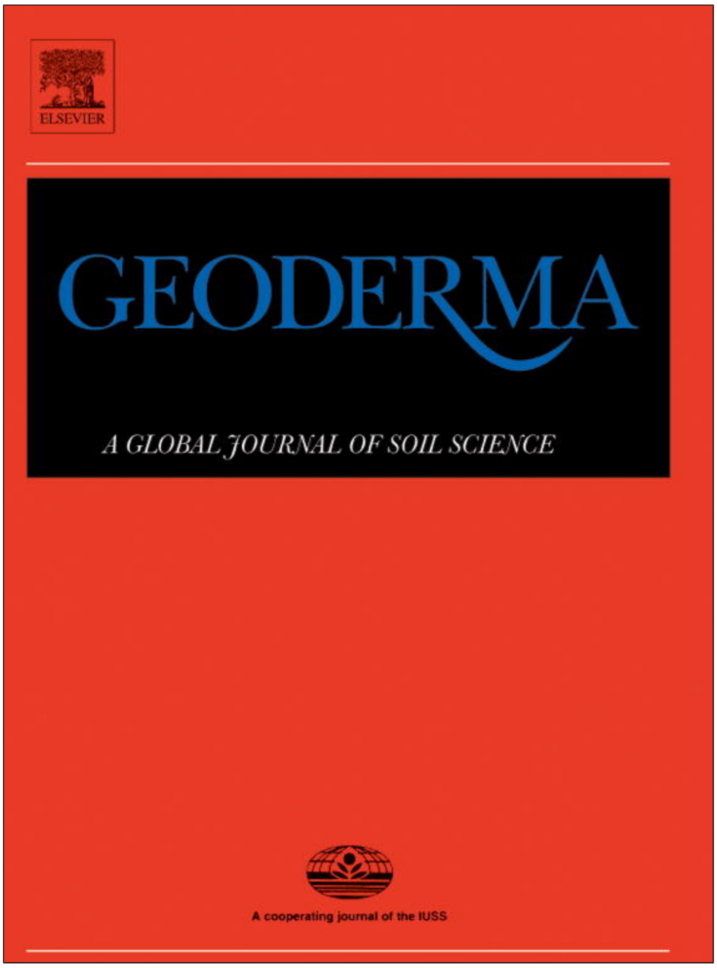
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Critical bulk density for a Mollisol and a Vertisol using least limiting water range: Effect on early wheat growth

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ABSTRACT

The least limiting water range (LLWR) integrates crop growth-limiting values based on easily measurable parameters such as soil water content and bulk density (BD) and has been validated as a valuable soil physical quality indicator for a wide range of soils, crops and management systems. When the LLWR is zero, the soil achieves the critical bulk density value (BDc). Another methodology to assess the level of soil compaction and its effect on crop growth is the shear strength (SS) of the soil. The aims of this work were: i) to obtain critical bulk density values for a Mollisol and a Vertisol using the LLWR and assess their effects on early wheat growth, and ii) to evaluate the variation in early wheat growth as affected by the increases in BD and SS. An experiment in pots containing disturbed soil from an Aquic Argiudoll and a Typic Hapludert was carried out. Soil cores obtained from agricultural paddocks were mechanically compacted to 1.1, 1.2, 1.3, 1.4 and 1.5 Mg m^{-3}. Wheat was grown on half of the pots for two months, and, after that, both shoot and root biomass were measured. LLWR and SS were evaluated in the remaining non-sowed cylinders as a function of the increase in BD. Critical bulk density was 1.44 Mg m^{-3} and 1.37 Mg m^{-3} for the Mollisol and the Vertisol, respectively. Although both soils fit in the same textural class (silty clay loam), the Vertisol has clay dominated by smectite mineralogy. In the Mollisol, wheat growth was limited when BD > 1.4 Mg m^{-3} due to the lack of aeration rather than to the high penetration resistance. The response of early wheat growth to increasing BD differed clearly between soils. In the Vertisol, early wheat growth was not affected by BD due to volumetric changes. The greater differences in volumetric changes between soils were recorded at lower BD values, being higher at 1.2 Mg m^{-3} (16.8%) and lower at 1.4 Mg m^{-3} (2%). Soil shear strength was significantly correlated with BD and was sensitive to soil water changes. Bulk density values higher than 1.35 Mg m^{-3} had high SS values. This measurement also allowed us to obtain a critical value for crop growth, but only for the Mollisol (50 kPa). LLWR and BDc were useful to determine a threshold for early wheat growth only in the Mollisol. These findings provide an interesting platform for the management of soils with similar textural classes and different clay mineralogy, particularly when they are present in the same paddock across the landscape.

Contents

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1. Introduction

Soil degradation is the loss of actual or potential productivity as a result of natural or anthropogenic factors (Lal, 1994). Many reports have highlighted the role of soil compaction as one of the most important causes of soil degradation (Dexter, 2004; Hamza and Anderson, 2005). Water supply, soil aeration, temperature and soil strength on plant roots are negatively affected by soil compaction (Håkansson, 1994; Lipiec et al., 1991; Soane and Van Ouweerkerk, 1995). In addition, soil compaction triggers physiological and morphological alterations in plants, which may lead to reductions in crop growth and yield (da Silva and Kay, 1996; da Silva et al., 1994; Gupta and Allmaras, 1987; Letey, 1985; Sadras et al., 2005).

In order to quantify trends in soil evolution and rates of change across soil type or soil management, soil quality indicators are needed. These indicators can reveal limitations to root growth, seedling emergence, infiltration or water movement within the soil profile by monitoring soil functioning if acceptable ranges or thresholds are established. Based on the concept introduced by Letey (1985), da Silva et al. (1994) proposed the least limiting water range (LLWR) as an indicator of soil structural quality for crop growth. The LLWR integrates crop growth-limiting values based on easily measurable parameters such as soil water content and bulk density (BD) and has been validated as a valuable soil physical quality indicator for a wide range of soils, crops and management systems (Betz et al., 1998; Chan et al., 2006; da Silva and Kay, 1997; Imhoff et al., 2001; Lapen et al., 2004; Leão et al., 2006; Mc Kenzie and Mc Bratney, 2001; Tormena et al., 1998). When the LLWR is zero, the soil achieves the critical bulk density value (BDc) (Imhoff et al., 2001; Leão et al., 2006; Tormena et al., 1999), which indicates that restrictive density affecting root growth and crop yield has been reached (Reichert et al., 2009).

Another methodology to assess the level of soil compaction and to estimate its effect on crop development is the soil shear strength (SS), which is related to BD. Some authors have reported that SS values are closely related to the structural conditions of the soil, such as macroporosity and soil strength (Ball and O'Sullivan, 1982; Carter, 1990). Soil shear strength depends on the cohesive forces between the soil particles and on the frictional resistance produced when the soil is forced to slide over the soil along some shear plane (Draghi and Hilbert, 2006; Hillel, 2005; Léonard and Richard, 2004). As a consequence, SS may be fairly variable according to soil granulometry, mineralogy, and organic and water content.

A pot experiment with soil samples of A horizons from two types of soils (a Mollisol and a Vertisol) was designed to: i) obtain critical bulk density values using the LLWR, and assess their effects on early wheat growth, and ii) evaluate the variation in early wheat growth as affected by the increases in BD and SS.

2. Materials and methods

2.1. Study site and soil

The study was carried out at the Paraná Experimental Station of the Instituto Nacional de Tecnología Agropecuaria (INTA) in Entre Ríos province, Argentina, (31° 51′ S and 60° 31′ W). The region has a subhumid (annual rainfall ≈ 1000 mm) and temperate climate (annual temperature ≈ 18.3 °C). Winter temperatures are rarely below 0 °C. Predominant soils of the area are Mollisols and Vertisols. Typical, representative soils of our region are Aquic Argiudol (Mollisol) and Typic Hapludert (Vertisol) (Soil Survey Staff, 1999), frequently associated in the regional landscape (Plan Mapa de Suelos, 1998).

2.2. Sample preparation

A completely randomized laboratory experiment was carried out with soil cores (three replicates, n = 60) starting in November 2007. Sixty cylinders (0.085 m high, 0.15 m in diameter) of PVC, 30 for each soil type, with perforated bottoms were filled with soil samples belonging to an A horizon from an fine, illitic, thermic Aquic Argiudoll of the Tezanos Pinto Series (Mollisol) and from a very-fine, smectitic, thermic Typic Hapludert of the Febré Series (Vertisol) (Table 1). Soil samples were extracted from fields conducted under no tillage for at least ten years, during the winter fallow period. Soil samples were air-dried, sieved (2 mm) and placed into the cylinders, to reach a 7-cm high soil column in each cylinder.

Soil samples were compressed with a rammer, by thin layers to assure bulk density homogeneity. Five compaction levels were obtained: 1.1, 1.2, 1.3, 1.4 and 1.5 Mg m^{-3} using different soil weights by volume unit. After that, soil samples were oven-dried at 60 °C for 3 days. Then, distilled water was gradually added with a sprinkler to achieve gravimetric water content at field capacity (θ_{FC}), i.e. 31.5 and 34.5% water content for the Mollisol and the Vertisol, respectively. Careful attention was paid to minimize hydraulic charges and rapid transfer through cracks and the soil–border interface.

Four wheat seeds per cylinder were planted in half of the cylinders (n = 30). Soils were kept at θ_{FC} at laboratory temperature (25 ± 3 °C) during the two-month experiment. Soils were kept at θ_{FC} by daily water additions using a fine spray sprinkler on the soil surface until reaching the desired weight in each pot. Hoagland nutritive solution was added three times a week also using a sprinkler, previous to water additions. Two plants per cylinder were finally the adjusted stand after stage 1 (Zadoks et al., 1974). Two months after the beginning of the experiment, shoots were removed, oven-dried at 60 °C and weighed. Roots were measured washing the soil contained in the cylinder with distilled water and sodium hexamethaphosphate (100 g l^{-1}), oven-dried at 60 °C and weighed. The root/shoot ratio was calculated for each cylinder.

2.3. Soil measurements

The remaining 30 cylinders, which were not cultivated, were allowed to dry by surface evaporation at room temperature (20–25 °C) in the laboratory until soil water near permanent wilting

Table 1
Background soil properties of the Mollisol and the Vertisol studied.

Soil	pH (1:2.5)	OC %	Clay	Sand	Silt	Textural class
			g kg^{-1}			
Mollisol	6.3	2.65	274	63	663	Silty clay loam
Vertisol	7.6	2.74	317	82	601	Silty clay loam

OC: organic carbon.

(θ_{WP}) point (17 and 24%w/w for the Mollisol and the Vertisol, respectively) was achieved. Soil columns were weighed once a day to record moisture changes (i.e. water loss). The SS was measured in seven different water contents with a 35-mm high, 19-mm diameter vane tester (Eijkelkamp ®, Holland) on the soil core surface, and soil penetration resistance (PR) was measured using a laboratory penetrologger (Marconi ®, Brazil) with a 30° cone and base area of 0.1256 cm^2 driven into the soil at a constant rate (2 cm s^{-1}). Soil penetration resistance was measured, in pots without plants, in a wide range of decreasing soil moisture. For each cylinder, three PR readings were obtained each 1 cm from 0 to 7 cm.

At the beginning (after the first wetting) and at the end of the experiment, mean heights of the soil columns without plants were recorded with a vernier to evaluate volumetric changes and to calculate variations in BD values, considering initial (BD_i) and final bulk density (BD_f). Soil water content at θ_{FC} (−33 kPa matric potential) and θ_{WP} (−1500 kPa matric potential) were measured in undisturbed cores obtained from columns without plants using a 100 cm^3 volume sample ring (one 5-cm-diameter and 3-cm-long core sampling from each pot) on pressure plates. Final bulk density was considered to calculate volumetric data.

The LLWR was determined for each core following the methodology proposed by da Silva (1994). The upper limit is defined by θ_{FC} or by the water content at air-filled porosity of 10% (θ_{AFP}), whichever is smaller. Air filled porosity of 10% was calculated as [1 − (BD/DP)] − 0.1, where BD is the bulk density in each treatment and DP is the particle density. Total porosity was considered equal to water content at θ_S and was calculated using the BD of the undisturbed 100 cm^3 cores and the measured particle density (2.55 Mg m^{-3} and 2.50 Mg m^{-3} for the Vertisol and the Mollisol, respectively). The lower limit is defined by θ_{WP} or by the water content where soil resistance reached 2 MPa (θ_{PR}), whichever is higher. The LLWR, therefore, incorporates characteristics related to pores and failure zones into a single variable (Kay et al., 1997; Wu et al., 2003; Leão et al., 2006). The frequency at which the water content fell outside the LLWR increased as the LLWR became smaller. The LLWR was calculated for each compaction level. When the LLWR was equal to zero, BD was considered as critical bulk density (BDc).

We used the relative water content (θ_r) to allow comparisons between the data of PR of the two soils at equal water status. Relative water content was calculated as the ratio between the water content at the PR measurement and that at soil saturation (θ_S) (de Orellana et al., 1997). The water content at which soil resistance becomes limiting (θ_{PR}), i.e. when PR is equal to 2.0 MPa, was estimated using a potential function as: $PR = a\ (\theta/\theta_s)^b$ where a and b are parameters that depend on the soil type and BD (Wilson et al., 2006).

2.4. Statistical analysis

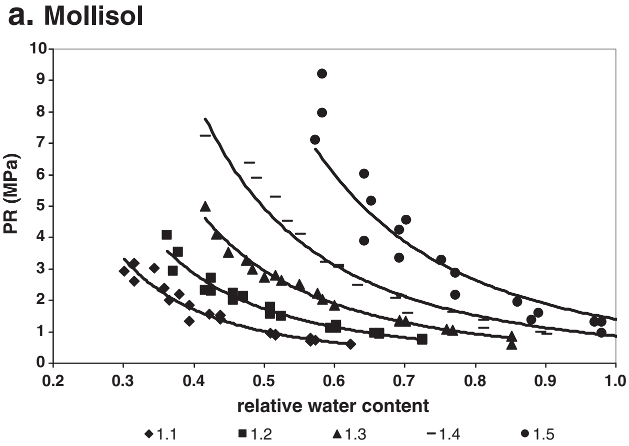
Correlations and regression analysis were performed using PROC REG, whereas ANOVA was performed using PROC GLM included in SAS (SAS Institute Inc., 1989).

3. Results and discussion

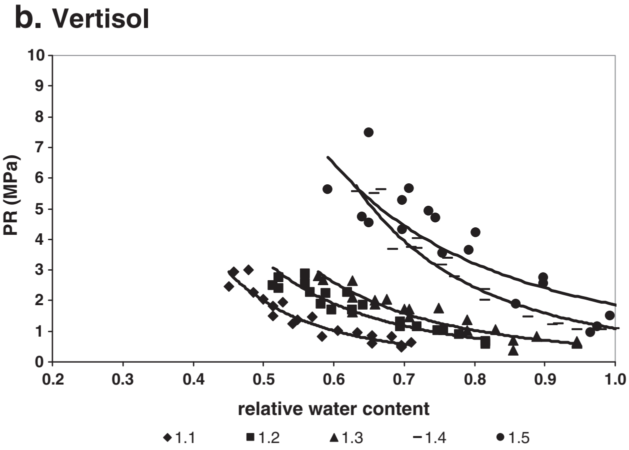
3.1. Soil penetration resistance

Fig. 1 shows the relationships between PR and θ_r for each soil and BD value. Penetration resistance showed an asymptotically function that depended on soil moisture, in coincidence with previous findings (Cass et al., 1994). At a given θ_r, PR increased with higher values of BD in both soils. The lower the θ_r within a BD value and a soil type, the greater the PR (Fig. 1). The parameters of each function are presented in Table 2.

Maximum values of PR were similar in both soils. However, they were reached at different θ_r values. As a consequence, the water content at which soil resistance became limiting (θ_{PR}), i.e. when PR was equal to 2 MPa, was reached at higher θ_r values in the Vertisol than in the Mollisol at a given BD. This indicates that, in the Mollisol, root growth could be limited by PR at lower values of θ_r that in the Vertisol, allowing crops to grow at a lower relative water content.



a. Mollisol



b. Vertisol

Fig. 1. Soil penetration resistance (PR) as a function of relative water content of two soils in different soil bulk densities. Symbols represent different soil bulk densities and lines are the fitted potential functions, whose parameters are presented in Table 2.

Variations in PR depend on several factors such as organic carbon content, soil texture and specific surface area (SSA) (Campbell and O´ Sullivan, 1991; Cassel, 1982). In fact, Paz Ferreiro et al. (2009) studied the SSA values of Mollisols and Vertisols from our study area and found values of 31–56 m^2 g^{-1} and 54–78 m^2 g^{-1}, respectively.

Table 2
Parameters of potential function fitted for the relationship between penetration resistance (PR) and relative water content for different soil bulk densities.

Bulk density	Parameters of potential function		R^2
Mg m^{-3}	a	b	
Mollisol			
1.1	0.18	−2.32	*0.95*
1.2	0.35	−2.30	*0.95*
1.3	0.54	−2.44	*0.98*
1.4	0.88	−2.53	*0.96*
1.5	1.40	−2.85	*0.92*
Vertisol			
1.1	0.16	−3.62	*0.92*
1.2	0.49	−2.64	*0.88*
1.3	0.50	−3.21	*0.88*
1.4	1.04	−3.80	*0.96*
1.5	2.02	−2.31	*0.78*

All functions were significant (P<0.0001).

These results suggest that higher values of SSA in Vertisols may increase the soil–metal interface during measurements, leading to increased PR, as compared to Mollisols.

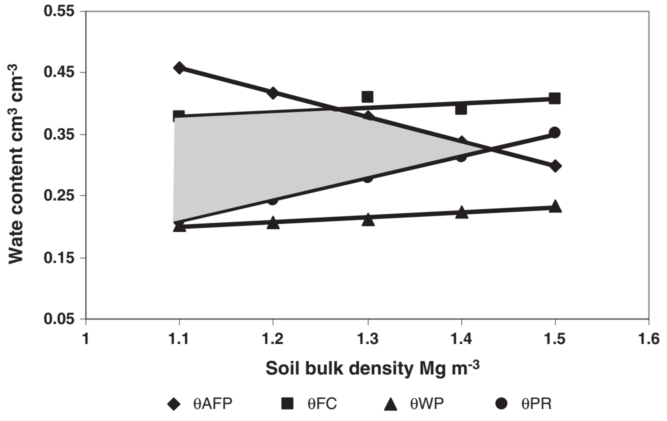
Although both soils fit in the same textural class, i.e. silty clay loam, the Vertisol has 4.3% more clay dominated by smectite mineralogy (de Orellana et al., 1997; De Petre and Stephan, 1998; Morrás et al., 1998; Stephan et al., 1983). Thus, PR seems not to depend on the textural class only, thus revealing the crucial role of clay mineralogy on this soil physical property.

3.2. Least limiting water range (LLWR)

The LLWR decreased as BD increased in both soils (Fig. 2). Maximum LLWR values were found at BD = 1.1 Mg m^{-3} and ranged from 0.169 cm^3 cm^{-3} to 0.141 cm^3 cm^{-3} for the Mollisol and Vertisol, respectively. The LLWR was higher in the Mollisol than in the Vertisol across the different BD values. In both soils, at high BD values (>1.3 Mg m^{-3}), the upper limit of LLWR was defined by θ_{AFP}, whereas at low BD values (1.1–1.2 Mg m^{-3}), the upper limit was defined by θ_{FC}. The lower limit of LLWR was defined by θ_{PR} across the different BD values for the two soils.

Critical bulk density (BDc) has been defined as the intersection of the lower and the upper limit of the LLWR, in which the LLWR becomes equal to 0 (Imhoff et al., 2001). BDc was higher in the Mollisol (1.44 Mg m^{-3}) than in the Vertisol (1.37 Mg m^{-3}). The shaded area in Fig. 4 represents the LLWR, which was evidently higher in the Mollisol than in the Vertisol. In a wide review, Reichert et al. (2009) reported that the BDc obtained using LLWR ranged from 1.16 to 1.63 Mg m^{-3} in Oxisols and from 1.70 to 1.80 Mg m^{-3} in Alfisols from Brazil. Chan et al. (2006) reported values as high as 1.54 Mg m^{-3}, in a surface layer (0.05–0.10 m) of a Vertisol with 320 g kg^{-1} of clay content, being LLWR essentially reduced to zero due to an air-filled porosity of only 0.07 cm^3 cm^{-3} and a PR higher than 2 MPa. These authors related BDc with conditions unfavorable to canola and wheat roots in areas of wheel tracks. Our results of BDc are comparable to those of Griffith et al. (1977), who found BDc between 1.4 Mg m^{-3} and 1.5 Mg m^{-3} for silty clay loam soils.

a. Mollisol



b. Vertisol

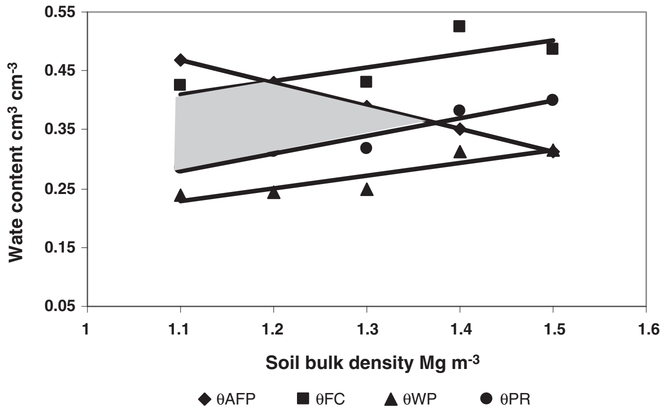


Fig. 2. Water content as a function of bulk density in a Mollisol (a) and in a Vertisol (b). θ_{AFP}, soil water content at air-filled porosity of 10%; $\theta_{FC,}$ water content at field capacity; $\theta_{WP,}$ water content at permanent wilting point and $\theta_{PR,}$ water content at soil resistance of 2 MPa. BDc, critical bulk density (LLWR = 0). The shaded area represents the LLWR.

Critical bulk density has been reported as highly dependent on soil texture (Ayers and Perumpral, 1982). Jones (1983) found BDc values at which root growth is severely affected at near-optimal soil water contents and reported highly significant negative relationships between the clay or clay + silt fraction and the bulk density. Pabin et al. (1998) reported that BDc values decreased with the increasing fraction <60 μm content. Reichert et al. (2009) presented a synthesis of published and unpublished data regarding BD and limits of degree of compactness for plant growth under no tillage in subtropical soils and proposed critical limits of bulk density. These authors also reported that BDc decreased as the content of clay and clay + silt fractions increased, proposing linear equations to estimate BDc based on the LLWR. Using those functions with our data, we obtained values of 1.59 Mg m^{-3} and 1.29 Mg m^{-3} for the clay and clay + silt fractions, respectively, for the Vertisol, and of 1.62 Mg m^{-3} and 1.28 Mg m^{-3}, respectively, for the Mollisol. Clearly, the values estimated using Reichert et al. (2009) functions are in disagreement with our results, probably due to the nature of the soils (Oxisols and Alfisols) used to build these functions.

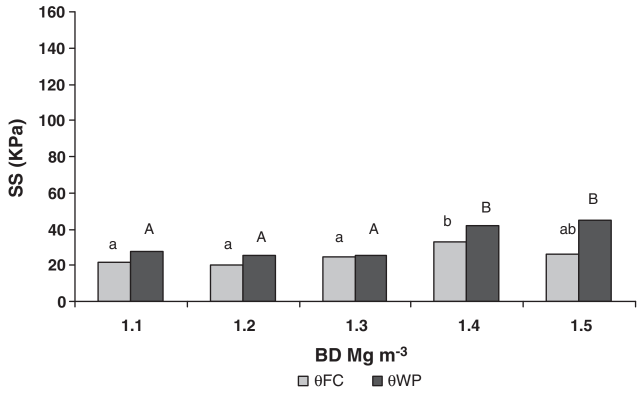
3.3. Soil shear strength

Soil shear strength (SS) varied during soil drying between θ_{FC} and θ_{WP} (Fig. 3). Shear strength values ranged from 10.9 to 68.4 kPa for the Mollisol and from 2.7 to 156 kPa for the Vertisol. Extreme values were recorded for the Vertisol. The lowest values were due to self-mulching of samples with BD values below 1.3 Mg m^{-3} after the first wetting (θ_{FC}), whereas the highest values were recorded when BD was 1.4 and 1.5 Mg m^{-3} at θ_{WP}. For these BD values, SS was consistently up to two-fold greater in the Vertisol than in the Mollisol at θ_{WP}. However, at $\theta_{FC,}$ there was no consistent difference in SS between the two soils studied.

Arvidsson and Keller (2011), who measured SS in 15 different soils of Sweden with clay contents ranging from 13 to 56%, found a strong relationship between soil water content and cohesion (derived from shear vane measurements). However, this relationship was stronger in soils with highest clay content. In the Vertisol of our work, there were combined effects of the high clay content and their smectitic mineralogy. In addition, 2:1 minerals show more SS when they are dry (Barzegar et al., 1995), whereas under high water content, the soil matrix is very viscous and sticky, which leads to low SS values.

Soil shear strength at θ_{WP} was related with BD_f for both the Mollisol ($P<0.001$; $R^2 = 0.63$; $SS = 103.4 * BD_f - 102.2$) and the Vertisol ($P<0.05$; $R^2 = 0.74$, $SS = 281.1 * BD_f - 267.0$), in agreement with Servadio et al. (2001), who found a significant correlation between SS and BD established by intensive movement of tractors.

Several studies have explored the relationship between SS and PR, although the results are contradictory. After a detailed revision, Arvidsson and Keller (2011) concluded that a general prediction could not be made and that this relationship is restricted to individual soils. In our work, the association between PR and SS at θ_{WP} or θ_{FC} was highly significant for the Vertisol ($r = 0.63$, $P<0.01$) and significant for the Mollisol ($r = 0.25$, $P<0.05$).


a. Mollisol

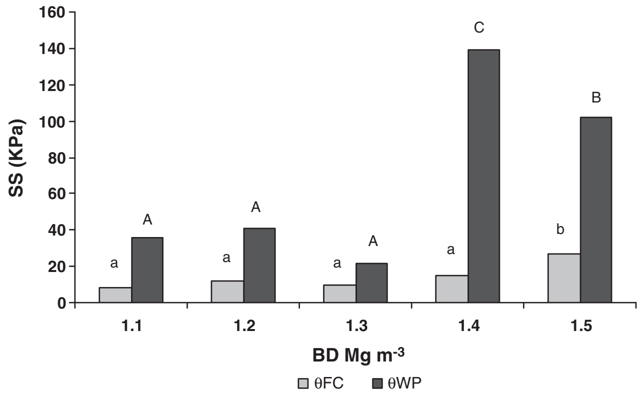

b. Vertisol

Fig. 3. Soil shear strength (SS) at two water contents (Field capacity—θ_{FC} and Permanent wiling point—θ_{WP}) at different bulk densities (BD); a) Mollisol and b) Vertisol. Different letters indicate significant differences between treatments within a given water content (Duncan $\alpha = 0.05$).

3.4. Volumetric change

Fig. 4 shows the volumetric change due to soil wetting after the compaction treatments in the non-cultivated cylinders. The pattern of volumetric changes indicates the different response of the mineralogical components of the two soils. The Mollisol reduced the volume at lower BD values (<1.3 Mg m^{-3}), which explained the classical field observation of soil compaction after rainfall in recently tilled soils. On the other hand, volumetric changes were positive when BD>1.3 Mg m^{-3}, being maximum at 1.4 Mg m^{-3} (>7.5% greater than the initial volume).

In the Vertisol, volumetric changes were evident across the different BD values, being maximum at 1.3 Mg m^{-3} (>19.2% greater than the initial volume). These volumetric changes were in agreement with previous findings under field conditions recorded in a similar soil (Wilson and Cerana, 2004). In our treatments of BD>1.3 Mg m^{-3}, volumetric changes decreased with respect to the maximum recorded. However, the values were higher than in the Mollisol.

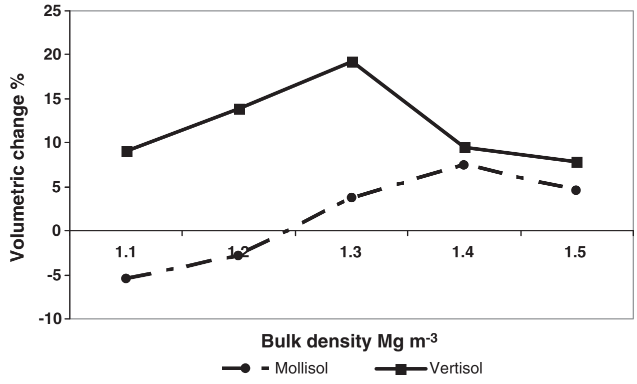


Fig. 4. Volumetric change as a function of bulk density in a Mollisol and a Vertisol.

The greater differences in volumetric changes between soils were recorded at lower BD values (Fig. 4), being higher at 1.2 Mg m^{-3} (16.8%) and lower at 1.4 Mg m^{-3} (2%). In Vertisols, the reports of volumetric changes are coincident in that this phenomenon provides the soil with self-decompaction capacity. In fact, volumetric changes due to shrinkage and swelling in Vertisols forms void spaces and can recover soil porosity in compacted soil layers (Dexter, 1988). Also, Chinn and Pillai (2008) showed that a single wet–dry cycle after compaction is sufficient to rank Vertisols in terms of self-repair structure.

3.5. Early wheat growth

The effects of soil compaction on plant growth have been deeply studied (Andrade et al., 1993; Masle and Passioura, 1987; Passioura, 1991, 2002; Sadras et al., 2005). The main impact of soil hardness, usually quantified by PR, on plant growth is the reduction of root growth (Bengough and Mullins, 1990; Materechera et al., 1991) and shoot growth (Andrade et al., 1993; Sadras et al., 2005). In our work, the response of wheat growth to BD differed clearly between soils (Table 3).

In the Mollisol, the shoot and root growth and root/shoot ratio were similar when BD values were below 1.3 Mg m^{-3}. With a BD of 1.4 Mg m^{-3} these growth parameters were reduced, whereas with a BD of 1.5 Mg m^{-3} no growth (i.e., no seedling emergence) was recorded. These results may be attributed to the lack of aeration in the treatments with high BD values, because relative water content was kept at field capacity, i.e. θ_{FC} was higher than θ_{AFP}. Furthermore, plant growth could be affected by the lack of aeration with BD values over 1.3 Mg m^{-3} but the relationship is not clear since the root/shoot ratio did not differ between BD of 1.3 Mg m^{-3} and 1.4 Mg m^{-3}. This lack of relationship between BD and growth may be due to the LLWR was determined in pots without plants. Roots play an important role in modifying the soil structure, but the measurements to obtain the LLWR were not reliable in our experiments, since the pots with plants were kept at constant water content.

Ball et al. (1997) found a relationship between bulk density and growth of spring barley roots in zero-tilled seedbeds. These authors reported that, in a humid climate, porosity affects crop yields and the environment more than strength because soils with small macropore volumes easily become anaerobic and hinder root growth because of denitrification.

The lower root and shoot growth caused by soil compaction leads to important penalties in resource capture (i.e. water and solar radiation) and crop yield (Sadras et al., 2005). The solar radiation capture is severely limited by soil compaction through the modulation of leaf expansion (Andrade et al., 1993; Masle and Passioura, 1987). Although the reduction of leaf expansion and shoot growth may be

Table 3
Shoot and root biomass and root/shoot ratio of wheat after a growing period of two months. Experiments conducted in pots with different soil bulk densities.

Bulk density	Mollisol			Vertisol		
	g per pot			g per pot		
Mg m^{-3}	Shoot	Root	Root/shoot	Shoot	Root	Root/shoot
1.1	0.29 a	0.05 a	0.15 a	0.31 a	0.05 a	0.15 a
1.2	0.25 a	0.04 ab	0.14 a	0.25 a	0.03 a	0.12 a
1.3	0.29 a	0.04 ab	0.13 ab	0.26 a	0.03 a	0.11 a
1.4	0.11 b	0.008 b	0.07 bc	0.31 a	0.03 a	0.12 a
1.5	0 b	0 b	0 c	0.29 a	0.02 a	0.08 a

Means followed by the same letter within a column are not significantly different at $P<0.05$ as determined by Tukey test.

Table 4
Probability and r of correlation analysis between final bulk density (BD_f) and shoot and root biomass and root/shoot ratio of wheat for two soils (Mollisol and Vertisol).

		Mollisol		Vertisol	
		p	r	p	r
BD_f vs	Shoot biomass	<0.01	0.78	ns	
	Root biomass	<0.01	0.77	<0.05	0.57
	Root/shoot	<0.01	0.84	<0.05	0.59

ns: not significant.

related to the inability of roots to supply enough water and nutrients, there are important evidences indicating that these responses are mediated by inhibitory root-to-shoot signals (Bingham, 2001; Passioura, 2002), since root growth is usually less affected than shoot growth (Andrade et al., 1993). Although our data seem to be in contrast with those findings, it should be noted that our experimental conditions included the soil at θ_{FC}, which may affect root biomass and root/shoot ratio because of insufficient aeration at BD > 1.3 Mg m^{-3}.

In the Vertisol, in contrast, early wheat growth was not affected by BD. Volumetric change seems to be involved in the lack of response of wheat growth to BD. Accordingly, it has been suggested that Vertisols are able to self-mulch to provide a good seed bed, even without tillage (Hussein and Adey, 1998), showing resilient soil behavior (Grant and Coughlan, 2002).

According to the BDc values obtained using the LLWR, the soil would achieve a BD restrictive to plant growth at 1.44 Mg m^{-3} and 1.37 Mg m^{-3} for the Mollisol and the Vertisol, respectively. In the Mollisol, the root/shoot ratio decreased following the LLWR, recording no growth (no seedling emergence) when the LLWR was zero (near 1.4 Mg m^{-3}). However, in the Vertisol, there were no significant differences in early wheat growth variables among BD treatments. Since roots grew over the BDc, the critical RP value of 2 MPa to establish the lower limit of the LLWR should be revised, mainly in soils with smectitic clays. In addition, Greacen and Gardner (1982) suggested that the air-filled porosity of 10% criterion may not be appropriate to limit the growth root in swelling soils.

Our results, added to further research in different types of soils, may be useful to increase a wide database to build robust functions to predict the LLWR from simple variables as soil texture.

In the Mollisol, final soil bulk density after soil drying (BD_f) accounted for 60–70% of growth variation (Table 4) ($P<0.01$), whereas in the Vertisol BD_f accounted for 32–35% of root biomass and shoot/root ratio ($P<0.05$). Our results support the findings of Venanzi et al. (2002), who reported a linear reduction of root biomass and leaf area of wheat with increasing BD values up to 1.2 Mg m^{-3}.

Also, root and shoot biomass and root/shoot ratio were related by SS at θ_{WP} for the Mollisol (Fig. 5). This indicates that the degradation of structural qualities associated with normal compaction could cause a decrease in wheat performance in this soil.

Ball et al. (1997) found that SS values greater than 65 kPa under drying conditions impede root exploration. In this work, the Mollisol showed SS values below that threshold in all the water contents analyzed and the critical SS value was near 50 kPa at θ_{WP} (Fig. 5). In the Vertisol, early wheat growth was not related to SS (Fig. 5), similarly to BD (Table 4). This could be attributed to the volumetric changes during soil wetting after compaction treatments. The pattern of volumetric changes indicates the different response of the mineralogical components of the two soils. In fact, in the Vertisol, a single wet–

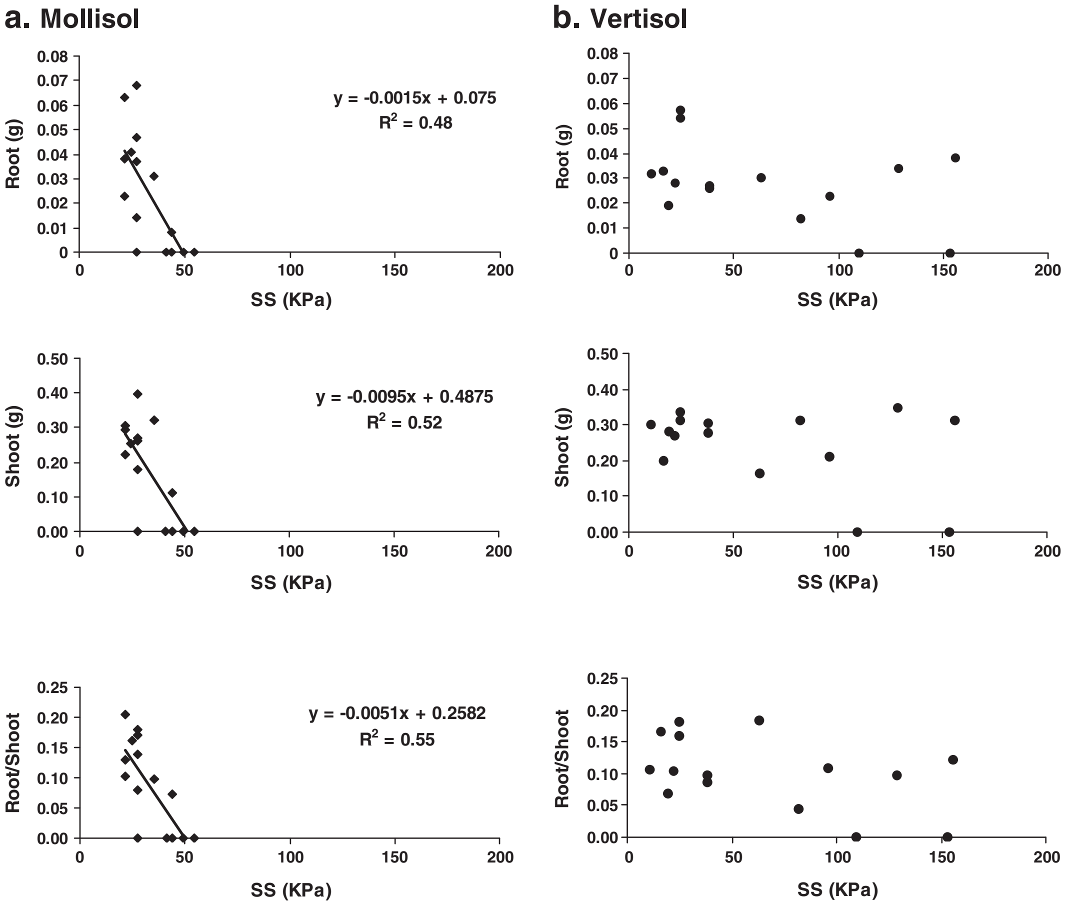


Fig. 5. Linear regression between root biomass, shoot biomass and root:shoot ratio and soil shear strength (SS).

dry cycle after compaction (shrinkage and swelling) was enough for self-repair. Sarmah et al. (1996) found that compacted Vertisols repair the structure via wet/dry cycles and increase the water infiltration rate associated with a decrease in the SS. Although no threshold may be obtained from our data set in the Vertisol, it is worth to note that at BD values >1.4 Mg m^{-3}, SS values were over 65 kPa. However, Mc Kenzie and Mc Bratney (2001) cited an SS of 130 kPa such as the critical value in Vertisol at which cotton root growth ceases.

The concept of LLWR and particularly BDc was useful to determine a threshold for early wheat growth in the Mollisol but were useless for the Vertisol. This finding provides an interesting platform for the management of soils with similar textural classes and different clay mineralogy. In our region, Mollisols and Vertisols are frequently present in the same paddock across the landscape. The knowledge of the functioning of each soil may reduce uncertainties in agricultural systems, improving the fine tune management of variability within paddocks.

4. Conclusions

The LLWR and BDc were useful to determine a threshold for early wheat growth in the Mollisol. In addition, wheat growth was limited at BD>1.4 Mg m^{-3} due to the lack of aeration rather than to the high PR. In the Vertisol, early wheat growth was not affected by BD. Volumetric changes seemed to be involved in the lack of response of wheat growth to BD.

Soil shear strength was significantly correlated with BD and was sensitive to soil water changes. Bulk densities higher than 1.35 Mg m^{-3} had high SS values, particularly at θ_{WP}. This measurement also allowed us to obtain a critical value for crop growth, but only for the Mollisol (50 kPa).

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