Multivariate analysis of spatial and temporal behavior of soil penetration resistance

Análisis multivariado del comportamiento espacial y temporal de la resistencia del suelo a la penetración

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Abstract

The study of agricultural soil compaction is of great relevance, due to its negative effects on crop development and productivity. A quickly and easy way to identify soil compaction is throughout penetration resistance (PR). The aim of this study was to define an approach to adequately characterize the vertical and horizontal variability of agricultural soil compaction, using multivariate analysis techniques. Soil penetration resistance was measured before tillage and after crop harvesting a field grown with maize (*Zea mays*), using a 32 point regular grid (25 m X 25 m), up to 60 cm of depth. To identify compacted areas and layers, multivariate analysis techniques were used. The hierarchical cluster analysis, considering the PR measurements by sampling point, allowed drawing contour maps with defined compacted areas. Meanwhile, when such an analysis was performed by depth, together with the principal component analysis, three soil layers were identified being the middle layer the one with the highest values of PR in both sampling periods. The approach performed, allowed characterizing the vertical and horizontal variability of PR in the field under study.

Key words: Andisol, cluster analysis, compaction, principal component analysis, soil

Resumen

La resistencia a la penetración (RP) es una forma fácil y rápida de identificar la compactación del suelo. El objetivo del presente trabajo fue evaluar un procedimiento para caracterizar adecuadamente la variabilidad vertical y horizontal de la compactación de suelos agrícolas, usando técnicas de análisis multivariado. Las mediciones de RP se realizaron antes de la labranza y después de la cosecha en un lote sembrado con maíz (*Zea mays*) en la sabana de Bogotá (Colombia), en una cuadrícula regular de 32 puntos (25 m x 25 m), hasta una profundidad de 60 cm. Para identificar zonas y capas compactas del suelo se utilizaron técnicas de análisis multivariado. El análisis jerárquico, realizado a partir delas lecturas de RP por punto de muestreo, permitió elaborar mapas de contorno con zonas delimitadas de compactación. A su vez, cuando el análisis se realizó por profundidad utilizando la metodología de componentes principales, se identificaron tres capas de suelo donde la capa intermedia presentó los mayores valores de resistencia a la penetración en ambos muestreos. El procedimiento utilizado permitió caracterizar las variabilidades vertical y horizontal de la RP en el lote del estudio.

Palabras clave: Análisis de componentes principales, análisis jerárquico, Andisol, compactación, suelo.

Introduction

Compaction is a condition of agricultural soils that limits development and productivity of crops (Soane *et al.*, 1981; Boivin *et al.*, 2006; Medina *et al.*, 2012) and has environmental implications (Soane and Ouwerkerk, 1994). The phenomenon occurs when the pressure applied to the soil reduces its porosity (Lipiec *et al.*, 2003), which depends on the water content in the soil at the moment of exerting pressure, the type and load time and climatic factors and soil characteristics (Cucunubá-Melo *et al.*, 2011). Depending on the type of load, the phenomenon can occur as a result of the transit of agricultural machinery, grazing or natural conditions (Bowen, 1981).

Mechanical strength is an indicator of soil compaction and for its measurement penetrographs and penetrometers are used (Utset and Cid, 2001), that measure the necessary force for driving a standard cone in the ground. The resistance to penetration (PR) is an indirect measure of the force required by the roots to penetrate the pores or the existing channels in the ground, or to deform its structure and advance in the porous medium in order to provide support and absorb nutrients and water for the proper development of crops (Medina *et al.*, 2012).

Typically, the PR is determined by searching average eigenvalues or profiles on a field, however this procedure does not recognize that the PR has spatial (horizontal and vertical) and temporal variations due to natural soil processes and management. Therefore, for accurately estimations, a large number of measurements are required at different locations and depths of the field, accompanied by subsequent spatial analyses (Medina *et al.*, 2012).

There are different techniques for the study of the PR, including the univariate analysis, geostatistics and multivariate analysis. Univariate analysis allows the evaluation the average behavior in a given area. Geostatistics allows viewing the spatial behavior, particularly by layers (depths), which imply a long process and sometimes with similar results among layers, however it clearly identifies layers and areas with compaction problems, which facilitates localized handling (Ramirez-Lopez *et al.*, 2008). On the other hand, multivariate statistics allows data clustering in a few significant intervals, through principal component analysis (PCA) and hierarchical clustering (HCA), which facilitates the identification of PRa correlations at different depths or between sampled points in space, thus eliminating the resulting redundancy of separate data analysis (Stelluti *et al.*, 1997; Orjuela-Matta *et al.*, 2012). For ease, to jointly include a high number of variables, these multivariate methods are applied to classify, model and assess results of environmental studies and agricultural production (Ramos *et al.*, 2007).

PCA is a multivariate technique that uses linear combinations to reduce the dimensionality of the data, transforming the original variables into a set of uncorrelated variables, called principal components (Ramos *et al.*, 2007). The first component is associated with greatest value and has the greatest variance; the second explains the highest variance not explained by the first component and so on for the other components. It is desirable that a small number of components explain large percentage of the total variance, which indicates that the data set is described in a smaller dimensional space (Ferreira, 2011). On the other hand, the HCA seeks to divide a data set into groups, so that the variables of the same group are similar and different from the other groups. HCA tends to combine the groups that have lower variances and can produce clusters that have equal variances (Ferreira, 2011). In this context, the objective of this study was to evaluate a method to properly characterize the spatial (vertical and horizontal) and temporal compaction variability of agricultural soils in the savannah of Bogotá, Colombia.

Materials and methods

The study was conducted between April 2006 and January 2007 in a semicommercial field of corn (*Zea mays*) located in an Andisol where PR spatial data were taken before tillage (S1) and after harvest (S2). The field is located in the town of Mosquera (Cundinamarca) at 4° 42' 00'' N and 74° 12' 59'' W, 2550 m.a.s.l. The area has an annual average temperature of 12.6 °C and a bimodal rainfall regime, concentrated between March and June and October and December, with annual rainfall of 670 mm. The field has a flat topography (slope < 1%) belongs to the Marengo series, with frank-silty and frank-clayey textures, and subangular-fine and medium-moderate structures. The A horizon is thick and dark, caused by lacustrine sediments with volcanic ash sprays and contributions from alluvial clays (Malagon, 2003), presenting a natural drainage between poor and imperfect.

The field of study has been devoted to annual crops (corn, peas and vegetables) treated with conventional tillage, disc tools and rotary disc plow. During the test period it was sown with maize (Zea mays). The first measurement of PR in situ was made prior to the work of tilling the soil (S1) and the second, after the maize harvest (S2). The farm work carried out consisted of a chisel plow pass at a depth of 30 cm and two passes of harrow at a depth of 0.22 m. Between the first and the second measurement of PR an accumulated rainfall of 690 mm was presented. It should be noted that 2006 was a year officially declared by the Climate Prediction Center with several months typical of La Niña phenomenon, with an annual precipitation of 860 mm for the study area.

For sampling, a regular grid of 32 points was designed, with distances of 25 m x 25 m. to obtain the PR data, a penetrograph with a standard cone of 30° and 12.83 mm diameter brand Eijkelkamp - model P1.51 was used, with which three measurements per site were made, up to 60 cm deep in the soil. To generate the database the average values of the PR of the three measurements per sampling point were taken, taking values of PR every 0.05 m, thus 12 values were obtained; in addition the value at 1 cm for the first layer of soil was taken, in order to obtain the surface PR. The average water content in the soil, measured by the gravimetric method in the first 30 of depth cm was 36.04 ± 4.30% for the first sampling, and 36.43 ± 6.27% for the second.

PR data were initially analyzed using descriptive statistics: mean, standard deviation, maximum and minimum values and coefficient of variation (CV), in order to identify the general behavior of the data for each depth. For the analysis of the CV it was taken into account the classification by Warrick and Nielsen (1980), with low variability for values < 12%, mean variability between 12 and 60% and high variability for values > 60%. Subsequently, multivariate statistics was applied to identify behavior by depth and PR extent, through hierarchical cluster analysis (HCA) and principal components (PCA). HCA groupings were formed by depth and by extent to establish the presence of layers and compact zones, using the Euclidean distance to separate the groups identified in the respective dendrograms. The results were obtained using the Ward algorithm, which calculates the distance by the sum of the squares between two groups. Finally, the PCA was performed to the different depths, using Varimax rotation.

Statistical analyzes were performed using SPSS software version 17. To improve understanding of the groups formed and corroborate the spatial behavior, contour maps were made through inverse interpolation of weighted distance (IDW) with the ArcMAP software, version 9.3. The curves of the behavior of the PR in the soil profile were also analyzed, in order to corroborate the results of the HCA.

Results and discussion

Descriptive analysis

The average values of PR in S1 (before land preparation) were < 2 MPa (Table 1), suggesting that compaction is not restrictive for the growth of the roots of crops (Soane *et al.*, 1981 Veronese Jr. *et al.*, 2006; Otto *et al.*, 2011). However, specific values were significantly higher even > 4 MPa, showing that the average alone is not suitable to describe compaction in this soil.

In the second assessment (after harvest) the average values of PR (S2) exceeded 2 MPa, except for the first 0.01 m, showing that over time the combination of factors such as soil preparation and machinery transit, as well as soil and climate conditions favor increases in the mechanical resistance of the soil that can restrict the growth of the roots of crops. In this case, possibly, the intensive use of farming machinery was the factor that affected the most the values of PR. It is known that the soil tends to reverse this human intervention and seeks its original structure by natural processes, a situation that is influenced by rainfall and irrigation during the growing season. In this process the soil particles are rearranged to form hard crusts in short periods after plowing with cohesion forces greater than those of the natural conditions, especially in soils with high content of fine particles (Soane *et al.*, 1981) as was observed in the soils of the present study.

According to Soane *et al.* (1981), Castrignano *et al.* (2002) and Veronese Jr. *et al.* (2006) initial values (S1) PR (< 0.02 MPa) in this study were suitable for growing maize but not the values found in step S2 (> 0.02 MPa). Taking as reference the proposal of Warrick and Nielsen (1980) an average variability for PR was observed in most depths in the soil, except for the first layer, which showed high variability, even with values of PR of zero (0) (Table 1). In S1, the CV values decreased between 1 and 30 cm and rose to a depth of 0.6 m, values that match those found by Veronese Jr. *et al.* (2006) and Medina *et al.* (2012). This behavior was probably due to the transit of machinery, mainly affecting the upper layers, making them more heterogeneous; also soil tillage modifies the structure and therefore the PR. In the S2 an inverse relationship between the CV and the depth was observed, being higher the variability in the surface layer; in general, the reduced dispersion of the CV values were affected by higher PR values found in this period.

Hierarchical clustering

The HCA allowed the identification of sites in the experimental field, according to the magnitude of the PR and differentiate those where PR is a limiting factor for the development of roots and crop productivity. In S1, the HCA presented three distinct groups (Figure 1A), where group 1 is made up of the highest values of PR (2.6 MPa) (Figure 1B) - lower left and upper right zones of the field- which had higher traffic of machinery. Group 2 corresponds to areas close to the Group 1, where PR values between 1.5 and 3 MPa were observed in one or more points of the analyzed depths, indicating the need to implement tillage work to reduce compaction. Group 3 corresponds to sites or areas where no compaction problems arose at the time of sampling and correspond to a strip that crosses the field from upper left to lower right, with values < 1.2 MPa in all analyzed depths.

In S2, an increment of PR in all sampling sites is observed when compared with the results obtained in S1, indicating a compacting process given that in both measurements moisture contents in the soil were similar. It should be noted that for the second sampling (S2), compaction values > 1.9 MPa were detected in the entire field, as a result of the cultivation labor and transit of machinery.

Table 1. Descriptive statistics of the penetration resistances (MPa) of the soil at different depths in states S1 and S2.

Depth (m)	Mean (MPa)	S.D.	Minimum (MPa)	Maximum (MPa)	CV (%)
			Before tillage (S1)		
0.01	0.65	0.58	0.00	2.20	88.25
0.05	1.05	0.67	0.10	2.70	64.18
0.10	1.53	0.71	0.30	3.10	46.28
0.15	1.73	0.76	0.30	4.10	44.00
0.20	1.78	0.72	0.60	4.00	40.57
0.25	1.73	0.57	0.90	3.20	32.71
0.30	1.74	0.54	1.10	3.10	31.02
0.35	1.74	0.55	1.10	3.00	31.68
0.40	1.78	0.67	0.80	3.70	37.89
0.45	1.78	0.72	0.80	3.70	40.58
0.50	1.76	0.76	0.70	3.70	43.40
0.55	1.71	0.75	0.70	3.80	44.09
0.60	1.68	0.76	0.50	3.80	45.58
			After tillage (S2)		
0.01	0.69	0.98	0.00	4.20	143.13
0.05	2.14	0.97	0.40	4.30	45.18
0.10	2.72	1.05	1.00	4.70	38.64
0.15	2.96	1.09	1.20	4.90	36.97
0.20	2.96	1.00	1.40	4.80	33.67
0.25	2.90	1.03	1.30	4.60	35.50
0.30	2.77	0.95	1.20	4.30	34.49
0.35	2.66	0.82	1.10	4.20	30.98
0.40	2.72	0.75	1.10	4.20	27.66
0.45	2.70	0.71	1.40	4.20	26.34
0.50	2.75	0.73	1.50	4.20	26.46
0.55	2.77	0.70	1.70	4.40	25.28
0.60	2.70	0.69	1.50	4.20	25.72

S.D. = Standard deviation. CV = Coefficient of variation.

The spatial distributions of the PR in S1 and S2 showed a direct and significant correlation (R^2 = 0.47) between the two sampling times for different depths. When this correlation was calculated, considering the different depths at each sampling site,

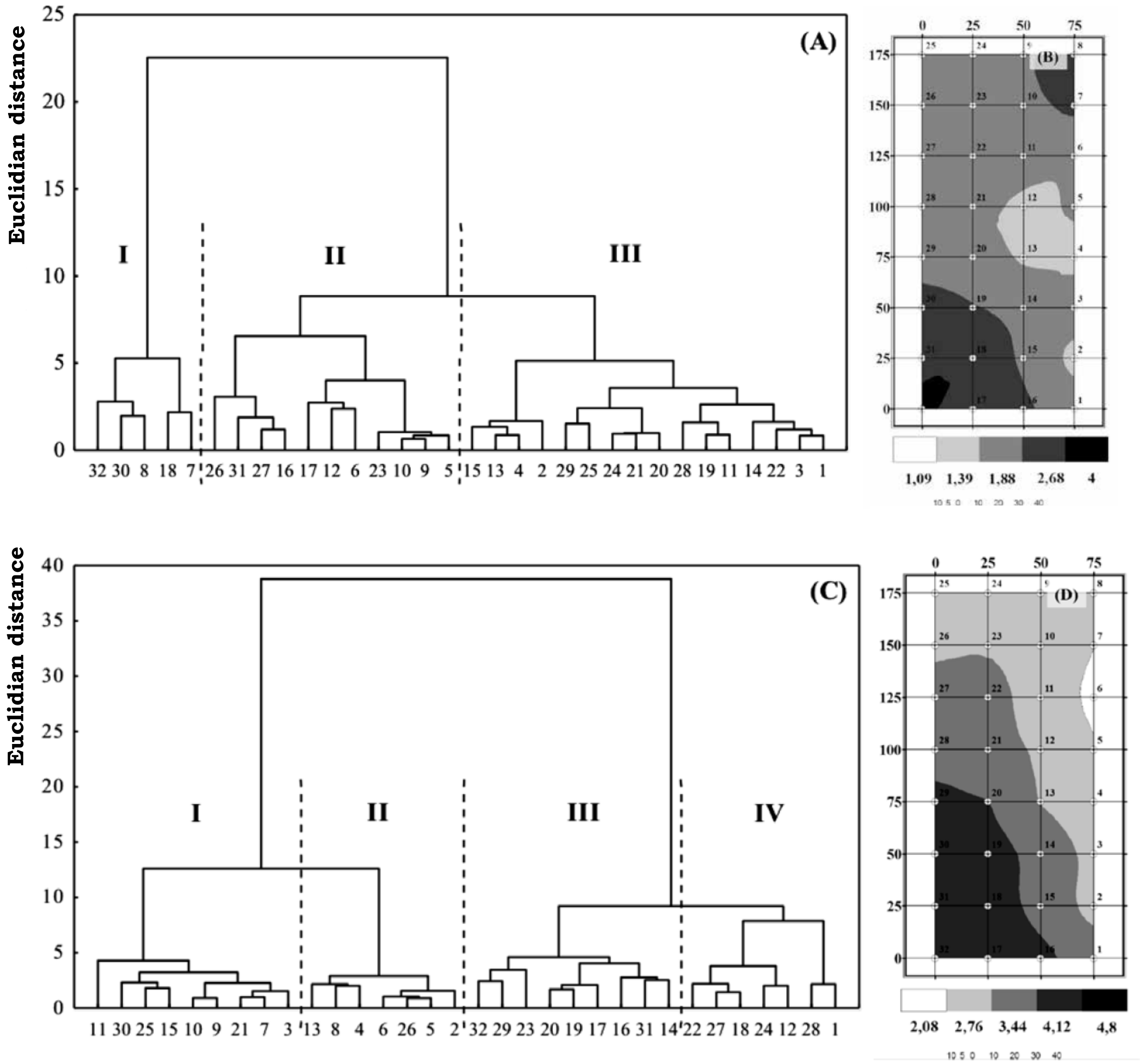

Figure 1. Hierarchical clustering dendrograms by soil sampling points before tillage (A) and after harvest (C), with their respective contour maps (B and D).

this trend continued in most of the area with variable correlations between R^2 = 0.34 and 0.92, where the lower values (not significant) corresponded to the transition between sites of lower to higher PR being, inclusive inverse in the top left area that corresponds to the entry area to the field.

The dendrogram for data from S2 presented four distinct groups (Figure 1C), where groups I and II showed lower values of PR, corresponding to the right strip of the field and a small area in the upper left. In S1 and S2, the HCA by depth presented three groups (Figures 2A and 3A) that also appear in the PCA (Figures 2C and 3C), which shows a clear trend of the PR in the soil profile at depths between 0 and 10 cm with the lowest values of PR (Group I); 10-35 cm with the highest values (Group II); and depths > 60 cm where the PR tended to decrease (Group III). These groups represent the typical curve of the PR in agricultural soils and confirm a different behavior for each depth (Werich-Neto *et al.*, 2006).

Up to 10 cm deep the PR in most points was < 1.5 MPa in S1 and 2.5 MPa in S2, however in some cases this value was higher due to the transit of machinery and the rearrangement of particles that occurs after tillage. Between 10 and 35 cm deep the soil evidenced the intensive use of machinery in the activity of tillage, which is usually done on a biannual basis. The reduction of the PR at depths greater than 35 cm is common in different types of soils used for agricultural production and its value depends on fluctuations in the water table, which under the conditions of this study during the rainy season can reach the surface. This could be confirmed by the visual observation of a hardened layer 20 to 30 cm deep in the profile, which is explained by the history of mechanized handling of the field.

Principal components analysis

The PCA for the PR values at different depths, in both S1 and S2, relates the

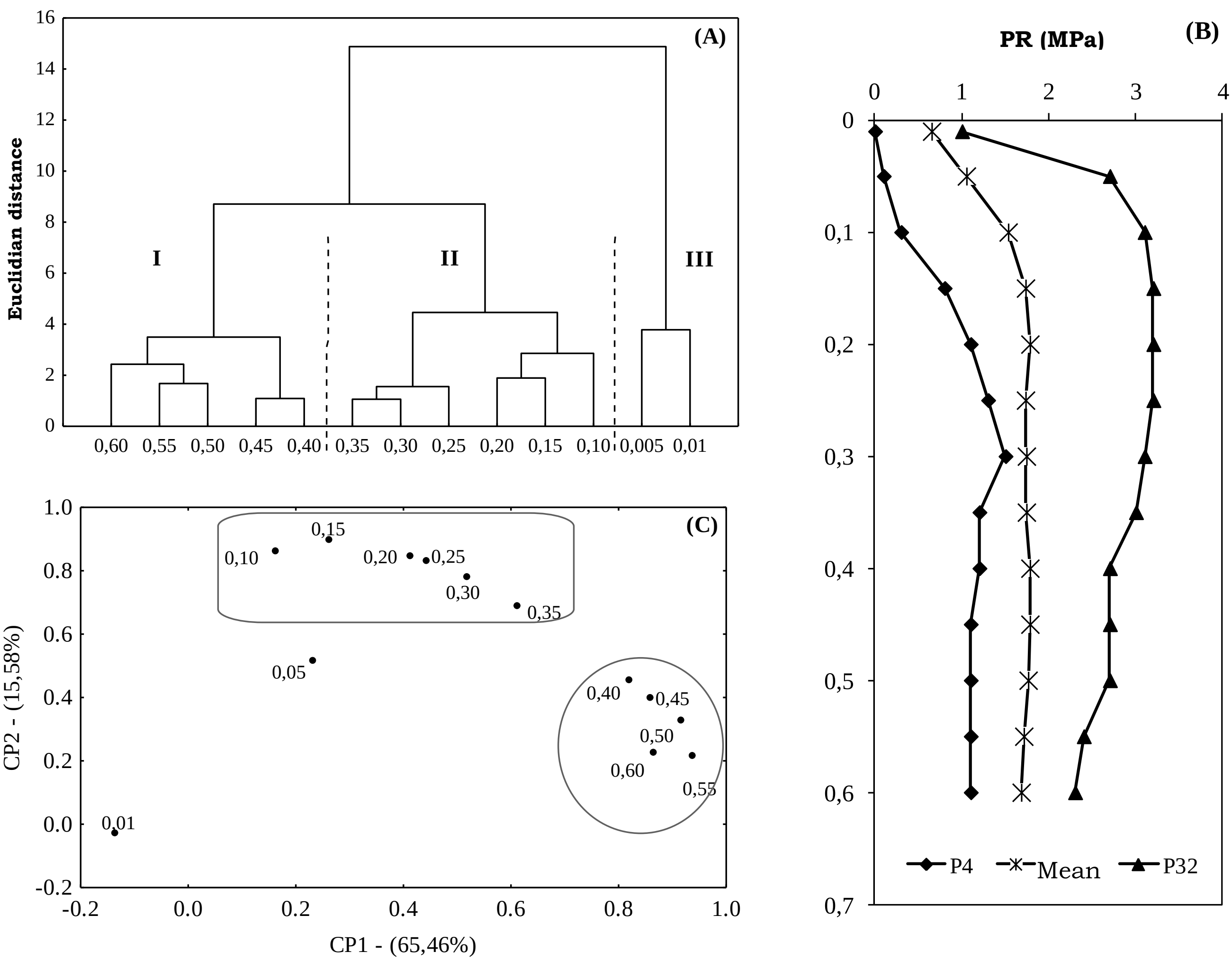

Figure 2. Penetration resistance behavior before tillage (PR) at different depths in the soil, from the hierarchical cluster analysis (A), PR curves (B) and principal component analysis (C) after harvest (C), with their respective contour maps (B and D).

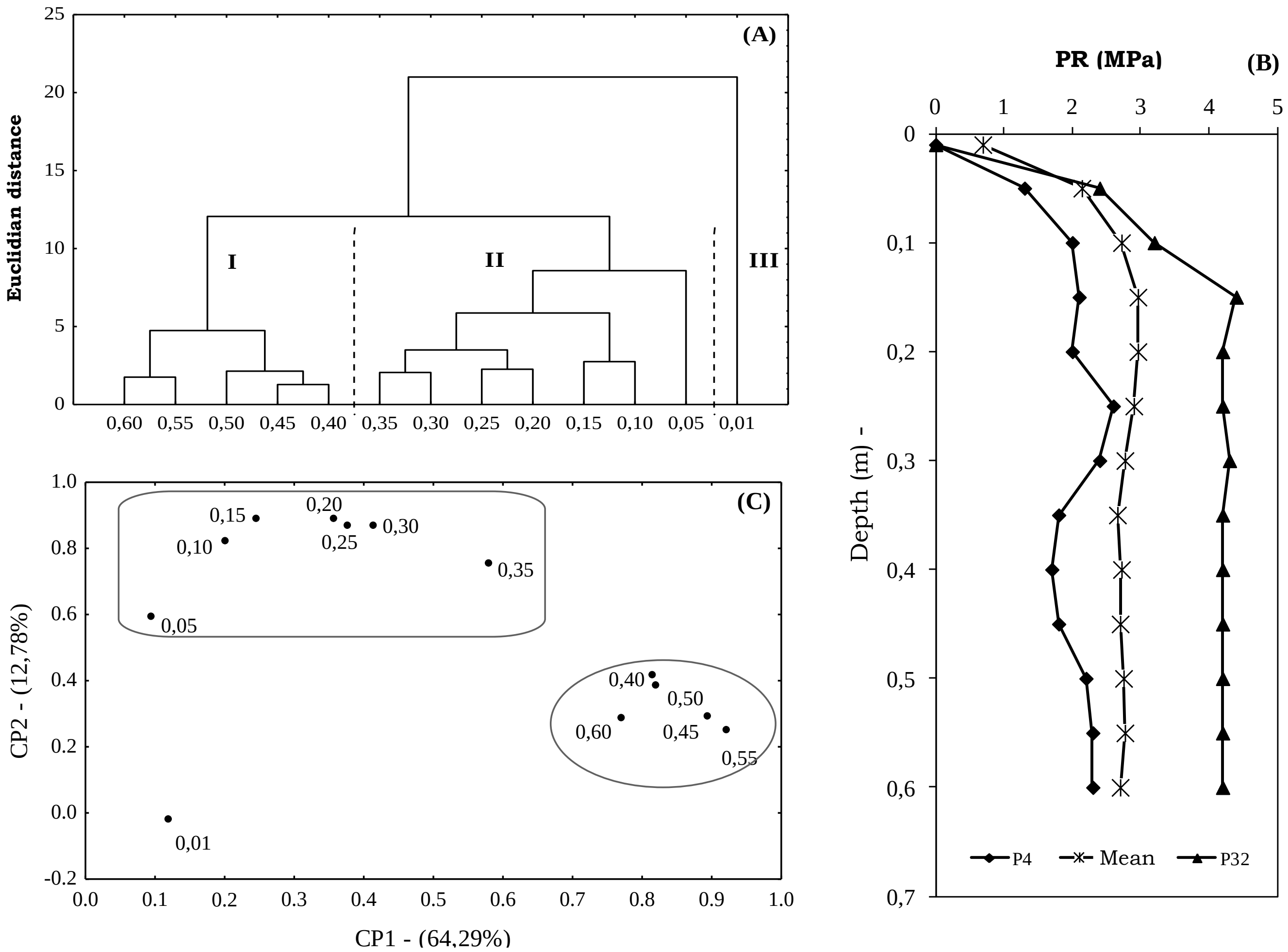

Figure 3. Penetration resistance behavior after the harvest (PR) of the soil at different depths, from the hierarchical cluster analysis (A), PR curves (B) and principal component analysis (C)

coefficients from the first three components, which presented eigenvalues > 1.0 and constitute an appropriate interval (Kaiser and Rice, 1974), which account for over 85% of the total variance (Table 2). Values common and close to 1 for the PR at different depths, demonstrate the representativeness of the components analyzed in this study. Moreover, the coefficients for each component show a positive correlation of the PR between the different depths and some degree of continuity between adjacent layers of soil, which coincides with the findings of Stelluti *et al.* (1998) and Medina *et al.* (2012). According to Soane *et al.* (1981) the pressure exerted in the soil surface is transmitted to deeper layers, dissipating its effects to a depth of 50 cm depending on the texture, water content in the soil and the contact pressure.

Table 2. Coefficients of the first three components (PC) of the penetration resistance at different depths, for S1 and S2.

Depth (cm)	CP1	CP2	CP3	Communality
		Before tillage (S1)		
0.01	-0.13543	-0.02575	**0.95855**	0.93783
0.05	0.23011	0.51973	**0.76153**	0.90299
0.10	0.16087	**0.86088**	0.30758	0.86160
0.15	0.26158	**0.89795**	0.14308	0.89521
0.20	0.41083	**0.84757**	0.04560	0.88923
0.25	0.44362	**0.83186**	0.04493	0.89082
0.30	0.51866	**0.78286**	-0.08459	0.88904
0.35	0.61111	0.68841	0.04819	0.84969
0.40	**0.81769**	0.45453	0.07367	0.88064
0.45	**0.85749**	0.40210	0.16972	0.92579
0.50	**0.91499**	0.33080	0.03274	0.94772
0.55	**0.93683**	0.21656	-0.09774	0.93408
0.60	**0.86452**	0.22515	-0.09655	0.80741
Autovalue	8.51	2.02	1.08	
Var. (%)	65.46	15.58	8.29	
Accum. Var. (%)	65.46	81.04	89.33	
		After tillage (S2)		
0.01	0.11798	-0.01606	**0.92725**	0.87396
0.05	0.09368	0.59399	0.65153	0.78609
0.10	0.20078	**0.82452**	0.39777	0.87836
0.15	0.24479	**0.89004**	0.22059	0.90075
0.20	0.35701	**0.89011**	0.05000	0.92225
0.25	0.37539	**0.86916**	-0.00914	0.89643
0.30	0.41377	**0.87136**	-0.06019	0.93410
0.35	0.57805	**0.75500**	-0.04858	0.90652
0.40	**0.81349**	0.41701	0.00236	0.83567
0.45	**0.89333**	0.29201	0.07464	0.88887
0.50	**0.92188**	0.25331	0.10425	0.92489
0.55	**0.82043**	0.38957	0.17180	0.85438
0.60	**0.77101**	0.28674	0.15167	0.69968
Autovalue	8.36	1.66	1.28	
Var. (%)	64.29	12.78	9.87	
Accum. Var. (%)	64.29	77.07	86.94	

The first component (CP1) represents about 65% of the total variance for both sampling times (S1 and S2) and confirms the presence of a layer between 40 and 60 cm deep, where the effects of tillage and machinery traffic have had little effect on the water table as heavy equipment has not been used (Werich- Neto *et al.*, 2006). The second component (CP2) constitutes 15.58% for S1 and 12.78% for S2 and is represented mainly by the soil layer between 0.10 and 0.30 m, the area of transition between the horizons A and B of the soil in the study zone, also showing the side effect of soil preparation work. The third major component (CP3) represents less than 10% of the total variance for both sampling periods and is related to the surface layer, where major reconsolidation processes are presented, which occurs in agricultural soils after being subjected to external forces, as well as climatic factors proper of the area.

Conclusions

- The study showed similar spatial patterns of PR for both sampling periods, with highly correlated points; however, the mechanized handling of maize caused increases in PR indicating a compacting process at the end of the growing season.
- By means of the methodology used, is possible to identify areas and layers with differences in levels of compaction, evidenced in the hierarchical analysis and principal components. This allows the establishment of management areas and depths for conducting site-specific farming.
- The procedure used, based on multivariate analysis techniques allowed proper characterization of the vertical and horizontal variability of the PR in the field of the study.

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