had the highest PR values, showed a decrease in PR from 54.17 to 6.65% with the reapplication 12 months later. The addition of organic and inorganic amendments reduced specific compacted soil areas on the surface horizon of an Aquic Argiudoll under no-tillage.

**Keywords:** penetration resistance; Mollisol; poultry litter; gypsum.

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## Introduction

Soil physical properties affect plant growth (Letey, 1985). The most important properties that directly affect plant growth are water and oxygen availability, temperature, and soil penetration resistance (PR), while the factors that indirectly affect root development include texture, structure, bulk density (Bd), and intrinsic characteristics of the soil profile, among others. The correlation between PR and root growth and crop production is proven (da Silva & Kay, 1996; Sadras, O'Leary, & Roget, 2005). Many studies have assessed the spatial variability of PR (Alves, Figueiredo, Oliveira, Grego, & Silva, 2018; Campos, Aquino, Oliveira, & Bergamin, 2013; Corado Neto et al., 2015; Miola, Pauletto, Lim, Pinto, & Timm, 2015) mainly in the 0–0.20 m layer due to the relevance of the anthropic effects on this layer (Bertol, Beutler, Leite, & Batistela, 2001).

According to Reicosky and Saxton (2007), the implementation of conservation agriculture has three principles or pillars: minimum disturbance of the topsoil by tillage, diversity of rotations and crop cover, and the continuous addition of crop residues on the soil surface. Thus, the main benefit of conservation agriculture and no-tillage (NT) systems is the increase in soil organic matter and its positive impacts on many processes that determine soil quality.

Currently, silt soils of the Pampa region in Argentina are predominantly cultivated under NT. This practice is adequate to mitigate erosion processes associated with tillage. However, NT can cause soil structure degradation, compaction, and reduced water infiltration rate when associated with the simplification of crop sequences or soybean monoculture, leading to an increased runoff (Sasal, Boizard, Andriulo, Wilson, & Léonard, 2017a and b). This problem is accentuated by the uncontrolled traffic and the repeated passage of machinery during the harvest of the main summer crops (soybean and corn) under soil moisture conditions above the optimum for the passage of wheels. In addition, the low capacity of natural regeneration of the soil structure is reduced due to the absence of freeze-thaw processes and the presence of illite clay, which has a low shrinkage-swelling capacity (Senigagliesi & Ferrari, 1993; Taboada, Micucci, Consentino, & Lavado, 1998; Hussein & Adey, 1998; Batey, 2009). In this sense, the natural recovery of porosity is much slower in reduced tillage systems (Boizard et al., 2013).

In general, the addition of organic amendments can positively influence soil structure, increasing the formation and stability of aggregates (Tisdall & Oades, 1982; Piccolo & Mbagwu, 1990; Sasal, Andriulo, Ullé, Abrego, & Bueno, 2000), decreasing Bd (Clapp, Stark, Clay, & Larson, 1986; Tester, 1990), and improving the water infiltration rates, hydraulic conductivity (Unc & Goss, 2006), and soil water retention capacity (Roldán et al., 2003). Rauber et al. (2012) improved the favorable physical conditions in the soil structure with the application of poultry litter or other organic amendments. Also, the use of inorganic amendments to improve soil physical properties has been usually oriented towards the formation and stabilization of aggregates (Norton & Dontsova, 1998), as well as aiming to reduce soil penetration resistance and increase macroporosity (Orellana & Pilatti, 1990). Gypsum application reduces dispersion and promotes flocculation. Flocculation is a necessary condition for the formation and stabilization of the soil structure and leads to an increase in water infiltration and percolation (McCray, Summer, Radcliffe, & Clark, 1991; Dontsova, Darrell Norton, Johnston, & Bigham, 2004; Norton, 2008).

In this context, this study assessed the short-term effects of different amendments on soil PR at several depths in an Aquic Argiudoll. Moreover, the spatial variability of PR on the surface horizon was described after the application of poultry litter (PL), gypsum (G), and the association PL+G under NT systems. The use of organic and inorganic amendments is expected to have different responses in the topsoil although we expect that the association of amendments will have a better performance.

## Material and methods

### Description of the experimental site

The study was carried out at the Paraná Experimental Station of the Instituto Nacional de Tecnología Agropecuaria (INTA), located in Entre Ríos province, northeast Argentina (31°50′57.20″ S and 60°31′54.11″ W, with an elevation of 110 m). The area was covered by a fine, illitic, thermic Aquic Argiudoll (Soil Survey Staff, 2010) of the Tezanos Pinto Series. A field experiment was started in June 2014 in a production plot with a soybean-corn (*Glycine max* and *Zea mays*, respectively) rotation under NT for at least 15 years. The experiment was carried out in a complete randomized block design with three replications. Four treatments were tested, consisting of surface applications of poultry litter (PL) as an organic amendment, gypsum (G) as an inorganic amendment, the combination of PL+G, and untreated control (T) (Gabioud et al., 2019).

Treatments were manually applied in August 2014 to achieve a uniform and accurate distribution of the amendments.

The amendment doses consisted of:

i) 7.5 Mg ha$^{-1}$ of dry PL (corresponding to approximately 3.5 Mg ha$^{-1}$ of carbon). Poultry litter (PL) is a mixture of feces, wasted feeds, feathers, and rice husks used as bedding material. The bedding material was stabilized in a pile for 5 months before application on the soil surface.

ii) 3.0 Mg ha$^{-1}$ of gypsum (G). The product consisted of the granulated agricultural gypsum YESOER85 of 1–5 mm, manufactured by Piedras Blancas S.A. (http://www.yesoer.com.ar/caracteristicas-del-producto/). The used dose was suggested by Wilson and Cerana (2004), who observed significant changes in soil physical conditions under rice cultivation with doses from 1.5 to 3.0 Mg ha$^{-1}$ of G, without causing phytotoxicity effects in crops.

The control treatment (T) consisted of inorganic fertilizers of traditional use in the region (tricalcium phosphate and granulated urea), with the dose adjusted to the nitrogen and phosphorus contents in the poultry litter.

The effects of PL reapplication on the soil surface were observed by applying the same PL dose to half of the surface of the PL+G and PL plots (PL+G+PL and PL+PL, respectively) at twelve months after the beginning of the experiment, in a split-plot design with three replications in 4 × 20-m plots.

## Field determinations

PR was measured with the soil water content retained at field capacity (30.5% vol vol$^{-1}$) at twenty months after amendment application. An Eijkelkamp penetrologger 2000 (Giesbeck, The Netherlands) was manually operated into a depth of 0.2 m (Wilson, Mirás-Avalos, Lado, & Paz-González, 2016). A cone with a base surface of 2 cm$^2$ and an apex angle of 30° was selected. Penetration speed was 2 cm s$^{-1}$. PR data sets were obtained at each point at 1-cm intervals and expressed in MPa units. PR data were collected following a 2-m length transect perpendicular to the sowing direction at 10 different sites separated 0.2 m from each other (Figure 1).

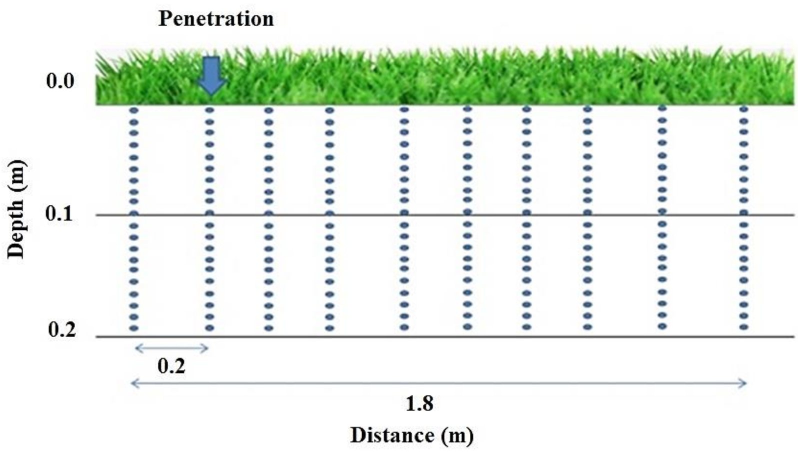


**Figure 1.** Soil sampling scheme for penetration resistance measurements at each plot.

## Data analysis

The main statistical moments commonly accepted as indicators of central tendency and data spread were computed for each treatment. It included examining the mean, variance, coefficient of variation, and minimum and maximum values. A normality test was performed to observe the initial behavior of the data, remove outliers, and facilitate the spatial analysis. The Shapiro and Wilk test at a 5% significance was conducted to test the normality or log normality hypothesis using the software SAS (Schlotzhaver & Littell, 1997). The variability of the attributes was classified, according to Pimentel-Gomes and García (2002) considering the magnitude of its coefficient of variation (CV), as low (CV ⩽ 10%), medium (10% < CV ⩽ 20%), high (20% < CV ⩽ 30%), and very high (CV > 30%).

In geostatistics, the spatial variability of a given soil property is quantified from correlograms and semivariograms, determining the spatial dependence between sample units and the extent of influence of each sampling point (Vieira et al., 1981). The semivariogram describes the type and form of spatial dependence, being the first stage of the geostatistical analysis before mapping (Vieira, Hatfield, Nielsen, & Biggar, 1983; Bonnin, Mirás-Avalos, Lanças, Paz González, & Vieira, 2010; Kuhwald et al., 2016). The experimental semivariogram is a graph of semivariance as a function of distance that characterizes the spatial dependence structure of the study variable. The semivariogram is defined according to Equation (1):

$$\hat{\gamma}(h) = \frac{1}{2N\,(h)} \sum_{i=1}^{N(h)} [z(x_i) - z(x_i + h)]^2 \qquad (1)$$

where $\gamma(h)$ is the experimental semivariance for a separation distance h, $z(x_i)$ is the property value at point i, and N(h) is the number of pairs of points separated by distance h. The plot $\gamma(h) \times h$ produces the experimental semivariogram, which may present a purely random or systematic behavior described by a given theoretical model (e.g., spherical, exponential, and Gaussian).

In the current study, the choice of the adjusted semivariogram model and its parameters was based on the sum of squared residuals and the coefficient of determination ($r^2$), using the cross-validation technique. Values were estimated at non-sampled sites by kriging after adjusting the model for the semivariogram, as it is a non-biased linear estimator (Webster & Oliver, 1990). Semivariograms, cross-validation, model adjustment, interpolation by ordinary kriging, and mapping were performed using the software GS+ Geostatistics for the Environmental Sciences version 9.0 (Robertson, 2004) and Surfer (Golden Software, 2002).

The nugget effect ($C_o$), range (Ao), and sill (C) were estimated for each semivariogram. $C_o$ reveals the discontinuity of the semivariogram for distances smaller than the shortest distance among samples. Ao represents the distance at which the semivariogram remains approximately constant. Finally, C is the sill value approaching the data variance. The spatial dependence estimator (SDE) was computed according to Equation (2) (Robertson, 2004):

$$SDE = [C/(C + Co)] \times 10 \quad (2)$$

where C is the sill and $C_o$ is the nugget effect.

The level of spatial dependence can be measured according to the degrees defined by Dalchiavon, Carvalho, Andreotti, and Montanari (2012): SDE ⩽ 20% – very low dependence, 20% < SDE ⩽ 40% – low dependence, 40% < SDE ⩽ 60% – medium dependence, 60% < SDE ⩽ 80% – high dependence, and 80% < SDE ⩽ 100% – very high dependence.

The effect of treatments on the computed parameters was assessed by analysis of variance through mixed general linear models (after checking ANOVA assumptions), Fisher LSD test for mean comparisons, and linear regressions, using the software InfoStat 2017 (Di Rienzo et al., 2017).

PR ranges were defined every 0.5 MPa to show spatial variability. The relative proportion of each PR range was calculated as the ratio between the area of each PR range and the total area of 2 m in length and 0.2 m in depth.

## Results and discussion

The statistical descriptors for soil PR are shown in Table 1.

**Table 1.** Statistical summary of soil penetration resistance (MPa) of an Aquic Argiudoll under no-tillage and organic and inorganic amendments in Entre Rios province, Argentina.

| Treatments[1] | N | Mean | Median | Value | | SD[2] | Coefficient | | | Normality test[3] | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | Minimum | Maximum | | Variation(%) | Kurtosis | Skewness | p-value | FD |
| | 200 | 1.24 | 1.21 | 0.53 | 1.96 | 0.29 | 23.28 | 0.200 | 0.121 | 0.0045 | IN |
| PL | 200 | 0.90 | 0.90 | 0.41 | 1.33 | 0.20 | 22.61 | -0.097 | -0.486 | 0.0002 | IN |
| G | 200 | 1.00 | 0.99 | 0.34 | 1.73 | 0.26 | 26.41 | 0.345 | 0.221 | 0.0589 | NO |
| PL+G | 200 | 1.18 | 1.22 | 0.40 | 1.71 | 0.31 | 26.17 | -0.412 | -0.502 | 0.0001 | IN |
| PL+PL | 200 | 1.02 | 1.02 | 0.42 | 1.49 | 0.19 | 18.60 | 0.492 | -0.194 | 0.2501 | NO |
| PL+G+PL | 200 | 1.00 | 1.03 | 0.21 | 1.75 | 0.29 | 28.91 | 0.439 | -0.360 | 0.0001 | IN |

[1]T, PL, and G are the control, poultry litter, and gypsum treatments, respectively; [2]SD: standard deviation; [3]Normality test, where Pr < w is the p-value for Shapiro-Wilk test and FD is the frequency distribution, IN: indeterminate type and NO: normal type.

The highest and lowest PR values were found in the T (1.96 MPa) and PL+G+PL treatments (0.21 MPa), respectively, with the highest variation (28.91%). The PL+PL treatment had lower variation compared to the other treatments (18.60%). Only G and PL+PL showed normal frequency distribution, while the other treatments had an absence of normality.

No significant differences were observed between treatments at the soil surface (0.01 m) (Table 2 and Figure 2). PL showed the lowest PR value (0.78 MPa) at a depth of 0.05 m, differing significantly from the treatments, and T had the highest PR value. Treatments with G (applied alone or associated with PL) presented intermediate values. Moreover, the PL and G treatments presented the lowest PR values at a depth of 0.10 m, with PL differing significantly from T and PL+G.

However, G and PL presented lower values than T and G+PL below 0.10 m. Although PR did not reach 2.00 MPa in the studied soil, a critical value for plant root development (Arshad, Lowery, & Grossman, 1996; Taylor & Gardner, 1963), poultry litter application reduced PR values throughout the soil profile. Silva, Nunes, Caldeira, Arantes and Souza (2012) worked with different types of organic and inorganic fertilizers and obtained favorable results for organic amendments, which is in line with the present study. Compaction can promote reductions of more than 50% in the soil macropore volume, with favorable results for organic amendments (Severiano et al., 2010).

Differences were observed at 0.01, 0.05, and 0.15 m when PL was reapplied on PL+G (PL+G+PL vs PL+G) (Table 3). In all cases, the lowest PR values corresponded to the PL reapplication. Increased PR values were observed at 0.01 and 0.05 m when PL was reapplied on PL+PL (PL vs PL+PL).

The data normality test showed that the PR values in the G and PL+PL treatments were not significant, accepting the hypothesis of data normality. The other treatments (T, PL, PL+G, and PL+G+PL) presented indeterminate frequency distribution, with kurtosis and skewness close to zero (−0.41 to 0.44 and −0.50 to 0.22, respectively). The semivariogram parameters and cross-validation for PR are shown in Table 4.

**Table 2.** Effect of amendments with poultry litter and gypsum on soil penetration resistance (MPa) at fixed depths in an Aquic Argiudoll under no-tillage in Entre Rios province, Argentina.

| Depth (m) | Control (T) | Gypsum | Poultry litter | Poultry litter + gypsum |
|---|---|---|---|---|
| 0.01 | 0.67 ns | 0.57 ns | 0.52 ns | 0.63 ns |
| 0.05 | 1.22 a | 0.97 b | 0.78 c | 0.97 b |
| 0.10 | 1.26 a | 1.07 ab | 0.93 b | 1.22 a |
| 0.15 | 1.15 a | 0.92 b | 0.84 b | 1.22 a |
| 0.20 | 1.04 a | 0.90 b | 0.88 b | 1.07 a |

Means followed by different letters in the row indicate significant differences between treatments (LSD Fisher at $p < 0.05$); ns: not significant.

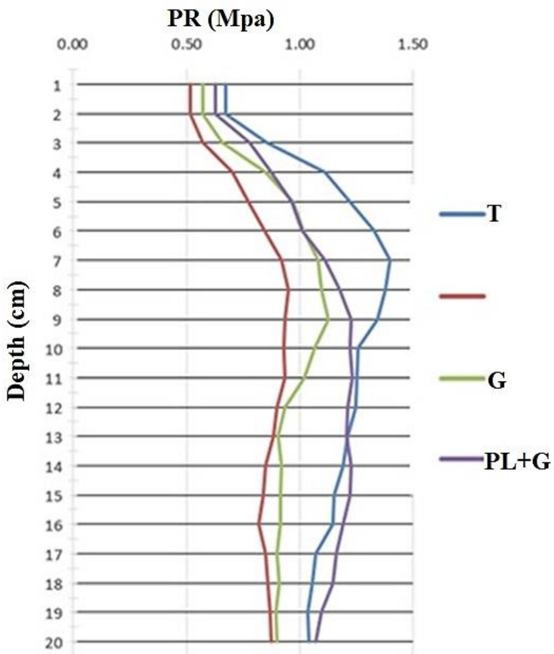


**Figure 2.** Soil penetration resistance (MPa) at different depths (0–20 cm) for each treatment (T: control; G: gypsum; G+PL: gypsum and poultry litter; PL: poultry litter).

**Table 3.** Effects of poultry litter reapplication 12 months after the beginning of the experiment on soil penetration resistance (MPa) at fixed depths in an Aquic Argiudoll under no-tillage in Entre Rios province, Argentina.

| Depth (m) | Poultry litter | Poultry litter + Poultry litter | Poultry litter + Gypsum | Poultry litter + Gypsum + Poultry litter |
|---|---|---|---|---|
| 0.01 | 0.57 | 0.83* | 0.69 | 0.48* |
| 0.05 | 0.85 | 1.15* | 1.06 | 0.88* |
| 0.10 | 1.03 | 1.11 | 1.34 | 1.14 |
| 0.15 | 0.92 | 0.95 | 1.34 | 1.12* |
| 0.20 | 0.96 | 0.99 | 1.18 | 1.08 |

*Significant difference ($p < 0.05$) between the original treatment and the treatment in which poultry litter was reapplied for a given soil depth.

**Table 4.** Parameters of the theoretical models fitted to the experimental semivariograms and cross-validation indicators for soil penetration resistance (MPa) of an Aquic Argiudoll under no-tillage and subjected to the application of organic and inorganic amendments in Entre Rios province, Argentina.

| Treatments[(1)] | Model | Nugget Effect ($C_0$) | Sill($C_0$ + C) | Range (m) | $r^2$ | SSR[(2)] | SDE[(3)] | | Cross-validation[(4)] | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | % | Class | a | b | r |
| T | Gaussian | $1.90x10^{-3}$ | $1.06x10^{-1}$ | 0.06 | 0.981 | $2.28x10^{-4}$ | 98.2 | VH | 0.04 | 0.966 | 0.960 |
| PL | Gaussian | $2.40x10^{-3}$ | $4.68x10^{-2}$ | 0.08 | 0.989 | $2.81x10^{-5}$ | 94.9 | VH | 0.01 | 1.000 | 0.966 |
| G | Gaussian | $9.00x10^{-4}$ | $7.01x10^{-2}$ | 0.06 | 0.977 | $1.20x10^{-4}$ | 98.7 | VH | 0.03 | 0.974 | 0.965 |
| PL+G | Spherical | $1.00x10^{-4}$ | $1.38x10^{-2}$ | 0.18 | 0.975 | $6.55x10^{-4}$ | 99.9 | VH | -0.03 | 1.022 | 0.977 |
| PL+PL | Exponential | $3.00x10^{-4}$ | $5.38x10^{-2}$ | 0.18 | 0.968 | $8.24x10^{-5}$ | 99.4 | VH | -0.08 | 1.080 | 0.925 |
| PL+G+PL | Spherical | $1.00x10^{-4}$ | $1.14x10^{-1}$ | 0.16 | 0.990 | $1.99x10^{-4}$ | 99.9 | VH | -0.03 | 1.028 | 0.984 |

[(1)]T, PL, and G are the control, poultry litter, and gypsum treatments, respectively; [(2)]SSR: sum of squared residuals; [(3)]SDE: spatial dependence evaluator, where VH means very high (Dalchiavon et al., 2012). [(4)]a, b, and r are the y-intercept, regression coefficient, and correlation coefficient in the cross-validation, respectively.

Figure 3 shows the theoretical models fitted to the experimental semivariograms for each treatment. The lowest range was observed for the T and G treatments, while the highest range corresponded to the PL+G and PL+PL treatments (Table 4). The second poultry litter application seemed to increase the range (0.18, 0.18, and 0.16 m for PL+PL, PL+G, and PL+G+PL, respectively), that is, the attribute is spatially dependent at longer distances, and the soil profile is more homogeneous. Thus, values of an attribute located within the area whose radius is equal to the range are similar in magnitude and should be managed similarly (Vieira, Nielsen, & Biggar, 1981; McBratney & Webster, 1985).

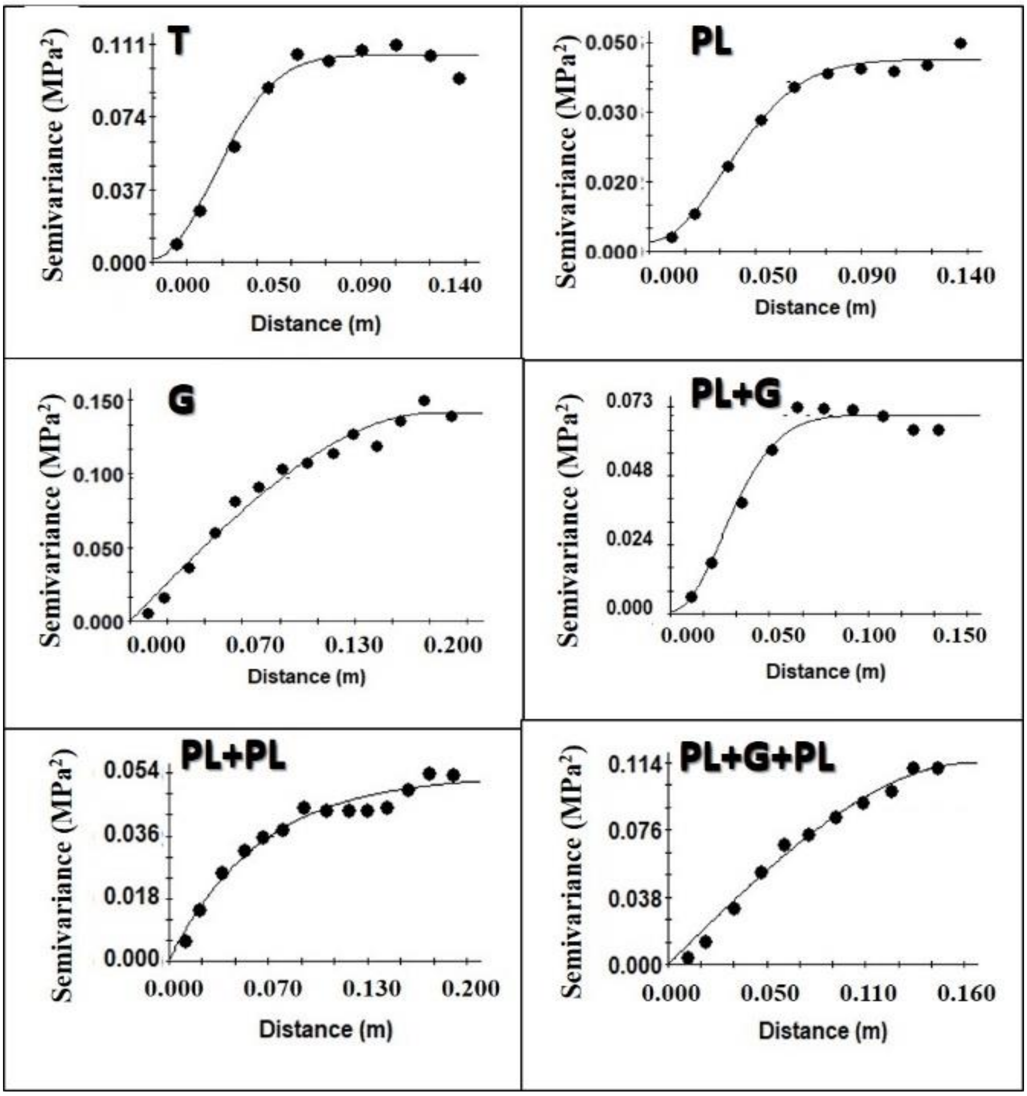


**Figure 3.** Theoretical models fitted to the experimental semivariograms of soil penetration resistance in an Aquic Argiudoll under no-tillage and subjected to the application of organic and inorganic amendments (T = control; G = gypsum; PL = poultry litter).

Regarding the performance of semivariograms, analyzed by the magnitude of the spatial coefficient of determination ($r^2$), the adjusted models showed high $r^2$ values, that is, always higher than 0.97, especially for the PL+G+PL and PL+G treatments (Table 4). Very high spatial dependence values (94.9 to 99.9%) were observed in all treatments, according to Dalchiavon and Carvalho (2012). The well-designed sampling grid (Figure 2) explains the high spatial dependence in this study. Sampling was very important for the study of spatial variability of soil attributes, and the number of samples and distance between them directly influenced SDE. Nagahama, Cortez, Pimenta, Patrocínio Filho, and Souza (2016) also studied the spatial variability of soil PR in an Argisol and observed high SDE, reflected in high $r^2$ values, which ranged from 0.85 to 0.99, similar to the results of the present study.

The nugget effect ($C_o$) ranged from $1\times10^{-4}$ to $2.4\times10^{-3}$ (Table 4). The accuracy of estimates increases the closer to zero are the nugget effect values. Kriging maps allowed analyzing more precisely the PR of each treatment (Figure 4).

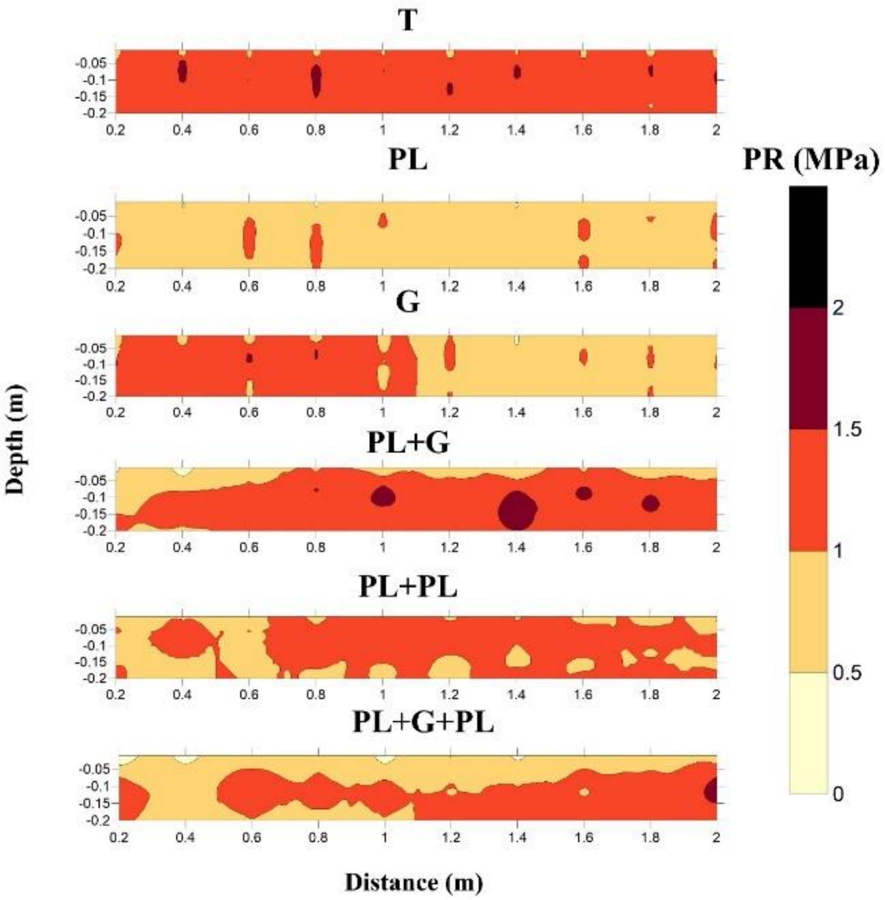


**Figure 4.** Estimation maps of soil penetration resistance generated by ordinary kriging. The area was 2 m long and 0.2 m deep. Treatments: T: control; G: gypsum; G+PL: gypsum and poultry litter, PL: poultry litter; and treatment with PL reapplication: PL+PL and PL+G+PL.

Although the conservationist benefits of no-tillage, Stefanoski, Santos, Marchão, Petter, and Pacheco (2013) indicated that soil compaction by machine traffic is the main cause of physical degradation of agricultural soils, increasing with increasing traffic intensity. Gao et al. (2016) found that layered soil compaction usually limits root growth and the efficiency of resources. The spatial variation in mechanical strength affects the degree of root grouping.

Figure 4 shows the estimation maps of soil penetration resistance generated by ordinary kriging. The highest PR values were observed for T, especially at a depth of 0.10–0.20 m associated with the PL+G treatment. The highest PR range in the control treatment represented 76.17% of the profile surface, while the 0.5–1.0 MPa range corresponded to 23.68%. This range represented 99.26 and 97.35% of the profile surface for PL and G, respectively. Treatments with poultry litter reapplication (PL+PL and PL+G+PL) showed profiles with lower PR and more homogeneous maps. The reapplication on PL (PL+PL) presented no effects on PR values. However, the reapplication on PL+G led to positive effects in all PR ranges. Thus, the PL+G+PL treatment, which had the highest PR values, showed a decrease in PR from 54.17 to 6.65% with the reapplication.

## Conclusion

The addition of organic and inorganic amendments reduced specific compacted soil areas on the surface horizon of an Aquic Argiudoll under no-tillage. However, the application of poultry litter associated with gypsum did not show the expected results. Poultry litter reapplication showed profiles with lower PR and more homogeneous kriging maps. Poultry litter reapplication on the area with the association of poultry litter with gypsum led to positive effects, reducing compacted soil areas.

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