Soil chemical attributes restricting grain yield in Oxisols under no-tillage system

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Abstract – The objective of this work was to identify soil chemical attributes restricting grain yield in Oxisols under the no-tillage system, using directed soil sampling. High, medium, and low yield zones were defined in two agricultural fields using historical yield data of several crops. The yield zones were defined based on the harvest maps of the following crops: corn in 2008/2009, white oat in 2009, and corn in 2012/2013 in field I, with 117.70 ha; and corn in 2009/2010, soybean in 2010/2011, and wheat in 2012 in field II, with 107.30 ha. Soil sampling points were georeferenced in each yield zone, where samples were collected at eight soil depths, spaced 0.05 m apart, totaling 80 variables. Low yields were associated with low cation exchange capacity, low phosphorus and organic matter contents, and high clay content. In both studied fields, the highest organic matter content in the subsurface layers was the main indicator of high yield. Soil sampling considering yield zones is an efficient strategy to identify chemical attributes restricting grain yield and also allows guiding more precise site-specific interventions.

Index terms: organic matter, precision agriculture, site-specific management, soil fertility, soil sampling, yield zones.

Atributos químicos do solo restritivos à produtividade de grãos em Latossolo sob sistema plantio direto

Resumo – O objetivo deste trabalho foi identificar atributos químicos do solo restritivos à produtividade de grãos em Latossolos sob sistema plantio direto, com uso de amostragem de solo dirigida. Foram definidas zonas de alta, média e baixa produtividade, em duas áreas agrícolas, por meio de um histórico de produtividade de diferentes culturas. As zonas de produtividade foram definidas de acordo com mapas de colheita das seguintes culturas: milho em 2008/2009, aveia-branca em 2009 e milho em 2012/2013, na área I, com 117,70 ha; e milho em 2009/2010, soja em 2010/2011 e trigo em 2012, na área II, com 107,30 ha. Os pontos de amostragem de solo foram georreferenciados em cada zona de produtividade, onde as amostras foram coletadas a oito profundidades, espaçadas entre si em 0,05 m, tendo totalizado 80 variáveis. Baixas produtividades estiveram associadas à baixa capacidade de troca de cátions, a baixos conteúdos de fósforo e matéria orgânica, e ao elevado conteúdo de argila. Em ambas as áreas estudadas, o maior conteúdo de matéria orgânica em camadas subsuperficiais foi o principal indicador de alta produtividade. A amostragem de solo, ao se considerar as zonas de produtividade, é estratégia eficiente para identificação de atributos químicos restritivos à produtividade de grãos e também permite orientar intervenções sitio-específicas mais precisas.

Termos para indexação: matéria orgânica, agricultura de precisão, manejo sítio-específico, fertilidade do solo, amostragem de solo, zonas de produção.

Introduction

The spatial variability of crop yield under the no-tillage system (NTS) is influenced by several factors, especially soil chemical attributes (Rodrigues et al., 2012, 2013; Santi et al., 2012). Knowledge of these limiting factors is essential for commercial crop planning (Rodrigues et al., 2012; Santi et al., 2012) and for site-specific management (Rodrigues et al., 2013; Corassa et al., 2016).

In order to determine cause and effect relationships between soil attributes and crop yield, the use of historical yield data has been proposed worldwide

(McBratney et al., 2005; Miao et al., 2006; Marques da Silva & Silva, 2008; Santi et al., 2012). The use of a large dataset aims to avoid substantial variation in grain yield throughout the years (McBratney et al., 2005; Rodrigues et al., 2013) and misguided management decisions (Rodrigues et al., 2013).

Regarding the effect of soil attributes on crop yield, Rodrigues et al. (2012) concluded that base saturation was the potential limiting attribute that best explained the spatial variability of corn (*Zea mays* L.) yield, while Rodrigues et al. (2013) reported that pH was the most influential attribute for this crop. Santi et al. (2012) also found that imbalances on the Ca:K and Mg:K ratios were limiting to the yields of both soybean [*Glycine max* (L.) Merr.] and corn. However, these studies only considered surface soil sampling (0.00–0.10 and 0.10–0.20 m), which may not be detailed enough to adequately represent soil fertility because of the vertical gradient formed in the NTS (Schlindwein & Anghinoni, 2000). The need for more detailed samplings is further stressed by the fact that, under satisfactory growing conditions, the roots of agricultural crops can exploit a large volume of soil (Hansel et al., 2017), far beyond the traditionally sampled layers.

Due to its higher level of detail, directed soil sampling should be an economic and rational alternative to site-specific interventions, which may entail high costs. Moreover, this method, which considers historical crop yield data as a reference, can contribute to effective site-specific interventions and, consequently, to reduce yield spatial variability.

The objective of this work was to identify soil chemical attributes restricting grain yield in Oxisols under the no-tillage system, using directed soil sampling.

Materials and Methods

The experiments were carried out in two fields of commercial grain crops, located in the municipality of Boa Vista das Missões, in the state of Rio Grande do Sul, Brazil. Field I, with 117.70 ha, is located at 27°43'15"S, 53°20'11"W, and field II, with 107.30 ha, at 27°43'10"S, 53°20'48"W. The soil, classified as a Latossolo Vermelho Aluminoférrico típico, according to the Brazilian soil classification system (Santos et al., 2006), is an Oxisol, i.e., a Typic Hapludox. Both fields have been cultivated under the NTS for more than 20 years without interruption, following a pre-established crop rotation plan with intercropping of white oat (*Avena sativa* L.), black oat (*Avena strigosa* Schreb.), wheat (*Triticum aestivum* L.), and forage turnip (*Raphanus sativus* L. var. *oleiferus* Metzg) during winter, and of soybean and corn in summer. The local climate is humid subtropical, Cfa according to Köppen, and the average annual temperature and rainfall are 18.1ºC and 1,919 mm, respectively (Maluf, 2000).

The variability in the yield potential of the fields was determined through the analysis of a series of historical yield maps, from 2008 to 2013, of the following crops: corn in 2008/2009, white oat in 2009, and corn in 2012/2013, in field I; and corn in 2009/2010, soybean in 2010/2011, and wheat in 2012, in field II. Yield data were obtained with the Axial-Flow 2399 combine harvester (Case IH, Araras, SP, Brazil), equipped with a GPS system with correction by internal algorithms. The data included grain yield and moisture content.

All maps were subjected to the filtering process using the methodology proposed by Menegatti & Molin (2004). Subsequently, each map was relativized and filtered to the same 40x40-m grid, where the mean values for the sampling points comprehended all the data within a 20-m radius. Data with a coefficient of variation higher than 30% were eliminated. Relative yield (RY) maps were overlaid, generating a single map for each field. Three yield zones (YZs) were defined based on the historical average: low, RY<95%; medium, 95<RY<105%; and high, RY>105% (Figure 1). Three georeferenced points were defined in each YZ, at the center of a grid generated with the yield values of the respective crops. Mean, relative, and cumulative yield data, in each sampling point, are shown in Tables 1 and 2.

In November 2013, when the experimental fields were in fallow (prior to soybean sowing), the directed soil samplings were carried out following the methodology of Tedesco et al. (2004). Three samples (replicates) were collected at each yield sampling point, which had been previously georeferenced, at eight soil depths: 0.00–0.05, 0.05–0.10, 0.10–0.15, 0.15–0.20, 0.20–0.25, 0.25–0.30, 0.30–0.35, and 0.35–0.40 m. The soil samples were oven-dried at 40°C, ground, sieved (2-mm), and analyzed according to Tedesco et al. (1995). Clay content was determined with the densimeter method, and soil organic matter (OM), with the wet combustion method. pH in water was obtained using the 1:1 soil to water ratio; phosphorus and potassium were extracted with the Mehlich-1 method; and calcium, magnesium, and aluminum were quantified with the KCl (1.0 mol L^{-1}) method.

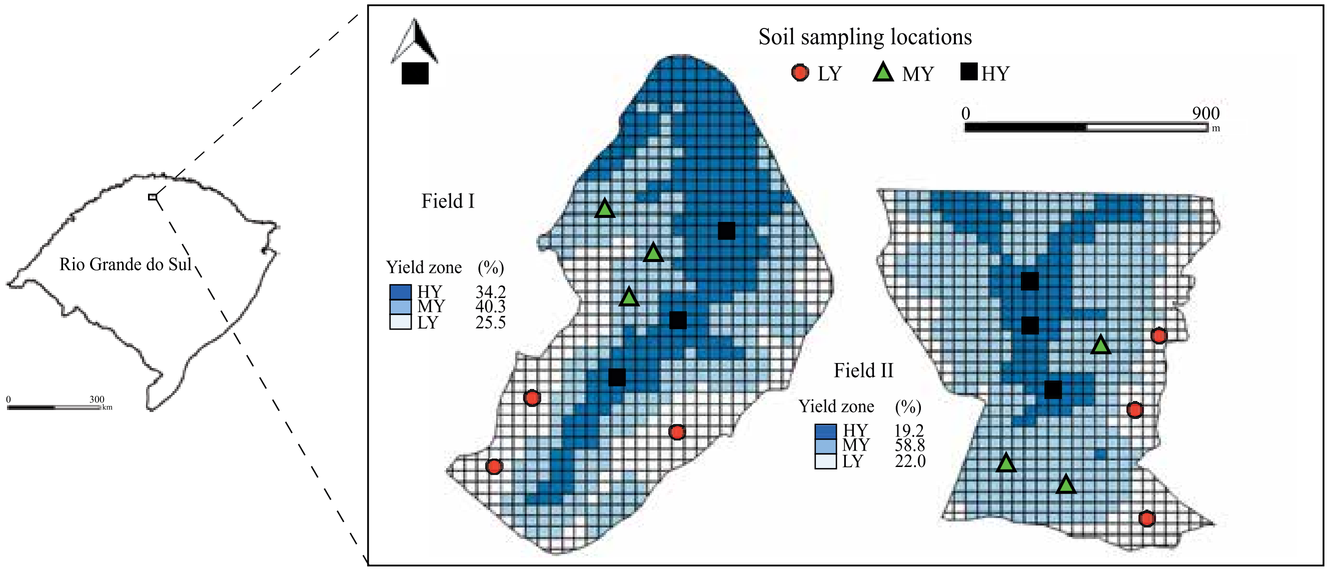

Figure 1. Soil sampling locations in experimental fields I and II for low (LY), medium (MY), and high (HY) yield zones.

Table 1. Mean, relative, and cumulative grain yield observed at soil sampling points (SSP) for each yield zone (YZ) in field I.

Yield zone[(1)]	SSP	Corn in 2008/2009		White oat in 2009		Corn in 2012/2013		Relative mean (%)	Cumulative yield (Mg ha^{-1})
		Mean (Mg ha^{-1})	Relative (%)	Mean (Mg ha^{-1})	Relative (%)	Mean (Mg ha^{-1})	Relative (%)		
LY	1	2.82	44.14	1.39	72.46	6.33	84.75	67.11	10.54
	2	2.85	44.50	1.50	78.52	6.16	82.38	68.52	10.51
	3	3.78	59.17	1.24	64.57	6.23	83.40	69.05	11.24
MY	1	6.24	97.79	1.81	94.55	7.63	102.16	98.17	15.68
	2	6.23	97.59	1.86	97.00	7.69	102.88	99.15	15.77
	3	6.63	103.95	1.95	102.02	7.69	102.92	102.96	16.27
HY	1	7.46	116.94	2.26	118.36	8.28	110.83	115.38	18.01
	2	7.58	118.79	2.50	130.80	8.70	116.46	122.02	18.78
	3	7.21	113.05	2.31	120.95	8.88	118.82	117.61	18.41

[(1)]LY, low yield; MY, medium yield; and HY, high yield. Corn, *Zea mays*; white oat, *Avena sativa*, and soybean, *Glycine max*.

Table 2. Mean, relative, and cumulative grain yield observed at soil sampling points (SSP) for each yield zone (YZ) in field II.

Yield zone[(1)]	SSP	Corn in 2009/2010		Soybean in 2010/2011		Wheat in 2012		Relative mean (%)	Cumulative yield (Mg ha^{-1})
		Mean (Mg ha^{-1})	Relative (%)	Mean (Mg ha^{-1})	Relative (%)	Mean (Mg ha^{-1})	Relative (%)		
LY	1	5.49	68.29	2.36	60.37	2.18	79.69	69.45	10.03
	2	4.97	61.79	1.43	36.67	1.90	69.37	55.94	8.30
	3	4.60	57.16	1.54	39.25	1.85	67.73	54.71	7.98
MY	1	8.19	101.84	3.67	93.79	2.98	108.93	101.52	14.83
	2	7.91	98.42	4.05	103.50	2.95	107.87	103.26	14.91
	3	8.23	102.40	4.06	103.71	2.92	106.73	104.28	15.21
HY	1	10.40	129.34	4.88	124.83	3.48	127.37	127.18	18.76
	2	10.82	134.61	4.36	111.45	4.14	151.56	132.54	19.32
	3	10.53	130.99	4.95	126.49	3.97	145.15	134.21	19.44

[(1)]LY, low yield; MY, medium yield; and HY, high yield. Corn, *Zea mays*; white oat, *Avena sativa*, and soybean, *Glycine max*.

P and K were determined via colorimetry and flame photometry, respectively, whereas Al was titrated with 0.025 mol L^{-1} NaOH. Base saturation (BS) and cation exchange capacity (CEC) at pH 7.0 were calculated as described in Tedesco et al. (2004). The attributes OM, clay, P, K, Ca, Mg, Al, BS, and CEC were combined with the eight soil depths, totaling 80 variables in each YZ.

Prior to the analysis of variance, assumptions of residual normality and homogeneity of variances were tested using the Shapiro-Wilk and Levene tests, respectively. As the necessary assumptions for the analysis of variance were not met for any of the variables, the analyses were then conducted with the two-way permutational analysis of variance (Permanova) based on the Euclidean distance, obtained with 9,999 random permutations, using the Past, version 3.14, software (Hammer et al., 2001). Permanova calculates the p-value using permutations instead of a table of F values, which assumes normality. The association of soil attributes and YZs was verified through the principal component analysis (PCA), also using the Past, version 3.14, software.

Results and Discussion

Directed soil sampling showed a significant simple effect for YZs and soil depths for most of the evaluated attributes (Table 3). In field I, pH, Mg, Al, and V differed significantly between YZs. Considering the eight depths analyzed, the mean pH values were 5.7, 5.7, and 5.3 for the low (LYZ), medium (MYZ), and high yield (HYZ) zones, respectively. The greatest Mg contents were found in the MYZ, followed by the LYZ and HYZ (Table 4). Due to the greatest Al contents in the HYZ, the mean V at 0.0–0.40 m also differed significantly between YZs, being higher in the MYZ and LYZ than in the HYZ.

In field II, pH, K, Ca, and Mg were the attributes that varied between YZs. The highest mean pH was observed in the MYZ, whereas K was higher in the LYZ (Table 4). The mean value of K in the LYZ was 105 mg dm^{-3}, which is considered high (Manual…, 2016), while, in the MYZ and HYZ, the K levels were 55 and 38 mg dm^{-3}, respectively. Considering the sampling points and the respective harvests evaluated in the present study, the HYZ had a cumulative yield of 19.17 Mg ha^{-1}, which was higher than that of 8.77 Mg ha^{-1} for the LYZ. This is an indicative that the lowest K contents in the HYZ were probably related to the higher nutrient export rates throughout the harvests. Currently, for each ton of grain produced, approximately 50, 16, and 6 kg ha^{1} K are exported for soybean (Bender et al., 2015), corn (Bender et al., 2013), and wheat (Tedesco et al., 2004), respectively. Based on these values and on the means of the harvests, the total export of K was 430 kg ha^{-1} in the HYZ and 181 kg ha^{-1} in the LYZ; these results show the importance of considering yield spatial variability for calculating replacement fertilizations. The averages of

Table 3. Summary of the two-way analysis of variance (p-values) by permutation using the Euclidean distance with 9,999 permutations between yield zone (YZ), soil depth (SD), and the YZ x SD interaction in fields I and II.

Attribute[(1)]	Source of variation[(2)]					
	Field I			Field II		
	YZ	SD	YZ x SD	YZ	SD	YZ x SD
OM (g kg^{-1})	0.0001***	0.0001***	0.0353*	0.0001***	0.0001***	0.0189*
Clay (g kg^{-1})	0.0002***	0.0001***	0.0042**	0.0001***	0.0001***	0.6404^{ns}
pH (1:1 soil to water ratio)	0.0001***	0.2115^{ns}	0.9736^{ns}	0.0118*	0.3793^{ns}	0.9980^{ns}
P (mg dm^{-3})	0.0195*	0.0001***	0.0045**	0.0001***	0.0001***	0.0035**
K (mg dm^{-3})	0.9488^{ns}	0.0001***	0.9752^{ns}	0.0001***	0.0001***	0.1752^{ns}
Ca ($cmol_c$ dm^{-3})	0.4171^{ns}	0.0001***	0.9881^{ns}	0.0001***	0.0002***	0.9802^{ns}
Mg ($cmol_c$ dm^{-3})	0.0001***	0.0001***	0.9984^{ns}	0.0001***	0.0031**	0.9899^{ns}
Al ($cmol_c$ dm^{-3})	0.0001***	0.0001***	0.5341^{ns}	0.1762^{ns}	0.2071^{ns}	0.9975^{ns}
BS (%)	0.0001***	0.0001***	0.8602^{ns}	0.0670^{ns}	0.0837^{ns}	0.9999^{ns}
CEC ($cmol_c$ dm^{-3})	0.0001***	0.0001***	0.0325*	0.0001***	0.0001***	0.0098**

[(1)]OM, organic matter; P, phosphorus extracted by Mehlich-1; K, potassium extracted by Mehlich-1; V, base saturation; and CEC, cation exchange capacity at pH 7.0. [(2)]Degrees of freedom: YZ = 2, SD = 7, YZ x SD = 14, residual = 48, and total = 71. *, ** and ***Significant at 5, 1, and 0.1% probability, respectively. ^{ns}Nonsignificant.

Ca and Mg were, respectively, 33 and 23% higher in the HYZ than in the LYZ (Table 4).

All attributes, except pH, varied significantly according to the assessed soil depths in field I. In field II, pH, Al, and V were not affected by the different depths (Table 3). The presence of vertical variability in the soil attributes was expected, since both experimental fields have been grown under the NTS for more than 20 years; during this period, crop residues were not incorporated and fertilizations were carried out on soil surface or sowing rows, favoring the formation of fertility gradients (Schlindwein & Anghinoni, 2000).

YZs interacted significantly with soil depths for some soil attributes (Table 3). In field I, OM was higher for the HYZ in all evaluated strata, but showed similar vertical distributions for the MYZ and LYZ (Figure 2 A). Similar results were found for potential CEC, where the greater values for the HYZ, compared with those of the LYZ, increased with increasing soil depths (Figure 2 C and D). Considering the intermediate layers of 0.00–0.05, 0.20–0.25, and 0.35–0.40 m, OM was 20, 19, and 34% higher in the HYZ than in the LYZ, respectively. In field II, the mean OM values were similar between YZs, until the 0.15-m depth. However, below this depth, these values were higher in the HYZ. For the 0.35–0.40-m layer, the HYZ had 54% more OM than the LYZ. These results highlight the importance of considering deeper soil layers for interpreting soil chemical analysis in the NTS.

The plot generated from the PCA, based on the correlation matrix between soil attributes (considering all depths) and YZs, showed that the HYZ were related to higher OM and P contents and to higher potential CEC values, in both fields (Figure 3 A and B). Due to its relationship with physical, chemical, and biological processes, OM is considered an important indicator of soil quality (Vezzani & Mielniczuk, 2009). In addition, given its the ability to complex cations, OM acts as an important neutralizing source of Al, removing it from the soil solution (Zambrosi et al., 2007). Therefore, it is possible that the higher Al contents found in the HYZ were associated with its also greater OM contents (Table 4). It should be noted that Al toxicity did not have negative effects in some fields under the NTS due to the complexation of Al by OM (Zambrosi et al., 2007). This could explain the occurrence of higher yields with the presence of greater Al contents in the HYZ (Figure 3).

Management practices that lead to increased OM in the soil can be an alternative to recover LYZ. Among these, stand out crop rotation plans that incorporate species with different root systems and high straw production. Cunha et al. (2011) found significant increases in OM content after four years of cultivation. Since the LYZ comprised approximately 25% of the evaluated fields (Figure 1), it is perfectly possible to

Table 4. Mean values of soil chemical attributes at the 0.00–0.40-m depth for low (LY), medium (MY), and high (HY) yield zones in fields I and II.

Attribute[(1)]	Yield zone					
	Field I			Field II		
	LY	MY	HY	LY	MY	HY
OM (g kg^{-1})[(2)]	23	22	29	24	27	28
Clay (g kg^{-1})[(2)]	770	742	693	81.7	65.6	66.0
pH in water (1:1 soil to water ratio)	5.7a*	5.7a	5.3b	5.7b	6.0a	5.7b
P (mg dm^{-3})[(2)]	5.5	8.5	11.9	5.9	12.7	15.3
K (mg dm^{-3})	31.0[ns]	33.0	32.0	105.0a	55.0b	38.0b
Ca ($cmol_c$ dm^{-3})	4.9[ns]	5.1	4.7	4.9b	6.5a	6.5a
Mg ($cmol_c$ dm^{-3})	3.0a	3.1a	2.5b	3.0b	3.9a	3.7a
Al ($cmol_c$ dm^{-3})	0.5b	0.4b	1.3a	0.4[ns]	0.2	0.6
V (%)	61.9a	64.7a	49.8b	62.9[ns]	70.4	62.4
CEC ($cmol_c$ dm^{-3})[(2)]	12.9	12.7	14.4	12.9	14.8	16.6

[(1)]OM, organic matter; P, phosphorus extracted by Mehlich-1; K, potassium extracted by Mehlich-1; V, base saturation; and CEC, cation exchange capacity at pH 7.0. [(2)]Yield zone x soil depth interaction. *Means followed by equal letters do not differ significantly by the t-test, at 5% probability. [ns]Nonsignificant.

implement crop rotation plans associated with soil and plant georeferenced management techniques, in order to improve crop yield, without impacting cultivation in the areas with higher economic return (MYZ and HYZ), which will continue to be grown in 75% of the fields.

Similarly to OM, P contents were significantly affected by the interaction between YZs and soil depths (Table 3), besides being positively related to the samples located in the HYZ (Figure 2). The mean value of P was higher in the HYZ, in both fields (Table 4), and the greatest differences between the HYZ and

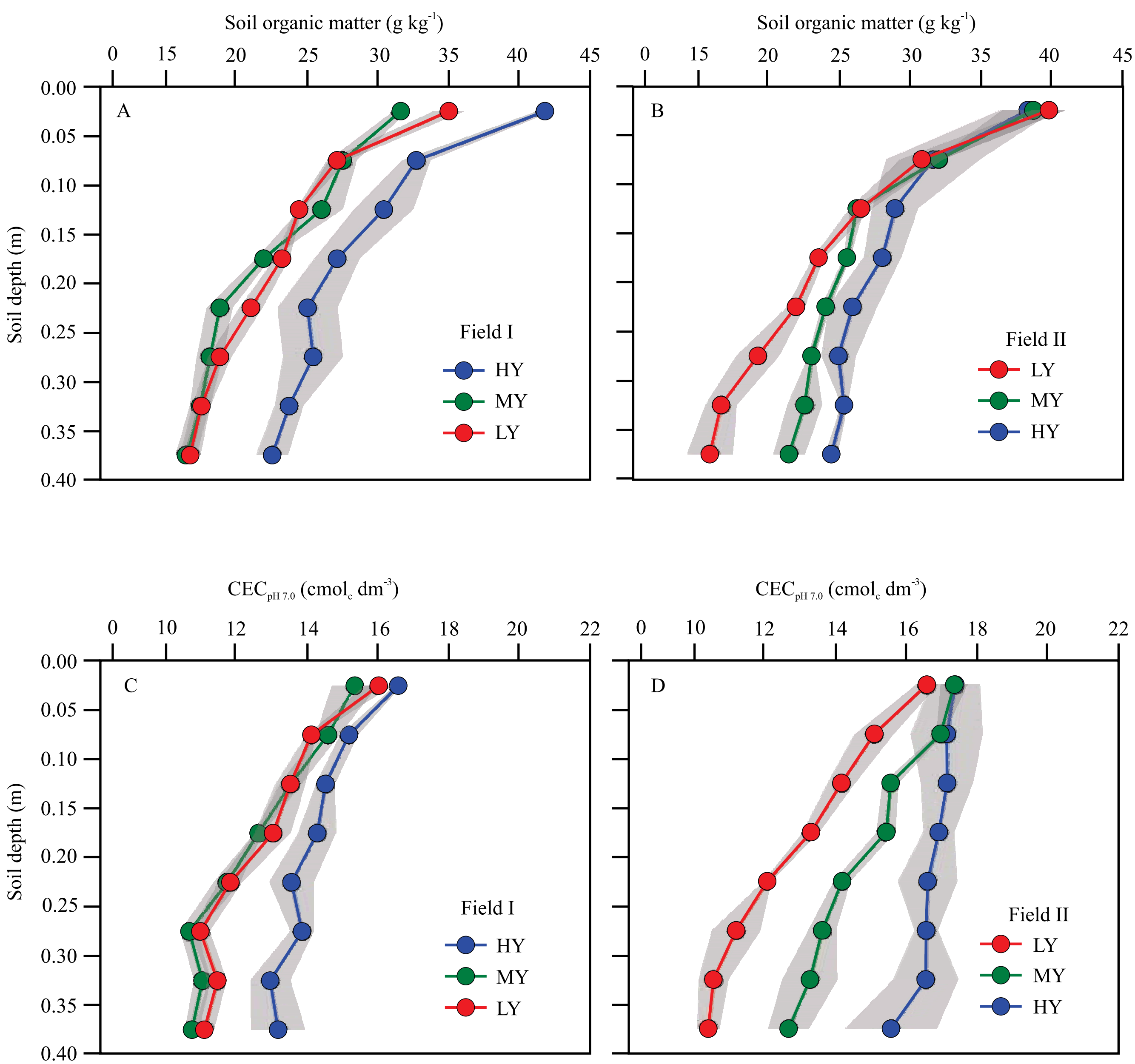

Figure 2. Mean values of soil organic matter (A and B) and cation exchange capacity at pH 7.0 ($CEC_{pH\ 7.0}$) (C and D) in fields I and II for low (LY), medium (MY), and high (HY) yield zones and at different depths. Gray shading indicates standard deviation.

LYZ were found at the 0.15-m depth, in field I, and at the 0.25-m depth in field II (Figure 4 C and D). High levels of P in subsurface layers may favor grain yield, as the roots can exploit a greater volume of soil under favorable conditions, according to Hansel et al. (2017). These authors reported increased soybean yield when P was applied at deeper soil layers (>0.20 m). Furthermore, studies have shown increased demand for P by modern cultivars/hybrids (Bender et al., 2013, 2015; Hansel et al., 2017). Therefore, in order to obtain high yields, the increase in P contents in the soil and in its subsurface layers should be recommended.

The greatest clay content was related to the LYZ in both fields (Figure 2). Similar results were obtained by Kitamura et al. (2007), who found negative correlations between clay content and bean (*Phaseolus vulgaris* L.) yield in an Oxisol managed under irrigation system. On average, the clay contents were 770 and 820 g kg^{-1} in fields I and II, respectively, for the LYZ, and 690 and 660 g kg^{-1} for the HYZ (Table 4). The HYZ and MYZ showed lower mean contents of clay in most of the evaluated depths, compared with the LYZ, except below 0.25 m in field I, where the obtained values for all YZs were statistically similar. In field II, a moderate difference was observed between clay contents in all depths (Figure 4). Below 0.20 m, the values were greater than 850 g kg^{-1} in the LYZ, but they did not exceed 750 g kg^{-1} in the HYZ. It is likely that, in the present study, the LYZ were more prone to soil compaction due to the higher clay content, which probably reduced the natural capacity of water storage and contributed to the decrease in crop yield. Several studies have shown that water infiltration in the soil is a limiting factor in sites with low yield potential (Nicoloso et al., 2008; Girardello et al., 2011; Santi et al., 2012).

Among the alternatives for improving soil physical quality, biological interventions, via cover crops with a broad root system, have shown to be more efficient and to have more lasting effects than mechanical interventions (Nicoloso et al., 2008; Girardello et al., 2011, 2014).

Directed soil sampling with a high level of detail allows identifying the factors responsible for driving crop performance in the fields. Considering the attributes evaluated in the present study, site-specific interventions, using cover crops with an aggressive root system and with increased straw production, are an alternative to low yield and may be used in conjunction with chemical interventions. In addition, the adoption of intelligent crop rotation planning considering YZs should be investigated in future studies.

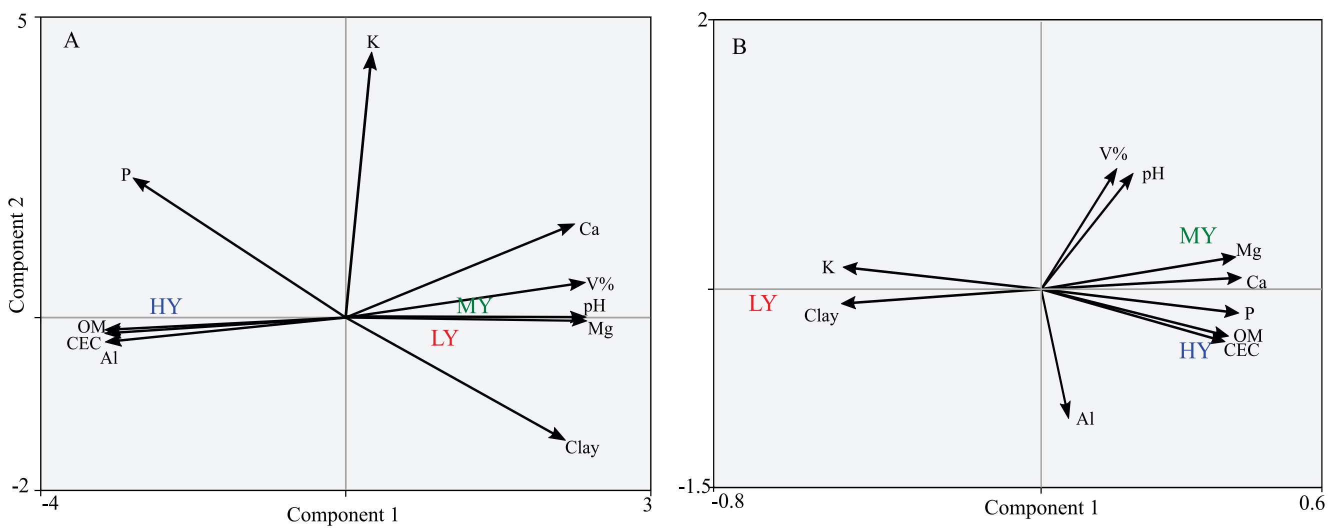

Figure 3. Principal components analysis based on the correlation matrix of soil chemical attributes, as well as low (LY), medium (MY), and high (HY) yield zones in fields I (A) and II (B). The first and second principal components account for the following percentages of data variance: 55.13 and 32.91% for field I (A), and 62.08 and 19.91% for field II (B), respectively. V, base saturation; CEC, cation exchange capacity at pH 7.0; and OM, organic matter.

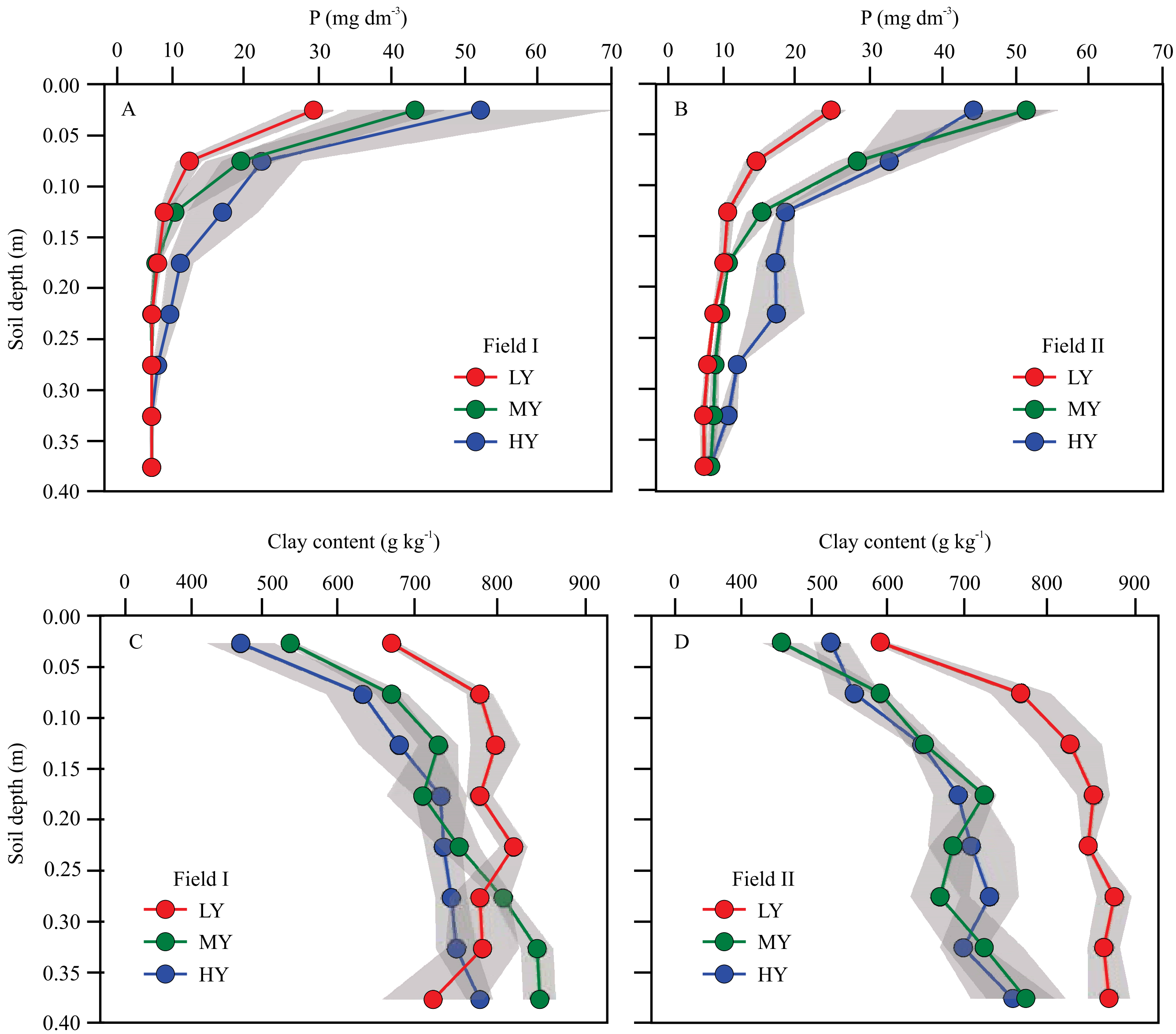

Figure 4. Mean phosphorous (A and B) and clay (C and D) contents in fields I and II for low (LY), medium (MY), and high (HY) yield zones and at different depths. Gray shading indicates standard deviation.

Conclusions

1. Low crop yield is associated with low potential cation exchange capacity, low phosphorus and organic matter contents, and high clay contents in Oxisols under the no-tillage system.
2. Soil organic matter at greater depths is an indicator of high yield zones.
3. Directed soil sampling considering historical yield data allows identifying chemical attributes that restrict grain yield and can guide more precise site-specific interventions.

Acknowledgments

To Conselho Nacional de Desenvolvimento Científico e Tecnológico (CNPq, process numbers 140508/2015-5, 140275/2016-9, 141144/2017-3, and 140550/2018-6), Coordenação de Aperfeiçoamento de Pessoal de Nível Superior (Capes, process number 88881.132762/2016-01), and to Programa de Pós-graduação em Agronomia: Agricultura e Ambiente (PPGAAA), for financial and technical support; and to the producers Eliseu Schaedler and Carlos Eduardo Dauve, for providing the experimental fields and technical support.

References

BENDER, R.R.; HAEGELE, J.W.; BELOW, F.E. Nutrient uptake, partitioning, and remobilization in modern, transgenic insect-protected maize hybrids. **Agronomy Journal**, v.105, p.161-170, 2013. DOI: 10.2134/agronj2012.0352.

BENDER, R.R.; HAEGELE, J.W.; BELOW, F.E. Nutrient uptake, partitioning, and remobilization in modern soybean varieties. **Agronomy Journal**, v.107, p.563-573, 2015. DOI: 10.2134/agronj14.0435.

CORASSA, G.M.; AMADO, T.J.C.; TABALDI, F.M.; SCHWALBERT, R.A.; REIMCHE, G.B.; DALLA NORA, D.; ALBA, P.J.; HORBE, T. de A.N. Espacialização em alta resolução de atributos da acidez de Latossolo por meio de sensoriamento em tempo real. **Pesquisa Agropecuária Brasileira**, v.51, p.1306-1316, 2016. DOI: 10.1590/s0100-204x2016000900030.

CUNHA, E. de Q.; STONE, L.F.; DIDONET, A.D.; FERREIRA, E.P. de B.; MOREIRA, J.A.A.; LEANDRO, W.M. Atributos químicos de solo sob produção orgânica influenciados pelo preparo e por plantas de cobertura. **Revista Brasileira de Engenharia Agrícola e Ambiental**, v.15, p.1021-1029, 2011. DOI: 10.1590/S1415-43662011001000005.

GIRARDELLO, V.C.; AMADO, T.J.C.; NICOLOSO, R. da S.; HÖRBE, T. de A.N.; FERREIRA, A. de O.; TABALDI, F.M.; LANZANOVA, M.E. Alterações nos atributos físicos de um Latossolo vermelho sob plantio direto induzidas por diferentes tipos de escarificadores e o rendimento da soja. **Revista Brasileira de Ciencia do Solo**, v.35, p.2115-2126, 2011. DOI: 10.1590/S0100-06832011000600026.

GIRARDELLO, V.C.; AMADO, T.J.C.; SANTI, A.L.; CHERUBIN, M.R.; KUNZ, J.; TEIXEIRA, T. de G. Resistência à penetração, eficiência de escarificadores mecânicos e produtividade da soja em Latossolo argiloso manejado sob plantio direto de longa duração. **Revista Brasileira de Ciencia do Solo**, v.38, p.1234-1244, 2014. DOI: 10.1590/S0100-06832014000400020.

HAMMER, Ø.; HARPER, D.A.T.; RYAN, P.D. Past: paleontological statistics software package for education and data analysis. **Palaeontologia Electronica**, v.4, art.4, 2001.

HANSEL, F.D.; RUIZ DIAZ, D.A.; AMADO, T.J.C.; ROSSO, L.H.M. Deep banding increases phosphorus removal by soybean grown under no-tillage production systems. **Agronomy Journal**, v.109, p.1091-1098, 2017. DOI: 10.2134/agronj2016.09.0533.

KITAMURA, A.E.; CARVALHO, M. de P. e; LIMA, C.G. da R. Relação entre a variabilidade espacial das frações granulométricas do solo e a produtividade do feijoeiro sob plantio direto. **Revista Brasileira de Ciência do Solo**, v.31, p.361-369, 2007. DOI: 10.1590/S0100-06832007000200018.

MALUF, J.R.T. Nova classificação climática do Estado do Rio Grande do Sul. **Revista Brasileira de Agrometeorologia**, v.8, p.141-150, 2000.

MANUAL de calagem e adubação para os estado do Rio Grande do Sul e de Santa Catarina. 11.ed. Santa Maria: Comissão de Química e Fertilidade do Solo – RS/SC, 2016. 376p.

MARQUES da SILVA, J.R.; SILVA, L.L. Evaluation of the relationship between maize yield spatial and temporal variability and different topographic attributes. **Biosystems Engineering**, v.101, p.183-190, 2008. DOI: 10.1016/j.biosystemseng.2008.07.003.

MCBRATNEY, A.; WHELAN, B.; ANCEV, T.; BOUMA, J. Future directions of precision agriculture. **Precision Agriculture**, v.6, p.7-23, 2005. DOI: 10.1007/s11119-005-0681-8.

MENEGATTI, L.A.A.; MOLIN, J.P. Remoção de erros em mapas de produtividade via filtragem de dados brutos. **Revista Brasileira de Engenharia Agrícola e Ambienta**l, v.8, p.126-134, 2004. DOI: 10.1590/S1415-43662004000100019.

MIAO, Y.; MULLA, D.J.; ROBERT, P.C. Spatial variability of soil properties, corn quality and yield in two Illinois, USA fields: implications for precision corn management. **Precision Agriculture**, v.7, p.5-20, 2006.

NICOLOSO, R. da S.; AMADO, T.J.C.; SCHNEIDER, S.; LANZANOVA, M.E.; GIRARDELLO, V.C.; BRAGAGNOLO, J. Eficiência da escarificação mecânica e biológica na melhoria dos atributos físicos de um Latossolo muito argiloso e no incremento do rendimento de soja. **Revista Brasileira de Ciência do Solo**, v.32, p.1723-1734, 2008. DOI: 10.1590/S0100-06832008000400037.

RODRIGUES, M.S.; CORÁ, J.E.; CASTRIGNANÒ, A.; MUELLER, T.G.; RIENZI, E. A spatial and temporal prediction model of corn grain yield as a function of soil attributes. **Agronomy Journal**, v.105, p.1878-1887, 2013. DOI: 10.2134/agronj2012.0456.

RODRIGUES, M.S.; CORÁ, J.E.; FERNANDES, C. Spatial relationships between soil attributes and corn yield in no-tillage system. **Revista Brasileira de Ciencia do Solo**, v.36, p.599-609, 2012. DOI: 10.1590/S0100-06832012000200029.

SANTI, A.L.; AMADO, T.J.C.; CHERUBIN, M.R.; MARTIN, T.N.; PIRES, J.L.; DELLA FLORA, L.P.; BASSO, C.J. Análise de componentes principais de atributos químicos e físicos do solo limitantes à produtividade de grãos. **Pesquisa Agropecuária Brasileira**, v.47, p.1346-1357, 2012. DOI: 10.1590/S0100-204X2012000900020.

SANTOS, H.G. dos; JACOMINE, P.K.T.; ANJOS, L.H.C. dos; OLIVEIRA, V.A. de; OLIVEIRA, J.B. de; COELHO, M.R.; LUMBRERAS, J.F.; CUNHA, T.J.F. (Ed.). **Sistema brasileiro de classificação de solos**. 2.ed. Rio de Janeiro: Embrapa Solos, 2006. 306p.

SCHLINDWEIN, J.A.; ANGHINONI, I. Variabilidade vertical de fósforo e potássio disponíveis e profundidade de amostragem do solo no sistema plantio direto. **Ciência Rural**, v.30, p.611-617, 2000. DOI: 10.1590/S0103-84782000000400009.

TEDESCO, M.J.; GIANELLO, C.; ANGHINONI, I.; BISSANI, C.A.; CAMARGO, F.A.O.; WIETHÖLTER, S. (Ed.). **Manual de adubação e de calagem para os estados do Rio Grande do Sul e de Santa Catarina**. 10.ed. Porto Alegre: Sociedade Brasileira de Ciência do Solo, Núcleo Regional Sul, 2004. 400p.

TEDESCO, M.J.; GIANELLO, C.; BISSANI, C.A.; BOHNEN, H.; VOLKWEISS, S.J.**Análises de solo, plantas e outros materiais**. 2.ed. rev. e ampl. Porto Alegre: UFRGS, 1995.

VEZZANI, F.M.; MIELNICZUK, J. Uma visão sobre qualidade do solo. **Revista Brasileira de Ciencia do Solo**, v.33, p.743-755, 2009. DOI: 10.1590/S0100-06832009000400001.

ZAMBROSI, F.C.B.; ALLEONI, L.R.F.; CAIRES, E.F. Teores de alumínio trocável e não trocável após calagem e gessagem em Latossolo sob plantio direto. **Bragantia**, v.66, p.487-495, 2007. DOI: 10.1590/S0006-87052007000300016.

Received on June 29, 2017 and accepted on December 22, 2017