Revista Brasileira de Ciência do Solo

Division - Soil Use and Management | Commission - Soil Fertility and Plant Nutrition

Soil Chemical and Physical Properties on an Inceptisol after Liming (Surface and Incorporated) Associated with Gypsum Application

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Received: October 7, 2015
Approved: February 5, 2016

How to cite: Bortolanza DR, Klein VA. Soil Chemical and Physical Properties on an Inceptisol after Liming (Surface and Incorporated) Associated with Gypsum Application. Rev Bras Cienc Solo. 2016;40:e0150377.

ABSTRACT: Inceptsoils have high aluminum contents, and amendments are required to ensure a satisfactory crop development. Liming is efficient in neutralizing Al^{3+}, but when applied to the topsoil its action is restricted to the surface layers, and sometimes lime incorporation into the soil is recommendable. However, tillage may negatively alter physical soil properties. Thus, gypsum could be an alternative to increase Ca^{2+} levels and reduce Al saturation in deeper layers, without requiring tillage. An experiment was initiated in 2010, to assess chemical and physical soil properties. Soil samples were collected in February 2013. A random block design with sub-subplots and two replications was used. Lime was applied to the surface of the main plot (0, 8 and 16 Mg ha^{-1}) and incorporated into the soil by plowing and light harrowing. Gypsum was applied to the subplot (0 and 6 Mg ha^{-1}), and the sub-subplots corresponded to the sampled layers (thickness of 0.05 m, to a depth of 0.25 m). The following parameters were evaluated: pH in water, base saturation, Al saturation, Ca^{2+}, Mg^{2+}, soil organic matter, water retention, and least limiting water range (LLWR). Lime incorporated into the soil reduced Al^{3+} and increased pH and Ca^{2+} levels, especially in the deeper soil layers, although pH levels did not exceed 5.1 and base saturation was lower than 60 %, still inadequate for crops. The gypsum rate of 6 Mg ha^{-1} did not decrease Al saturation, but reduced Mg^{2+} levels in top soil layers. Soil water retention and LLWR were not affected by plowing and harrowing within a period of three years. Gypsum rates below 6 Mg ha^{-1} were not effective in reducing Al saturation and increasing Ca^{2+} levels. Incorporated lime is more effective in correcting the acidity of the soil profile and, after three years, soil water retention and LLWR were similar under both liming methods.

Keywords: Al saturation, soil water retention, least limiting water range.

INTRODUCTION

Agricultural soils are affected by human activities associated with management practices that change their properties and functionality. A good-quality soil must supply plants with water, nutrients and air, aside from being free of restrictions (chemical, physical or biological) for the growth of the root system. In most part of Brazil, acidity levels in the soil subsurface layers are growth-limiting (Rampim et al., 2011). Because of the low solubility and mobility of limestone in the soil profile, acidity in the subsurface is not influenced by surface liming (Veronese et al., 2012). Even after surface liming at appropriate rates, Al levels in the soil subsurface can still be too high (Caires et al., 2006). In the tillage system used by most farmers, where liming is applied to soil surface (Rodrighero et al., 2015), gypsum can be an alternative to reduce Al saturation in the subsurface layers (Caires et al., 2001).

The description of the soil as *Cambissolo Húmico Alumínico típico* (Streck et al., 2008), i.e. Inceptisol, indicates the difficulty of correcting these soils, due to the high Al concentration. Cambisols are pedological units in process of formation, typically with an incipient B horizon, usually with high silt contents. Due to their genesis, these soils are susceptible to environmental problems such as high soil losses and contamination levels, especially of water, both of soil water and surface waters (Mello et al., 2006).

Soil porosity and mechanical resistance to penetration (PR) are soil physical properties that can easily be modified by soil tillage systems (Tormena and Silva, 2002). Thus, while lime incorporation is desirable to improve chemical properties in the deeper soil layers, soil tillage can change the physical properties.

The least limiting water range (LLWR) can be used to establish parameters that are more sensitive to changes in soil structure, characterized in terms of soil density (BD) rather than only plant-available water (Silva et al., 1994). The LLWR is defined as the range of soil water content with minimal restrictions for plant growth in terms of the soil water potential (Ψ) at which water is retained, aeration and PR. The water content was therefore determined experimentally for each of these conditions from the BD (Silva et al., 1994; Tormena et al., 1999), for being considered an indicator of the structural quality of agricultural soils.

The hypothesis of the study was that lime incorporation improves the chemical properties in the deeper layers, influences the soil physical and hydraulic properties and that the surface application of gypsum could make limestone incorporation superfluous. The objective of the study was to evaluate the influence of surface and incorporated liming, coupled with the surface application of 6 Mg ha^{-1} gypsum on the soil chemical and physical-water properties.

MATERIALS AND METHODS

The study was carried out in an agricultural area in the municipality of Bom Jesus, Rio Grande do Sul (50° 37’ W and 28° 28’ S, 1,100 m asl) on a soil classified as *Cambissolo Húmico Alumínico típico* (Streck et al., 2008), an Inceptsoil (Soil Survey Staff, 2014), with an incipient B horizon. According to the Köppen classification system, the climate is Cfa and the mean annual rainfall 1,724 mm (Rio Grande do Sul, 2010). Particle size analysis indicated a soil composition of 165 g kg^{-1} sand, 241 g kg^{-1} silt, 594 g kg^{-1} clay.

The experimental area was covered by natural pasture until 2002, and thereafter used for annual no-tillage grain crops with no soil disturbance.

To correct the soil acidity, at the beginning of grain production, lime rates of 6, 4 and 3 Mg ha^{-1}, respectively, were applied to the surface in 2002, 2005 and 2009. In 2010, the experiment was installed, and undisturbed (volumetric cylinder 0.05 × 0.05 m) and disturbed soil samples (cutting shovel) were collected at the beginning of 2013 (0.00-0.05, 0.05-0.10, 0.10-0.15, 0.15-0.20 and 0.20-0.25 m layers). The crops planted between the beginning of the experiment and sampling were maize, wheat, soybean, oat, and common bean. The experiment was arranged in a randomized block design in split plots, with two replications. Rates of 0, 8 and 16 Mg ha^{-1} dolomitic limestone (reactivity rate 80 %, neutralization power 95 %, relative power of total neutralization 76 %, CaO 27 %, MgO 17 %) were applied to the soil surface of the main plots and incorporated with a plow and by light harrowing. The subplot received gypsum rates of 0 and 6 Mg ha^{-1} (20 % Ca and 16 % S). The sub-subplots corresponded to the 0.05 m thick sampled layers. From the beginning of the experiment until sampling, the cultivation system was always no-tillage.

For the chemical analysis, the samples were analyzed according to Tedesco et al. (1995) in duplicate. Base saturation was calculated as the ratio between the sum of bases and cation exchange capacity at pH 7. Aluminum saturation was computed by the ratio of exchangeable Al^{3+} and the sum of Ca^{2+}, Mg^{2+}, K^+, and Al^{3+}.

In the soil physical evaluations, the two forms of lime application (surface and incorporation) were compared. Gravimetric water content was obtained at potentials of -0.001, -0.003, -0.006, -0.010, and -0.014 MPa in Haines funnels, at -0.1 and -0.3 MPa in a Richards chamber and at -1.5 MPa by a WP4-T® psychrometer. Volumetric water content (θ) was determined from moisture based on weight and BD. Soil water retention curves were obtained for θ from Ψ by adjusting the mathematical model of van Genuchten (1980) to the data:

$$\theta = \theta r + (\theta s - \theta r)/[1 + (\alpha\ \Psi\ m)^n]^m \qquad \text{Eq. 1}$$

where θ is the water content (m^3 m^{-3}), θs the saturated water content (m^3 m^{-3}), θ residual water content (m^3 m^{-3}) defined as the water content, where $d\theta/d\Psi = 0$ (Tormena and Silva, 2002), and α, n and m are empirical parameters of the equation. The restriction $m = 1-1/n$ was adopted for the parameter (van Genuchten and Nielsen, 1985). For θs, the total porosity value [(1 – (BD/DSS)] was used, where BD was bulk density, and DSS the density of soil solids. The latter was determined by the volumetric flask method described by Claessen (1997). The coefficients θr, α and n were obtained iteratively by fitting the model to the data.

The LLWR was determined for both soil management systems, i.e., for surface and incorporated liming. To determine the least limiting water range, θ at field capacity was considered as Ψ = -0.006 MPa (Reichardt, 1988) and the permanent wilting point (PWP) as Ψ = -1.5 MPa (Savage et al., 1996). Data were fit to the non-linear equation of Ross et al. (1991), including BD in the model, as proposed by Leao et al. (2005):

$$\theta = \exp(a + b\ BD)\ \Psi^c \qquad \text{Eq. 2}$$

where θ is the water content (m^3 m^{-3}), BD bulk density (Mg m^{-3}), ψ the water potential (-MPa) and a, b and c are the model fitting parameters.

Air-filled porosity (AP) was calculated with 1- [(BD/DSS) – 0.1] and linearized data from BD.

Penetration resistance was measured by a static penetrometer (operating speed 0.17 mm s^{-1}, cone base diameter 4 mm, 30° angle). The samples were penetrated at different moisture levels. Some samples were penetrated immediately after exposition the last tension and others to gradual moisture loss in the laboratory environment. From the data measured at different moisture levels and the corresponding BD of each sample, the non-linear mathematical model of Busscher (1990) was adjusted (Equation 3) and later 2 MPa was used to calculate critical θ in function of BD (Equation 4):

$$PR = a\ BD^b\ \theta^c \qquad \text{Eq. 3}$$

$$\theta = [2/(a\ BD^b)]^{1/c} \qquad \text{Eq. 4}$$

where PR is the soil penetration resistance (MPa), BD bulk density (Mg m^{-3}), θ water content (m^3 m^{-3}), and a, b and c are empirical parameters of model fitting.

The data of pH(H_2O), base saturation, Ca, Mg, Al saturation and soil organic matter (SOM) were subjected to analysis of variance and when significant, means were compared by the Tukey test ($p \leq 0.05$). To determine the coefficients of equations 1, 2 and 3, we used the least square method of deviations and Levenberg-Marquardt algorithm.

RESULTS AND DISCUSSION

The results are shown when significant differences were detected in the analysis of variance. No triple interaction between management limestone rates, gypsum rates and depth was observed for any of the variables. In the event of interactions, isolated significant factors were not considered.

For surface application, the three limestone rates altered the pH, especially in the surface layers. Even at the 0 Mg ha^{-1} rate, the pH of the soil surface was higher than when lime was incorporated, which can be attributed to the residual effect of 13 Mg ha^{-1} applied prior to the experiment (Figure 1a). In general, the higher rates raised the pH more, but the most noticeable difference resulted from the form of lime application. The action of limestone to neutralize subsoil acidity is hampered by the increased cation retention, due to the generation of variable negative electric charges (Caires et al., 2003). In addition, anions resulting from their dissolution, causing the correction of soil acidity, are also consumed in reactions with other acid cations (Al^{3+}, Mn^{2+} and Fe^{2+}) in the layer of limestone application.

Surface-applied lime corrected the acidity of the top soil layer and altered the deeper layers slightly. Lime incorporation resulted in homogenous acidity levels in the assessed profile, although the soil pH was not raised to desirable values for no-tillage fields (pH >5.5) (CQFSRS/SC, 2004). Perhaps, higher lime rates would be necessary to reach the recommended pH values. In a study by Rheinheimer et al. (2000), pH correction was also more homogenous when limestone was incorporated and the effects of correction were proportional to the applied rates.

The pattern of base saturation was very similar to that of pH in response to lime rates and forms of incorporation (Figure 1b). Although base saturation was not raised to over 65 % by lime incorporation, as recommended by CQFSRS/SC (2004), the values increased greatly in the deeper layers, compared with the three limestone rates applied on the surface. In the deeper layers, the values were very low (close to 10 % at 0 and 8 Mg ha^{-1}). The gypsum rate of 6 Mg ha^{-1} did not increase Ca^{2+} to significant levels for base saturation.

The values of Al saturation approached zero in the surface layer when limestone was not incorporated (Figure 1c). That Al was completely corrected only in the soil surface was also observed by Bilibio et al. (2010). Aluminum saturation was statistically equal for all treatments in the upper two evaluated layers, but below a depth of 0.15 m, Al saturation increased in the treatments without lime incorporation, and increased even more in the deeper layers. There was no effect of gypsum on Al saturation in the studied soil layers, which can be explained by the gypsum rate of 6 Mg ha^{-1}, which is high, but may have been insufficient in view of the high Al concentrations of the soil.

The Ca^{2+} levels had a pattern similar to that of pH and base saturation (Figure 1d). When limestone is not incorporated, the basic anions from limestone dissolution (OH^- and HCO_3^-) are moved by mass flow into deeper soil layers, where they react with acid cations (H^+, Fe^{2+}, Al^{3+}, and Mn^{2+}), causing the end of the alkalizing reactions in soils with abundance of these acid cations (Pauletti et al., 2014). Thus, Ca from limestone loses its companion ion already in the surface layers.

Soil organic matter decreased only in the 0.00-0.05 m layer due to plowing and harrowing for lime incorporation (Figure 1e). However there was no difference between treatments in the layers below 0.05 m. For an Inceptisol plowed once and harrowed twice compared with a no-tillage system, Andrade et al. (2012) obtained similar results of total organic C. The highest SOM levels in the soil surface resulted from crop residues left on the soil surface. The presence of straw on the surface in no-tillage systems helps maintain soil moisture and prevents the direct incidence of sun rays, reducing the temperature in the soil surface layer and consequently SOM mineralization (Loss et al., 2014). The high SOM levels found in this soil can be assigned to the altitude of the location at around 1,100 m, where temperatures are low, preventing the action of decomposing microorganisms.

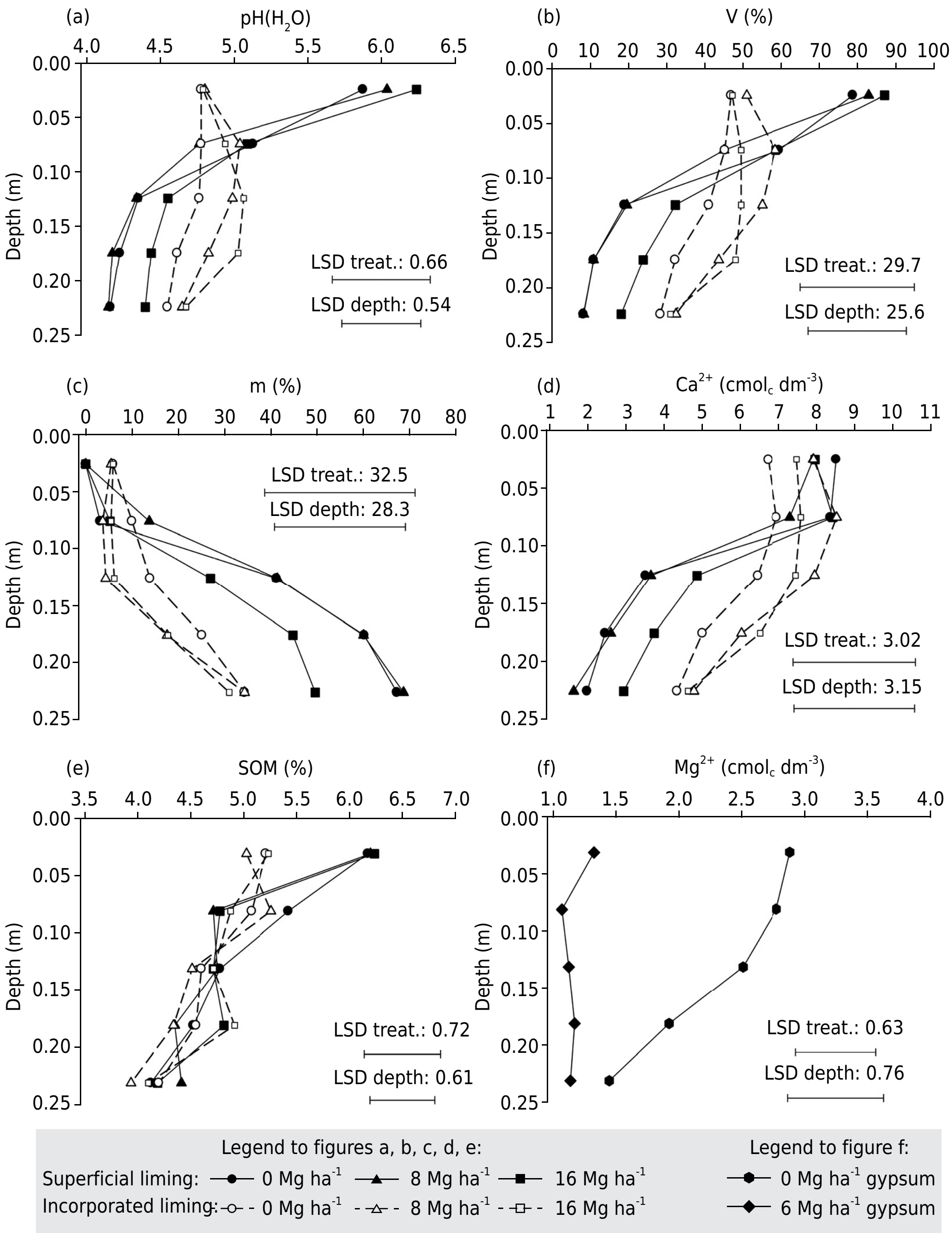

Figure 1. Effect of treatments on pH in water – pH(H_2O) of the soil (a) base saturation – V (b), Al saturation – m (c), Ca^{2+} content (d), soil organic matter – SOM (e) and Mg^{2+} content (e). Horizontal bars represent the least significant differences by the Tukey test ($p \leq 0.05$) for the applied treatments (LSD treat) and evaluated layers (LSD depth).

Gypsum significantly reduced Mg contents to a depth of 0.20 m (Figure 1f). The vertical movement of the bases was associated with the formation of neutral ion pairs such as $K_2SO_4^0$, $CaSO_4^0$ and $MgSO_4^0$ (Ramos et al., 2013), facilitating percolation of these cations through the profile, since the colloids and soil organic matter were not bound to negatively charged residues. Gypsum was not significant for the Ca and Al levels. This can be explained by the insufficiency of the 6 Mg ha^{-1} rate, due to the high soil buffering potential.

Soil physical and hydraulic properties were compared, considering only the two forms of liming (surface and incorporated). Water retention in the soil at high matrix potentials was due to the capillarity process and therefore strongly affected by the arrangement of soil particles due to the presence of structural, inter-aggregate pores (Carducci et al., 2011). Soil movement caused by plowing and harrowing modifies the pore structure and can induce changes in water retention, which was however not the case for this soil. There was no statistical difference between the estimators of the van Genuchten model (van Genuchten, 1980) and the confidence interval (0.95) (Table 1). This fact becomes evident in an analysis of the soil water retention curves (Figure 2).

Table 1. Estimators of the parameters of equations of soil water content (θ)[1]

Parameter	Coefficient	Lower CI[2]	Upper CI	t	p
		Surface liming			
θr	0.047	- 0.057	0.152	0.90	0.370
α[3]	5.631	3.824	7.437	6.12	<0.001
n	1.098	1.068	1.129	70.82	<0.001
F = 3,182.75 p<0.001					
		Incorporated liming			
θr	0.163	0.112	0.215	6.22	<0.001
α	4.016	2.778	5.254	6.37	<0.001
n	1.149	1.112	1.185	61.38	<0.001
F = 2,702.86 p<0.001					

[1] $\theta = \theta r + \{(\theta s - \theta r)/[1+(\alpha \times \Psi)^n]^{1-1/n}\}$, where θ is water content (m^3 m^{-3}), θs the saturated water content (m^3 m^{-3}), θr the residual water content (m^3 m^{-3}), and Ψ is the soil water potential (MPa). [2] CI: confidence interval (0.95); [3] α = 1/kPa.

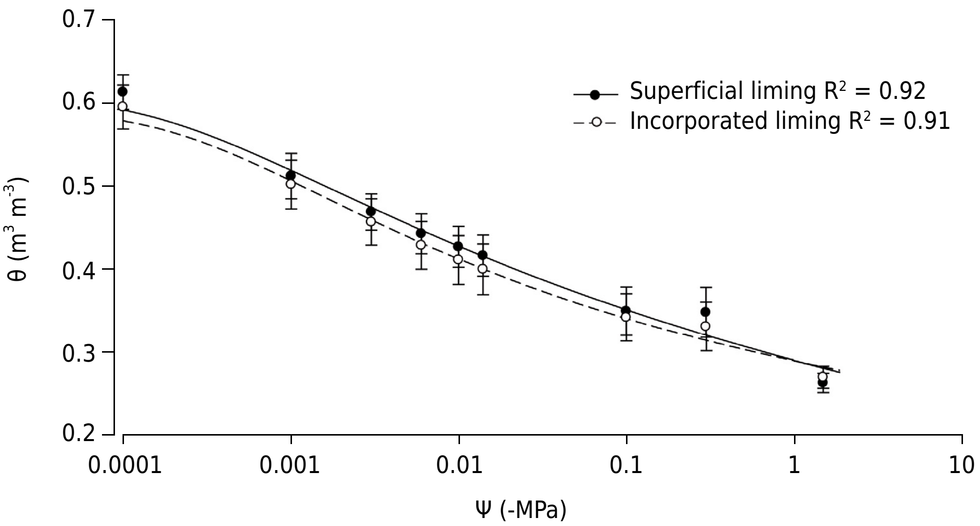

Figure 2. Soil water retention curves for surface liming and incorporated liming, estimated by the function $\theta = \theta r + \{(\theta s - \theta r)/[1 + (\alpha\times\Psi)^n]^{1-1/n}\}$, where θ is the water content (m^3 m^{-3}), θs is the saturated water content (m^3 m^{-3}), θr is the residual water content (m^3 m^{-3}), and Ψ is the soil water potential (MPa). Bars represent the mean standard deviation of θ observed at each Ψ (n = 60).

The effects of mechanical intervention on the soil physical properties did not persist for longer than 4.5 years in an Oxissol (Drescher et al., 2011) and for 1.5 years in an Ultisol (Nunes et al., 2014). In both studies, the authors explained that the tillage-induced changes were temporary, due to natural reconsolidation processes by successive wetting and drying cycles, aside from the traffic of agricultural machinery.

The mathematical fit of the Busscher model (Busscher, 1990) to the data showed that the increase in PR as a function of θ and BD was more evident in the soil tilled for liming (Figures 3a and 3b), but without statistical significance, since a comparison of the two soil management systems showed no overlap of the confidence intervals (Table 2). All parameters were significant, since the value zero was not contained in their confidence interval (Glantz and Slinker, 1990). The negative coefficient "c" indicated that PR decreased with increasing θ, due to the lubricating effect of water, by reducing particle cohesion in the soil matrix (Tormena et al., 2007). The positive coefficient "b" indicated that PR increased with increasing bulk density (BD), due to the compaction effect, leading to an interparticle contact or friction (Table 2).

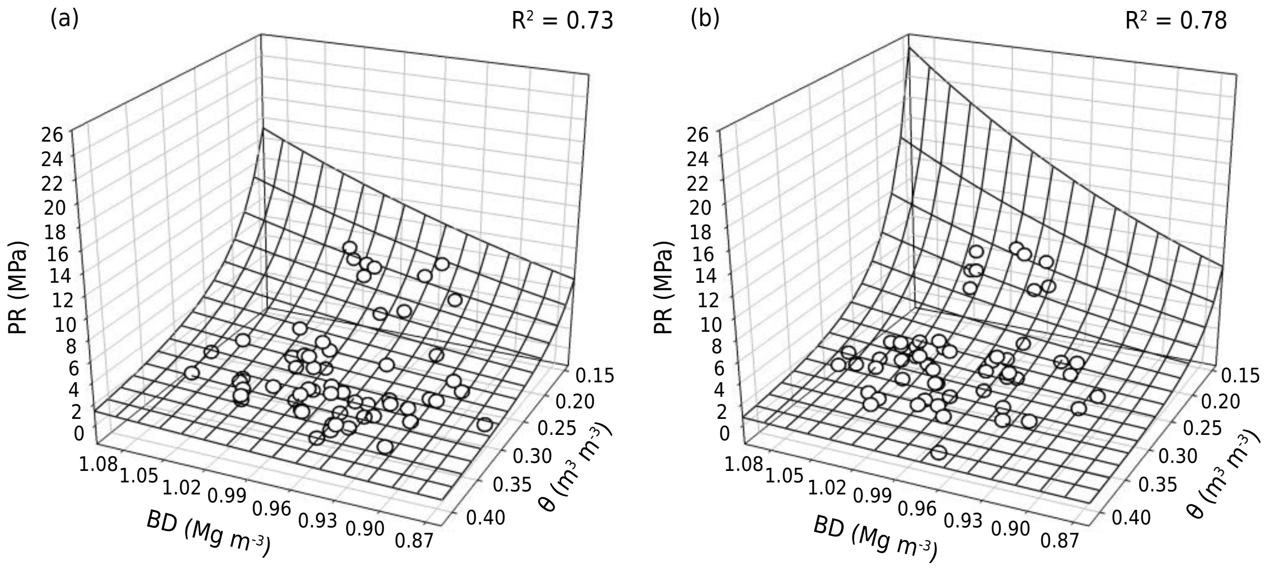

Figure 3. Response surface of soil penetration resistance (PR) as a function of bulk density (BD) and moisture (θ) estimated by the model fit PR = a × BD^b × $θ^c$. Surface liming (a) and incorporated liming (b).

Table 2. Estimators of the parameters of equation of soil penetration resistance (RP)[(1)]

Parameter	Coefficient	Lower CI[(2)]	Upper CI	t	p
		Surface liming			
a	0.132	0.054	0.210	3.38	0.001
b	3.612	1.002	6.221	2.77	0.008
c	-2.294	-2.670	-1.919	-12.24	<0.001
F = 147.656 p<0.001					
		Incorporated liming			
a	0.032	0.007	0.058	2.52	0.015
b	4.493	1.327	7.658	2.85	0.006
c	-3.162	-3.662	-2.663	-12.70	<0.001
F = 167.147 p<0.001					

[(1)] RP = a × BD^b × $θ^c$, where: PR: soil penetration resistance (MPa); BD: bulk density (Mg m^{-3}); θ: soil water content (m^3 m^{-3}). [(2)] CI: confidence interval (0.95).

The difference in θ at which the soil reaches the critical PR of 2 MPa in function of BD (Figure 4) was not significant for the two forms of liming. With increasing BD, increases in θ were required to maintain the same PR. Thus, the BD influenced θ at which the limiting PR of 2 MPa was reached, as observed by the significant coefficient "b" for both lime application modes (Table 2).

For the treatments with surface liming (Figure 4), θ varied along with the BD range from 0.247 to 0.341 m^3 m^{-3}, and from 0.235 to 0.302 m^3 m^{-3} for the treatments with soil disturbance for liming. In practice, this means that at the higher BD values, the critical PR occurs at Ψ below -0.140 and -0.514 MPa (values calculated from the soil water retention curve: Tables 1 and 2), corresponding to surface liming and lime incorporation, respectively. The values of water potential Ψ were low, and only became limiting at the highest BD, making restrictions for the root development due to PR rather unlikely. Even at lower BD, for both forms of liming, the PR would be much lower than the PWP values.

A graphical representation of the equation of table 3 is shown in figure 5. The coefficient of determination was high for surface liming (R^2 = 0.92) as well as incorporated liming (R^2 = 0.93), indicating a good fit of the model.

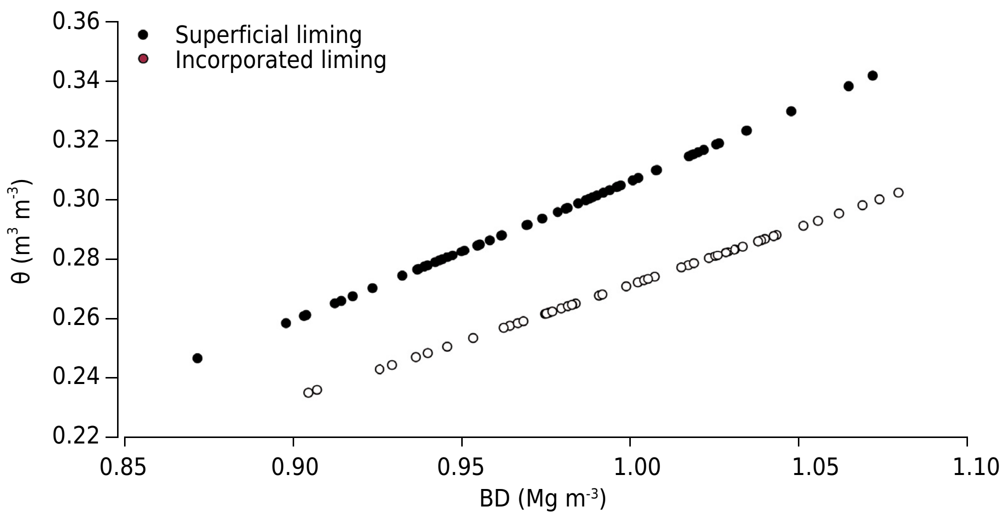

Figure 4. Water content (θ) at which soil penetration resistance (PR) becomes critical (2 MPa) for surface liming and incorporated liming.

Table 3. Estimators of the equation of soil water content (θ)[1]

Parameter	Coefficient	Lower CI[2]	Upper CI	t	p
		Surface liming			
a	-1.420	-1.537	-1.302	-23.74	<0.001
b	0.200	0.080	0.319	3.27	0.001
c	-0.080	-0.082	-0.078	-82.43	<0.001
F = 3,549.3 p<0.001					
		Incorporated liming			
a	-1.276	-1.414	-1.138	-18.22	<0.001
b	0.031	-0.105	0.168	0.45	0.652
c	-0.079	-0.081	-0.077	-73.14	<0.001
F = 2,766.2 p<0.001					

[1] $\theta = \exp(a + b \times BD) \times \Psi^c$, where θ: soil water content (m^3 m^{-3}); BD: bulk density; Ψ: water potential (MPa). [2] CI: confidence interval (0.95).

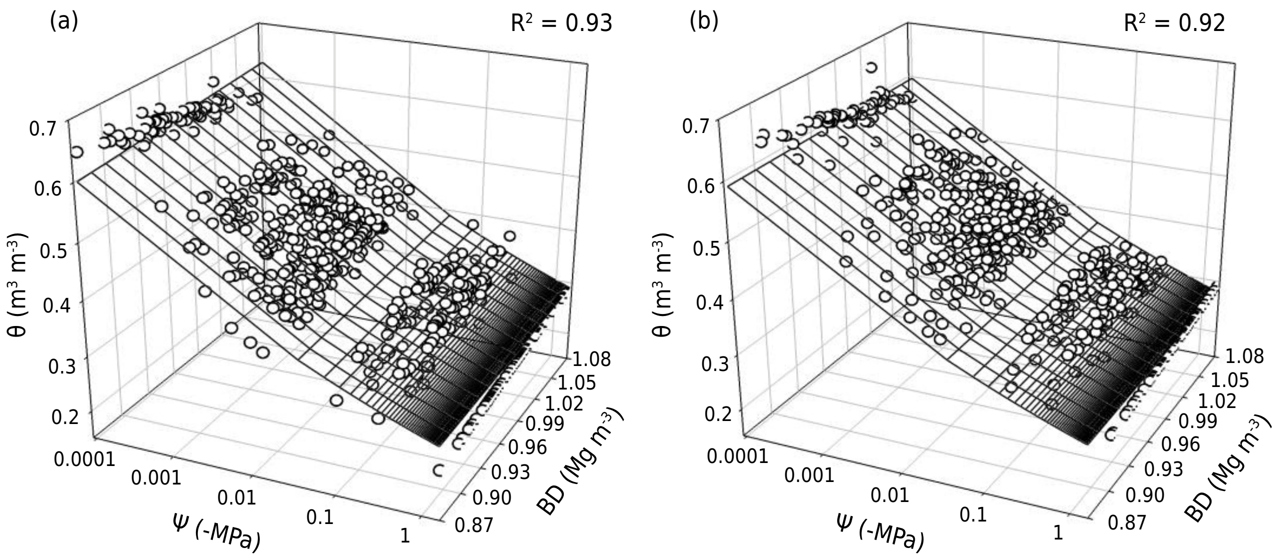

Figure 5. Response surface of water content (θ) as a function of bulk density (BD) and the soil water potential (Ψ) estimated by the function $\theta = \exp(a + bBD) \times \Psi^c$. Surface liming (a) and incorporated liming (b).

All coefficients of equation 2, except coefficient "b" for lime incorporation (Table 3), were statistically significant, for not including the value zero in their confidence intervals, as recommended by Glantz and Slinker (1990). The inclusion of the value zero in the confidence interval of parameter "b" indicated that the explanatory power of BD to estimate water content, in the case of lime incorporation, was insufficient. The weak influence of BD on water content at water potentials of -0.006 and -1.5 MPa on the soil tilled for liming can be seen in the representation of LLWR (Figure 6b), where the slope of the lines that defines these limits was negligible.

Air-filed porosity decreased linearly with increasing BD in both managements. The equation that determined the decrease in AP due to the higher BD was AP = 0.87791 – 0.37478 BD ($R^2 = 0.60$; $p<0.001$) for surface liming and AP = 0.82228 – 0.32858 BD ($R^2 = 0.30$; $p<0.001$) for lime incorporation. However, AP was not a limiting factor for this soil. This indicates the good physical structure of the soil, with sufficient total porosity to be unrestrictive to LLWR at any level of BD because of aeration deficiency. The critical upper limit of LLWR was the field capacity in both cases (Figures 6a and 6b).

At the lower limits of LLWR, the PWP was the critical limit up to a BD of 0.952 Mg m^{-3} [$\exp(-1.420 + 0.200\ BD) \times 1.5^{-0.080} = 2/(0.132\ BD^{3.612})^{1/-2.294}$], and when higher, BD was replaced by the limit of PR, corresponding to 61 % of the soil samples with surface liming (Figure 6a). In the soil with lime incorporation, PWP was the critical limit up to a BD of 1.022 Mg m^{-3} [$\exp(-1.276+0.031\times BD)\times 1.5^{-0.079} = 2/(0.032\times BD^{4.493})^{1/-3.162}$], corresponding to 33 % of the samples (Figure 6b). Thus, PR was the most limiting factor for the undisturbed soil. The results were comparable to those reported by Tormena et al. (1998) in an evaluation of the LLWR of an untilled Oxisol. The residual effect of soil disturbance, even three years after plowing and harrowing, may have contributed to reduce the percentage of samples with critical PR, when compared with the untilled soil (without limestone application).

Despite the small differences, the undisturbed soil had a wider LLWR up to a BD of 0.97 Mg m^{-3}, while above this BD, the LLWR of the plowed soil was widened (Figure 7). The LLWR remained constant up to the BD at which the lower limit of the PWP was replaced by PR and, thereafter, decreased with the increase in BD, in both evaluations. The decrease in LLWR was noticeable in both soil management systems when the lower limit of PWP was replaced by the limit of PR, which occurs at the BD mentioned above.

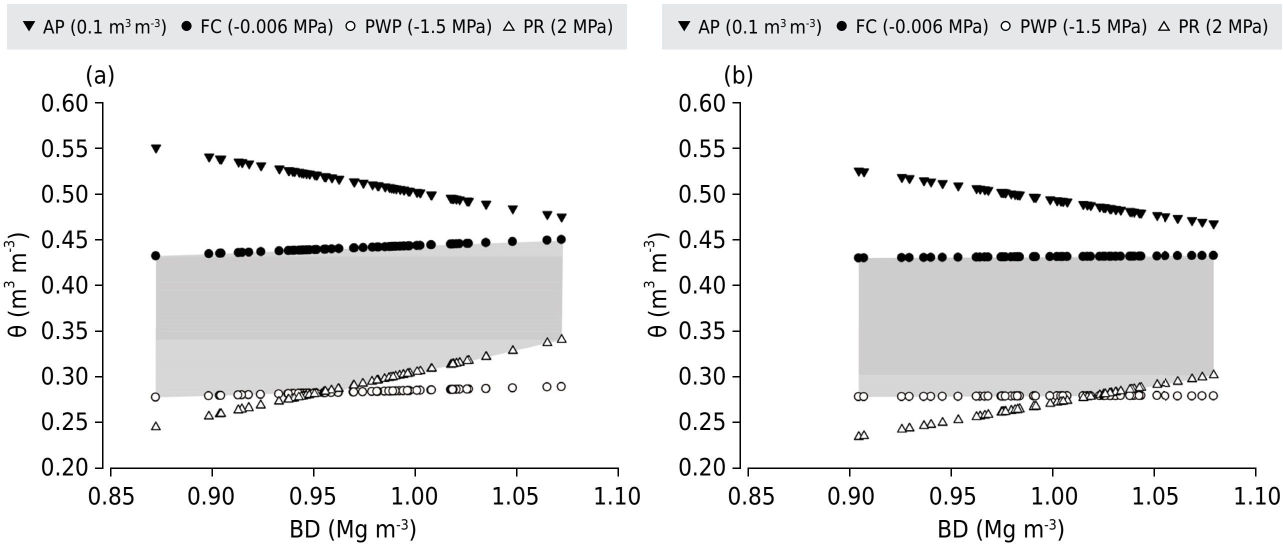

Figure 6. Water content (θ) with the variation of bulk density (BD) for field capacity (FC), permanent wilting point (PWP), aeration porosity (AP), and limiting penetration resistance (PR). The shaded area represents the LLWR. Surface liming (a) and incorporated liming (b).

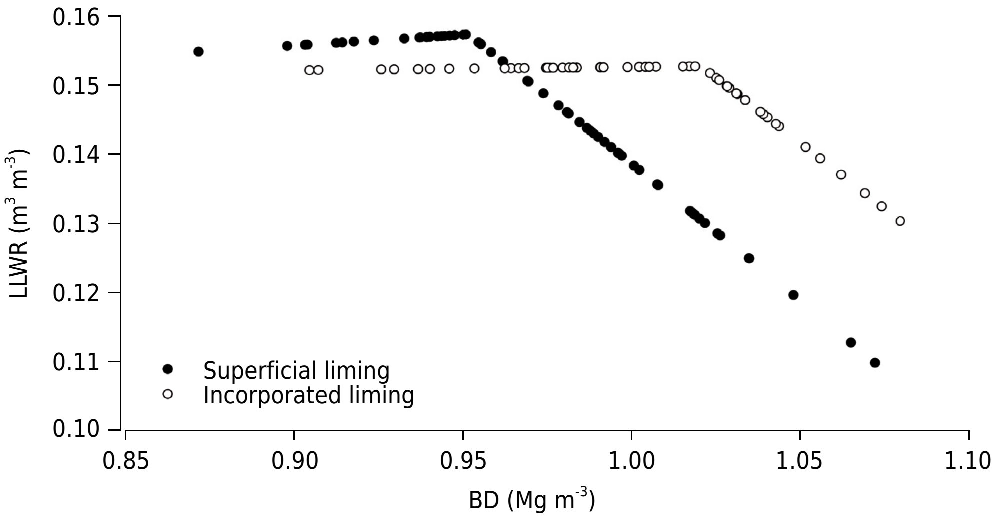

Figure 7. Least limiting water range (LLWR) in function of bulk density (BD) for surface liming and incorporated liming.

There was no critical bulk density, defined as the BD at which LLWR is zero, reflecting the good physical structure of the soil. Under these conditions, restrictions to root growth, due to deficiency in aeration, water availability and PR are minimal (Silva et al., 1994).

The LLWR found for both management systems was wider than that of other soils evaluated elsewhere (Silva et al., 1994; Tormena et al., 1998, 1999; Lima et al., 2012), whereas the LLWR for the Inceptsoil has not been determined so far by other authors, for comparison. Many soils of this region are being used for grain production, increasing the relevance of our findings. The high SOM levels probably contributed to these results.

CONCLUSIONS

Lime applied on the soil surface has no effect on the acidity of subsurface layers.

At a rate of 6 Mg ha^{-1}, gypsum did not reduce the characteristically high Al^{3+} content of this soil, for being insufficient to raise the Ca^{2+} levels and base saturation.

Water retention in the soil is unchanged three years after plowing and harrowing the soil.

The least limiting water range indicates that the physical and hydraulic properties of the Inceptsoil are good and not significantly different in soil tilled for limestone incorporation.

ACKNOWLEDGEMENTS

The authors are indebted to the Coordenação de Aperfeiçoamento de Pessoal de Nível Superior (CAPES) and the Universidade de Passo Fundo for a scholarship and they wish to thank the Fundação de Amparo à Pesquisa do Rio Grande do Sul (FAPERGS) for financing the project (2115/13-4) and the Conselho Nacional de Desenvolvimento Científico e Tecnológico (CNPq) for a research productivity fellowship.

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