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Reference bulk density and critical degree-of-compactness for no-till crop production in subtropical highly weathered soils

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ABSTRACT

The concept of degree of compactness (DC), referred to as field bulk density (BD) as a percentage of a reference bulk density (BD_{ref}), was developed to characterize compactness of soil frequently disturbed, but for undisturbed soil such as under no-tillage critical degree of compactness values have not been tested. The objective of this study was to compare methods to determine BD_{ref} and limits of DC and BD for plant growth under no-tillage in subtropical soils. Data from the literature and other databases were used to establish relationships between BD and clay or clay plus silt content, and between DC and macroporosity and yield of crops under no-tillage in subtropical Brazil. Data of BD_{ref} reached by the soil Proctor test on disturbed soil samples, by uniaxial compression with loads of 200 kPa on disturbed and undisturbed soil samples, and 400, 800 and 1600 kPa on undisturbed soil samples, were used. Also, comparisons were made with critical bulk density based on the least limiting water range (BDc LLWR) and on observed root and/or yield restriction in the field (BDc Rest). Using vertical uniaxial compression with a load of 200 kPa on disturbed or undisturbed samples generates low BD_{ref} and high DC-values. The standard Proctor test generates higher BD_{ref}-values, which are similar to those in a uniaxial test with a load of 1600 kPa for soils with low clay content but lower for soils with high clay content. The BDc LLWR does not necessarily restrict root growth or crop yield under no-tillage, since field investigations led to higher BDc Rest-values. A uniaxial load greater than 800 kPa is promising to determine BD_{ref} for no-tillage soils. The BD_{ref} is highly correlated to the clay content and thus pedotransfer functions may be established to estimate the former based on the latter. Soil ecological properties are affected before compaction restricts plant growth and yield. The DC is an efficient parameter to identify soil compaction affecting crops. The effect of compaction on ecological properties must also be further considered.

1. Introduction

Critical limits of soil bulk density (BD), considering ecological properties, such as porosity and hydraulic conductivity, or crop growth and yield, have been pursued. Nevertheless, optimal and critical limits of soil bulk density for crop growth depend upon soil texture, mineralogy, particle shape, and organic matter, which affect soil structure and, thus, water, air and mechanical resistance of the soil. Crops and cultivars respond differently to soil compaction depending upon their rooting system (Guimarães et al., 2002).

Soil porosity and hydraulic conductivity are ecological properties due to their narrow relation with the environment, particularly with gas exchange with the atmosphere (Horn et al., 1995) and surface run off and erosion (Hamza and Anderson, 2005).

The knowledge of the critical values would help decisions about soil management and, consequently, improvements in soil quality for crop growth and yield. An increase in the bulk density is not necessarily detrimental to crop growth, because at certain limits this increase may contribute to soil water storage and load support ability when trafficked with machines or animal trampling. However, what are the limits of soil bulk density acceptable for adequate crop growth and yield while avoiding or minimizing soil and environmental degradation? This is one of the questions addressed in this paper.

Besides trying to establish critical bulk density values, a measure of soil compactness that is more independent of soil type has been pursued. The best, or at least the simplest estimate, is to relate the field bulk density to a reference bulk density, which is

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named degree of compactness (DC). As reference density, Pidgeon and Soane (1977), Carter (1990) and Silva et al. (1994) used the maximum bulk density from the Proctor test at a given amount of impacting energy. Håkansson (1990), Silva et al. (1997) and Håkansson and Lipiec (2000) used the bulk density reached by the soil under uniaxial compression with a vertical, normal load of 200 kPa to calculate the degree of compactness. The Proctor test which is mostly used for disturbed soil material usually results in greater values of reference bulk density, and this difference depends on type and load or energy level, ranging from 7 to 17% in Swedish soils (Håkansson, 1990) and from 10 to 18% in South African soils (Smith et al., 1997a,b).

The various tests have not yet been compared and their usefulness tested as related to plant growth (Håkansson and Lipiec, 2000). In addition, the concept of degree of compactness was developed to characterize compactness of soil frequently disturbed by plowing, disking or chiseling/subsoiling. Thus, for undisturbed soil such as under no-tillage critical degree of compactness have not been tested. There are no studies in the international literature comparing different methods to obtain the reference bulk density for no-tilled soils and limits of degree of compactness have not been defined for soil ecological properties and crop growth.

For no-till soils, a reasonable assumption is that optimal DC-values are similar to those for annually loosened soils (Håkansson, 2005), but there is some evidence that high DC-values are less detrimental. Under conditions where optimal DC-values for annually ploughed soil is about 87, there were only slight reductions in crop growth and yield with DC-values about 95 after 8 years of reduced tillage (RT) on a clay soil or 15 years of RT on clay and silt loam soils (Comia et al., 1994; Etana et al., 1999). The yield reduction was equally small on a sandy loam where the DC-value after 15 years of RT was over 100 (Etana et al., 1999).

Under long-term no-tillage, the whole previous ploughpan layer remains compacted (Håkansson, 2005), although the pore functioning is improved if the no-till is linked to low load input by confining the machinery traffic (Reichert et al., 2003; Horn, 2004). Typically, a layer from about 7 to 15–20 cm has high bulk density, low porosity, and high mechanical resistance, which could be referred to as a 'no-till pan'. The aforementioned layer underlies an upper layer (from 0 to about 7 cm) of reduced compaction due to rearrangement of soil particles and aggregates by various processes (Horn, 2004; Håkansson, 2005), such as biological processes, which are most intense near the surface mulch layer (Reichert et al., 2003), and action of coulters and shanks of no-till seeders and planters coulters (Genro Jr., 2002). The latter estimated that 30% of the soil surface is mobilized when cropping with wheat (17 cm row spacing), and most of the soil surface if taking account soybean (45 cm row spacing). Below the 'no-till pan' layer, a plow pan may reminisce.

Under no-tillage, a more stable and porous structure can be formed and newly formed pores and rearrangement of soil particles preserved if operations are carried out with light machines (machines with low ground pressure), preserving the newly formed pores and rearrangement of soil particles (Horn, 2004). Finer intraaggregate pores are formed as a result of shrinkage and rearrangement of particles (Horn, 1995), and biopores with greater strength against compression are formed by biological activity. Such pores are necessary to sustain proper pore functioning and soil mechanical properties in maintaining the long-term no-tillage.

Thus, considering that different methods to establish a reference bulk density have not yet been compared for no-till soil nor the usefulness of the degree of compactness concept tested, the objective of this paper is to make a synthesis of published and unpublished data regarding reference bulk density and limits of degree of compactness for plant growth under no-tillage in subtropical soils, and to propose critical limits of bulk density for no-till soils. This will contribute for the development of a tool to assess soil compaction and structural quality and make decisions about soil management, particularly the need for mobilization (plowing or chiseling) of no-till soils.

2. Material and methods

Data from the literature and a database belonging to the authors were used to establish statistical relationships between critical and reference bulk density with clay or clay plus silt content, and between degree of compactness and macroporosity, hydraulic conductivity and yield of crops under predominantly no-tillage in subtropical Brazil, mainly in the southernmost state Rio Grande do Sul.

Clay (particles smaller than 0.002 mm) and silt (particles between 0.002 and 0.05 mm) contents were determined after dispersion with sodium hydroxide. Organic matter (OM) was destructed only at a content greater than 50 g kg^{-1}.

The degree of compactness (DC) relates the bulk density in the field (BD) to the BD reached through a soil compaction test in the laboratory (BD_{ref}), as follows:

$$DC = \frac{BD}{BD_{ref}} \times 100$$

The BD was estimated by three strategies. One of them was to define the BD from the least limiting water range (LLWR) concept (Silva et al., 1994). The least limiting water range is an index based on soil bulk density, which considers the soil moisture range where no limitations to the plant growth are expected when considering soil aeration, penetration resistance and plant available water. The critical values considered to obtain the LLWR was the water content in the field capacity (matric tension of 0.01 MPa), permanent wilting point (matric tension of 1.5 MPa), water content when soil penetration resistance is equal to 2 MPa, and water content when air-filled porosity is 0.10 $m^3 m^{-3}$. Herein, the critical bulk density value (BDc LLWR) was considered as the density where the LLWR is zero. The data are shown in Table 1.

Similarly, data of critical bulk density that restricts root growth or reduces crop yield are herein called BDc Rest, and the data (obtained under field conditions) are shown in Table 2. The BDc Rest was defined by a reduction in root growth or in crop yield (Streck, 2003; Secco, 2003; Beutler et al., 2004; Collares, 2005; Suzuki, 2005). For root growth, several parameters have been used such as root density (root mass/volume of soil) (De Maria et al., 1999; Beutler and Centurion, 2004), root dry mass and root surface (Beutler and Centurion, 2004), restriction to tap root growth (Streck, 2003; Collares, 2005; Suzuki, 2005). All these studies were conducted under field conditions, whereas preserved soil samples were used to determine soil bulk density values. Equations developed by Jones (1983) were also included, where he defined soil bulk density as critical when roots had their growth reduced by 20% compared to maximum growth at field capacity, for soils with a wide range in percentage clay and silt. The critical bulk density which restricts root growth (BDc Jones) can be estimated by the following equations: BDc = 1.77 − 0.00063 clay (r^2 = 0.82) and BDc = 1.83 − 0.00043 (clay + silt) (r^2 = 0.76). These equations, although developed for temperate soils and controlled conditions, were included as a reference because no such quantitative relations are yet available for tropical soils under field conditions.

Different strategies were used to estimate the BD_{ref}. To estimate the BD_{ref} based on Proctor test were used data from Seixas et al. (1998), Klein (1998), Figueiredo et al. (2000), Beutler et al. (2005), Marcolin (2006) and Mentges et al. (2006).

Table 1
Critical bulk density considering the least limiting water range (BDc LLWR) for different crops and soil texture for soils from Brazil

Source	Texture			Soil type	Soil management	Crop[a]	BDc LLWR ($Mg\ m^{-3}$)
	Sand ($g\ kg^{-1}$) (2–0.05 mm)	Silt ($g\ kg^{-1}$) (0.05–0.002 mm)	Clay ($g\ kg^{-1}$) (<0.002 mm)				
Tormena et al. (1998)	50	150	800	Oxisol	No-tillage	Corn	1.28
Tormena et al. (1999)	50	150	800	Oxisol	No-tillage	Corn	1.27
Imhoff et al. (2001)	730	80	190	Alfisol	Semi-permanent crop	Sugarcane	1.70
Silva (2003)	660	220	120	Alfisol	No-tillage	Black bean	1.80
	250	250	500	Oxisol	No-tillage	Soybean	1.43
	100	300	600	Oxisol	No-tillage	Soybean	1.40
Beutler et al. (2004)	687	42	271	Oxisol	Chisel plow	Rice	1.63
Leão et al. (2004)	535	66	399	Oxisol	Permanent crop	Pasture	1.43
Collares (2005)	622	295	83	Alfisol	No-tillage	Black bean	1.75
Marcolin (2006)	537	136	327	Oxisol	No-tillage	Not mentioned	1.63
	363	168	469	Oxisol	No-tillage	Not mentioned	1.43
	295	135	570	Oxisol	No-tillage	Not mentioned	1.44
	48	294	658	Oxisol	No-tillage	Not mentioned	1.27
	12	231	757	Oxisol	No-tillage	Not mentioned	1.16

[a] Corn (*Zea mays*); sugarcane (*Saccharum officinarum*); black bean (*Phaseolus vulgaris*); soybean (*Glycine max*); rice (*Oryza sativa*).

Data of BD_{ref} reached by the soil under uniaxial compression with a load of 200 kPa, when using disturbed soil samples, were from the international literature (Håkansson, 1990; Lipiec et al., 1991; Comia et al., 1994; Etana et al., 1999) (BD_{ref} 200 kPa dist – Intern). Additionally, unpublished data for soils from southern Brazil, which were tested with a multistep uniaxial compressor in northern Germany (BD_{ref} 200 kPa dist – Brazil), were used. The undisturbed soil samples were collected at depths varying from 0.07 to 0.165 m and equilibrated at 30 kPa tension. To ease the comparison of the data, regression considering these two data base was made (BD_{ref} 200 kPa dist).

Bulk density data for undisturbed soil samples (preserved soil structure) uniaxially compressed with a load of 200 kPa (BD_{ref} 200 kPa undist), 400 kPa (BD_{ref} 400 kPa undist), 800 kPa (BD_{ref} 800 kPa undist) and 1600 kPa (BD_{ref} 1600 kPa undist) were from Suzuki (2005), Lima et al. (2006) and from a database for soils from southern Brazil. The samples were collected in cylinders with 0.025-m height and 0.061-m diameter, at the layer of 0.08–0.13 m, the soil layer with highest bulk density and mechanical penetration resistance under no-tillage due to the concentration of loading by farm machinery traffic and absence of soil tillage. For the uniaxial compression test, the soil samples were saturated and then equilibrated at a tension of 33 kPa using pressure plates (Klute, 1986). Most samples were then sequentially loaded with 12.5, 25, 50, 100, 200, 400, 800 and 1600 kPa, some of them were only loaded with 200, 400, 800 or 1600 kPa. All loads were applied during 5 min, when 99% of soil deformation has occurred. Bulk densities from both types of loading were similar at the individual

Table 2
Critical bulk density considering restriction to root elongation or yield decrease (BDc Rest) for different crops and soil texture for soils from Brazil

Source	Texture			Soil type	Soil management	Crop[a]	BDc Rest ($Mg\ m^{-3}$)	Macro ($m^3\ m^{-3}$)	Restriction
	Sand ($g\ kg^{-1}$) (2–0.05 mm)	Silt ($g\ kg^{-1}$) (0.05–0.002 mm)	Clay ($g\ kg^{-1}$) (<0.002 mm)						
De Maria et al. (1999)	50	200	750	Oxisol	No-tillage	Soybean	1.21	–	Root elongation
Streck (2003)	614	297	89	Alfisol	No-tillage	Black bean	1.79	0.06	Root elongation/ yield
						Soybean	1.81	0.05	
Secco (2003)	221	224	555	Oxisol	No-tillage	Wheat/corn/ soybean	1.62	–	Wheat yield
	100	290	610	Oxisol	No-tillage		1.54	–	Corn and wheat yield
Beutler et al. (2004)	687	42	271	Oxisol	Chisel plow	Rice	1.63	–	Yield
Beutler and Centurion (2004)	687	42	271	Oxisol	Chisel plow	Soybean	1.68	0.06	Root elongation
Collares (2005)	217	176	607	Oxisol	No-tillage	Black bean	1.53	0.07	Root elongation/ yield
					Chisel plow		1.49	0.12	
	614	297	89	Alfisol	No-tillage		1.76	0.09	Root elongation
							1.84	0.08	Root elongation/ yield
Suzuki (2005)	391	331	278	Alfisol	No-tillage	Soybean	1.66	0.07	Root elongation
	143	457	400	Alfisol	No-tillage		1.52	0.06	
	114	341	546	Oxisol	No-tillage		1.39	0.10	
	86	261	654	Oxisol	No-tillage	Soybean/corn	1.36	0.05	Root elongation/ yield

[a] Soybean (*Glycine max*); black beans (*Phaseolus vulgaris*); wheat (*Triticum aestivum*); corn (*Zea mays*); rice (*Oryza sativa*).

loads (Suzuki, 2005); thus, the sequential loading was chosen to allow the use of data from other authors working with soil compressibility curves.

Relationships between the degree of compactness (DC) and soil macroporosity (Mac), defined as pores drained at 6 kPa tension, corresponding to pores of diameter larger than 50 μm, were established from data of Streck (2003), Barreto (2004), Secco et al. (2004), Collares (2005), Suzuki (2005), and Lima et al. (2006), which all used tension table to determine soil macroporosity. Saturated hydraulic conductivity ($K_{\theta s}$) data from Silva (2003), Streck (2003), Barreto (2004) and Lima et al. (2006) were also related to DC. Different methodologies were used to obtain $K_{\theta s}$. A Guelph permeameter in the field (Elrick et al., 1987) was used by Streck (2003) and Barreto (2004) and a constant-head permeameter (Libardi, 2005) by Silva (2003) and Lima et al. (2006). In this case, to calculate the DC, BD_{ref} Proctor and BD_{ref} 200 kPa dist were estimated with the equations in Table 4 relating BD_{ref} to clay content, while BD_{ref} 200 kPa undist, BD_{ref} 400 kPa undist, BD_{ref} 800 kPa undist and BD_{ref} 1600 kPa undist were taken directly from the literature and also from a database for soils from southern Brazil.

Relationships between DC and relative yield (RY) were established by using data from Streck (2003), Secco (2003), Secco et al. (2004), Suzuki (2005), and Lima et al. (2006) for soybeans; from Streck (2003), Barreto (2004), Collares (2005) and Lima et al. (2006) for black beans; and from Secco (2003) and Collares (2005) for wheat.

3. Results

3.1. Choice of critical (BDc) and reference (BD_{ref}) bulk densities

Critical bulk density (BDc) decreased with increasing content of clay (Fig. 1a) and clay plus silt (Fig. 1b). The highest values of BDc were reached when taking into account restriction to root growth or yield, and the lowest values when considering the least limiting water range. BDc-values estimated by Jones (1983) for soil conventionally tilled are in between the BDc Rest and BDc LLWR. The coefficient of determination was always higher when relating BDc with clay than with clay plus silt (Table 3).

The angular coefficients (slope) for the three equations for BDc are similar, both for clay and clay plus silt as independent variables (Table 3).

Irrespective of method used, the BD_{ref} decreased with an increase in clay (Figs. 2a and 3a) and clay plus silt (Figs. 2b and 3b) content, with a higher coefficient of determination (r^2) for the former (Table 4).

Among all different alternatives of defining BD_{ref}, the highest values were reached for the method applying a vertical, normal load of 1600 kPa under uniaxial compression, followed by the Proctor test for soil with low clay content, and by the load of 800 kPa on samples with preserved structure for soils with high clay content. The lowest values of BD_{ref} are for a load of 200 kPa on disturbed soil samples. These differences in BD_{ref} thus also affect the estimated degree of compactness.

3.2. Critical degree of compactness (DC) for ecological properties and crop growth and yield

Soil compaction affects important ecological properties such as water and air flow, besides affecting root growth and function and ultimately plant growth and yield.

In this study, with an increase in the degree of compactness, the soil macroporosity (Fig. 4) and the log saturated hydraulic conductivity (Fig. 5) were linearly reduced. The equations show that as clay content decreases, macroporosity increases for a given degree of compactness (Table 5).

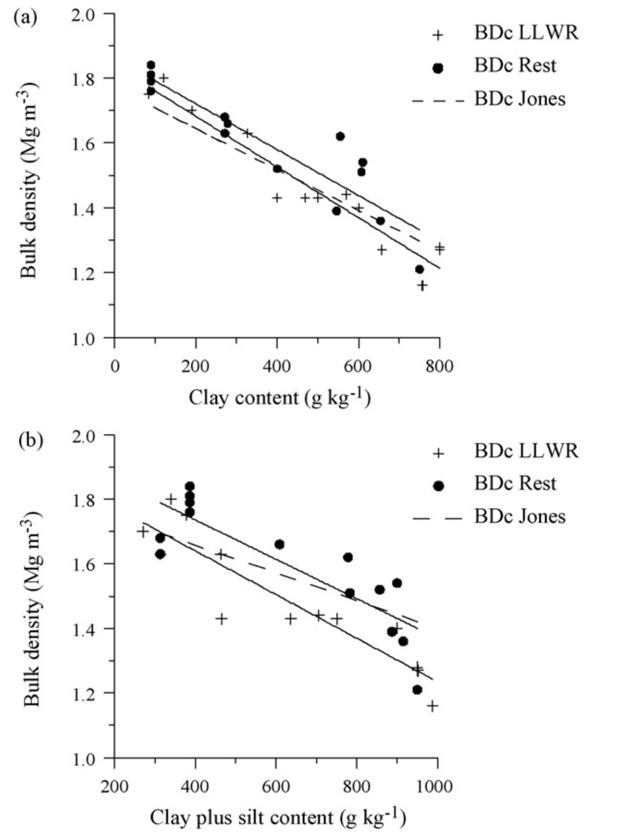

Fig. 1. Critical bulk density considering the least limiting water range (BDc LLWR), restriction to root elongation or yield decrease (BDc Rest) and considering the equation of Jones (1983) (BDc Jones), as functions of clay (a) and clay plus silt content (b).

Table 3
Equations for estimating BDc based on the contents of clay or clay plus silt, for three methods of BDc determination

Method	Equation	r^2	Probability
BDc LLWR	BDc = −0.00078 clay + 1.83803	0.92	<0.0001
BDc Rest	BDc = −0.00071 clay + 1.86180	0.84	<0.0001
BDc Jones	BDc = −0.00063 clay + 1.77000	0.82	
BDc LLWR	BDc = −0.00067(clay + silt) + 1.90982	0.85	<0.0001
BDc Rest	BDc = −0.00061(clay + silt) + 1.97956	0.71	<0.0001
BDc Jones	BDc = −0.00043(clay + silt) + 1.83000	0.76	

The critical DC for a soil macroporosity of 0.10 $m^3\,m^{-3}$ may be estimated with equations from Table 5, then the estimated DC is used to calculate $K_{\theta s}$ with equations from Table 6. The limit of 0.10 $m^3\,m^{-3}$ macroporosity for satisfactory plant growth was established in studies by Baver (1949), Vomocil and Flocker (1966), and Grable and Siemer (1968), and latter by Gupta and Allmaras (1987). The estimated values of DC are presented in Table 7, showing values of log $K_{\theta s}$ from 1.07 to 1.46 mm h^{-1} for soils with clay content in the range of 68–103 g kg^{-1}, from 1.38 to 1.90 mm h^{-1} for clay content 211–338 g kg^{-1}, from 1.54 to 2.18 mm h^{-1} for clay content of 339–721 g kg^{-1}. Thus, changes in $K_{\theta s}$ are small both within method of BD_{ref} and also within clay content ranges.

With an increase in clay content, the $K_{\theta s}$ increased independently of BD_{ref} and the DC when macroporosity is equal to 0.10 $m^3\,m^{-3}$ decreased (Table 7). The link between soil macroporosity and $K_{\theta s}$ is important since a decrease in macroporosity causes a reduction in $K_{\theta s}$ and consequently larger runoff and erosion.

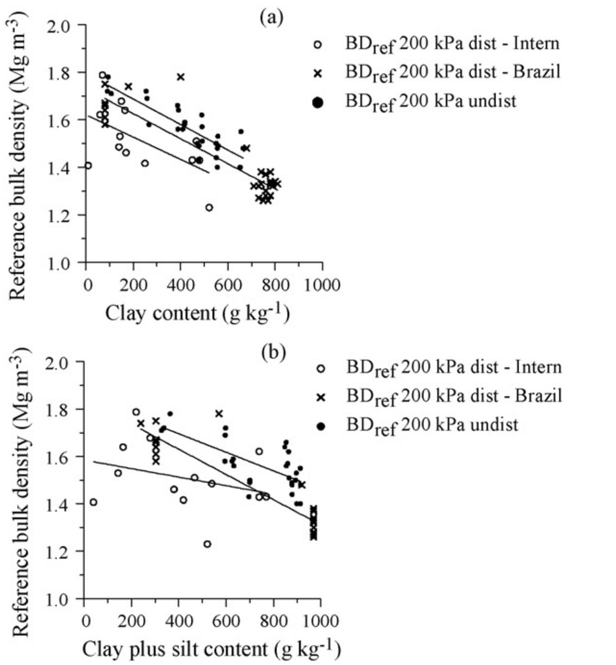

Fig. 2. Reference bulk density by load of 200 kPa in the uniaxial compression test form, on disturbed soil samples using data from international literature (BD_{ref} 200 kPa dist – Intern) and from southern Brazil (BD_{ref} 200 kPa dist – Brazil), and undisturbed soil samples (BD_{ref} 200 kPa undist), as functions of clay (a) or clay plus silt content (b).

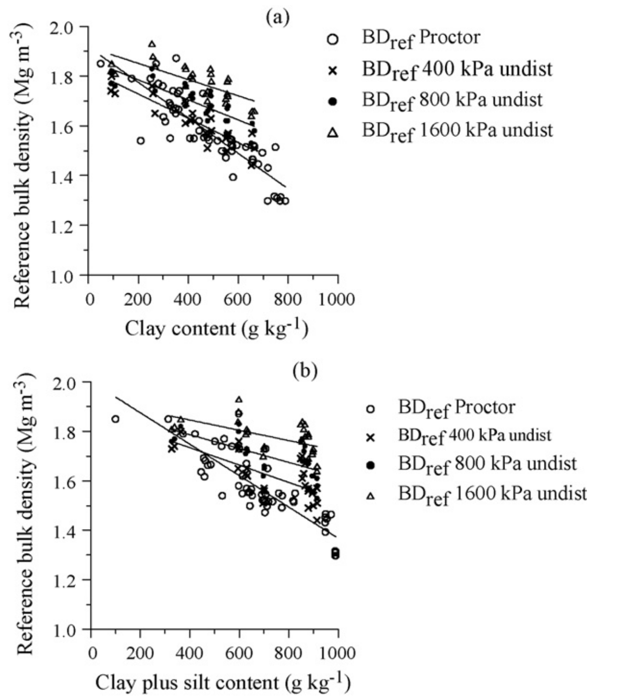

Fig. 3. Reference bulk density by standard Proctor test (BD_{ref} Proctor) and load of 400 kPa (BD_{ref} 400 kPa undist), 800 kPa (BD_{ref} 800 kPa undist) and 1600 kPa (BD_{ref} 1600 kPa undist) in undisturbed soil samples in the uniaxial compression test, as functions of clay (a) or clay plus silt content (b).

The highest relative crop yield for soybean was obtained at DC higher than for black beans and wheat (Figs. 6–8 and Table 8). The DC for highest crop yield decreased with increased load applied in the reference test, and was higher when using DB_{ref} 200 kPa dist than DB_{ref} 200 kPa nudist.

Using the equations for estimating BDc LLWR (Table 3) and the BD_{ref} (with the six methodologies presented in Table 4), it is possible to calculate a degree of compactness critical (DCc) to crop growth based on the least limiting water range concept, for soils with varying clay contents, as follows:

$$\mathrm{DCc} = \frac{\mathrm{BDc\ LLWR}}{\mathrm{BD_{ref}}} \times 100$$

If the limits used to define BDc LLWR are actually relevant to all soils and if BD_{ref} is suitably chosen, this DCc-value should be independent of clay content, but this was not observed in our study. This raises a question whether the limits used to define DCc LLWR should vary between soils.

Irrespective of the method used to define BD_{ref} the DCc-value was affected by clay content (Table 9). The BD_{ref} based on uniaxial compression with 200 kPa load produced the highest DCc-value independent of soil sample type (disturbed or undisturbed). The smallest DCc-value was obtained with BD_{ref} based on the uniaxial compression test at 1600 kPa load. Nevertheless, BD_{ref} based on the Proctor test produced the smallest variation in the DCc-value, but not sufficient yet to be defined as independent of clay content. This small variation was a result of similar slopes in the equations for estimating BD_{ref} Proctor and BDc LLWR.

Table 4
Equations, coefficient of correlation (r^2) and probability for the different methods relating BD_{ref} with clay and clay plus silt for six methods of BD_{ref} determination

Method	Equation	r^2	Probability
BD_{ref} Proctor	$BD_{ref} = -0.00071$ clay + 1.91804	0.75	<0.0001
BD_{ref} 200 kPa dist – Intern	$BD_{ref} = -0.00047$ clay + 1.62254	0.34	<0.0351
BD_{ref} 200 kPa dist – Brazil	$BD_{ref} = -0.00052$ clay + 1.73138	0.81	<0.0001
BD_{ref} 200 kPa dist[a]	$BD_{ref} = -0.00044$ clay + 1.66215	0.65	<0.0001
BD_{ref} 200 kPa undist	$BD_{ref} = -0.00054$ clay + 1.79462	0.72	<0.0001
BD_{ref} 400 kPa undist	$BD_{ref} = -0.00049$ clay + 1.82586	0.76	<0.0001
BD_{ref} 800 kPa undist	$BD_{ref} = -0.00040$ clay + 1.86557	0.69	<0.0001
BD_{ref} 1600 kPa undist	$BD_{ref} = -0.00033$ clay + 1.91655	0.56	<0.0001
BD_{ref} Proctor	$BD_{ref} = -0.00063$(clay + silt) + 2.00278	0.75	<0.0001
BD_{ref} 200 kPa dist – Intern	$BD_{ref} = -0.00018$(clay + silt) + 1.58673	0.09	<0.3104
BD_{ref} 200 kPa dist – Brazil	$BD_{ref} = -0.00053$(clay + silt) + 1.84321	0.84	<0.0001
BD_{ref} 200 kPa dist[a]	$BD_{ref} = -0.00042$(clay + silt) + 1.75157	0.64	<0.0001
BD_{ref} 200 kPa undist	$BD_{ref} = -0.00039$(clay + silt) + 1.85287	0.49	<0.0001
BD_{ref} 400 kPa undist	$BD_{ref} = -0.00035$(clay + silt) + 1.87462	0.50	<0.0001
BD_{ref} 800 kPa undist	$BD_{ref} = -0.00028$(clay + silt) + 1.89893	0.43	<0.0002
BD_{ref} 1600 kPa undist	$BD_{ref} = -0.00021$(clay + silt) + 1.92971	0.29	<0.0038

[a] Regression using the data of BD_{ref} 200 kPa dist – Intern and BD_{ref} 200 kPa dist – Brazil.

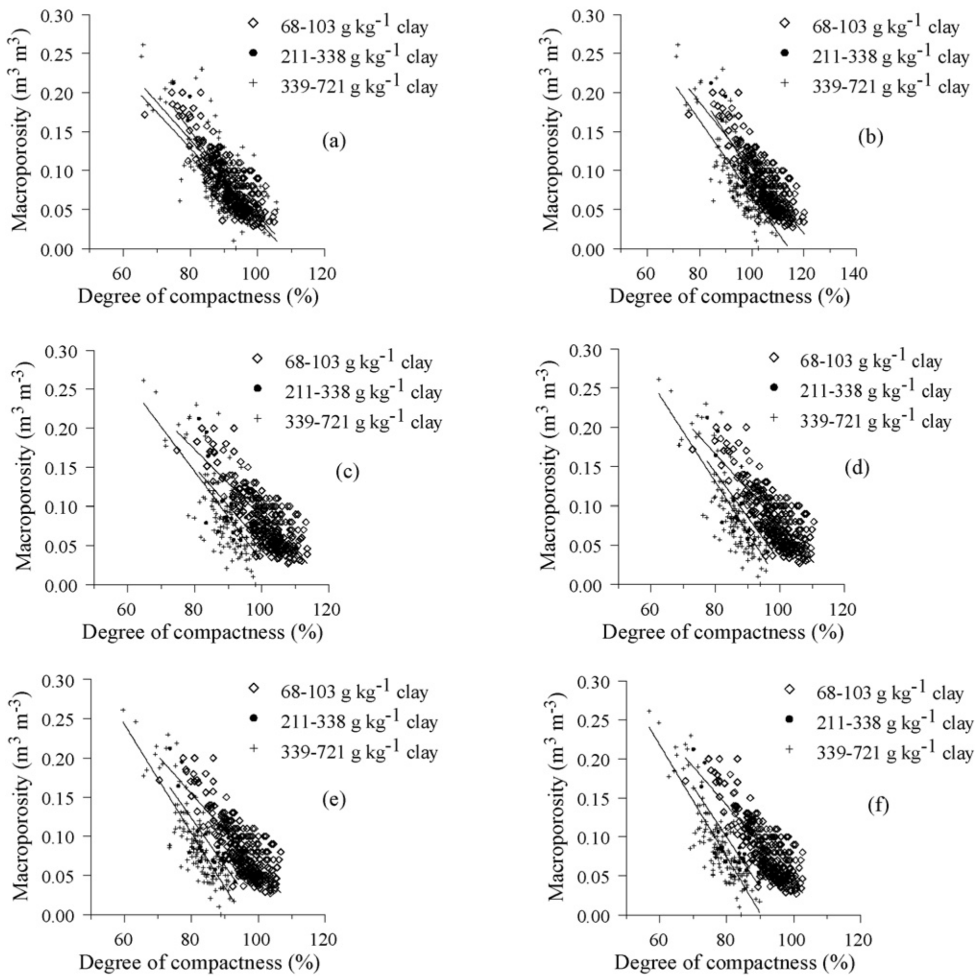

Fig. 4. Macroporosity (Mac) as function of degree of compactness (DC) calculated on the basis of BD_{ref} Proctor (a), BD_{ref} 200 kPa dist (b), BD_{ref} 200 kPa undist (c), BD_{ref} 400 kPa undist (d), BD_{ref} 800 kPa undist (e) and BD_{ref} 1600 kPa undist (f), for soils from southern Brazil. The clay content range was established based on texture of the studied soils, namely sandier Ultisols in the first group, medium texture Ultisols in the second group, and clayey Ultisols and Oxisols in the third group.

4. Discussion

Among the equations established to estimate the critical bulk density (Fig. 1, Table 3), the critical values when considering the least limiting water range is actually lower than the critical values which restrict crop growth. For the LLWR, the four limits are defined as the water contents at field capacity (matric tension 0.01 MPa) and at the permanent wilting point (matric tension 1.5 MPa), and the bulk-density/water-content combinations when air-filled porosity is 0.10 $m^3 m^{-3}$ and penetration resistance is 2 MPa (Silva et al., 1994). The latter limits are clearly not proper for no-till soils since plants can grow even when the LLWR is zero, which means that the soil bulk density is such that the soil is simultaneously thought to be too dry to allow root growth due to mechanical resistance and too wet for adequate aeration. Therefore, the limits must be adjusted for no-tillage conditions. The equations for BDc were highly significant and with an intercept similar among them (Fig. 1).

Restrictions to root growth do not necessarily translate into reduced crop growth or yield, and root system of crops may have varying tolerance to soil compaction. Taylor and Brar (1991) say that roots with reduced length may still provide proper supply of water and nutrients. Silva et al. (2004) demonstrated experimentally that values of air-filled porosity (0.10 $m^3 m^{-3}$) and of mechanical penetration resistance (2 MPa) regarded to be critical did not stop corn growth; the crop continued to grow but at a lower rate.

Figs. 2 and 3 clearly show that different methods to obtain a reference bulk density result in different values of BD_{ref} for a given soil clay content, thus affecting the DC-value. The Proctor test and uniaxial compression test with 1600 kPa load on undisturbed samples produced lower DC-values than the other methods. The low BD_{ref} defined from tests with lower load led to higher DC-values, but this also leads to higher optimum or critical DC-values.

Altough BD_{ref} 200 kPa dist – Intern and BD_{ref} 200 kPa dist – Brazil use disturbed soil samples and the load of 200 kPa is applied in the uniaxial compression test, the differences in the equations may be attributed to differences in soil sample size, strategy of soil moisture equilibration, loading time and soil organic matter.

The load or energy level used in the reference test should not be too low. Then some samples or some parts of the samples used in the test may have been precompacted at higher loads, and this would make BD_{ref} less well-defined. For a uniaxial test, this leads to a demand that the BD_{ref}-value should be situated on the virgin compression line, where the bulk density increases linearly with the log of the load. Figs. 2 and 3 indicate that this demand is met by uniaxial loads of 400 kPa and higher but not by loads of 200 kPa. This can be seen because the distance between the regression lines

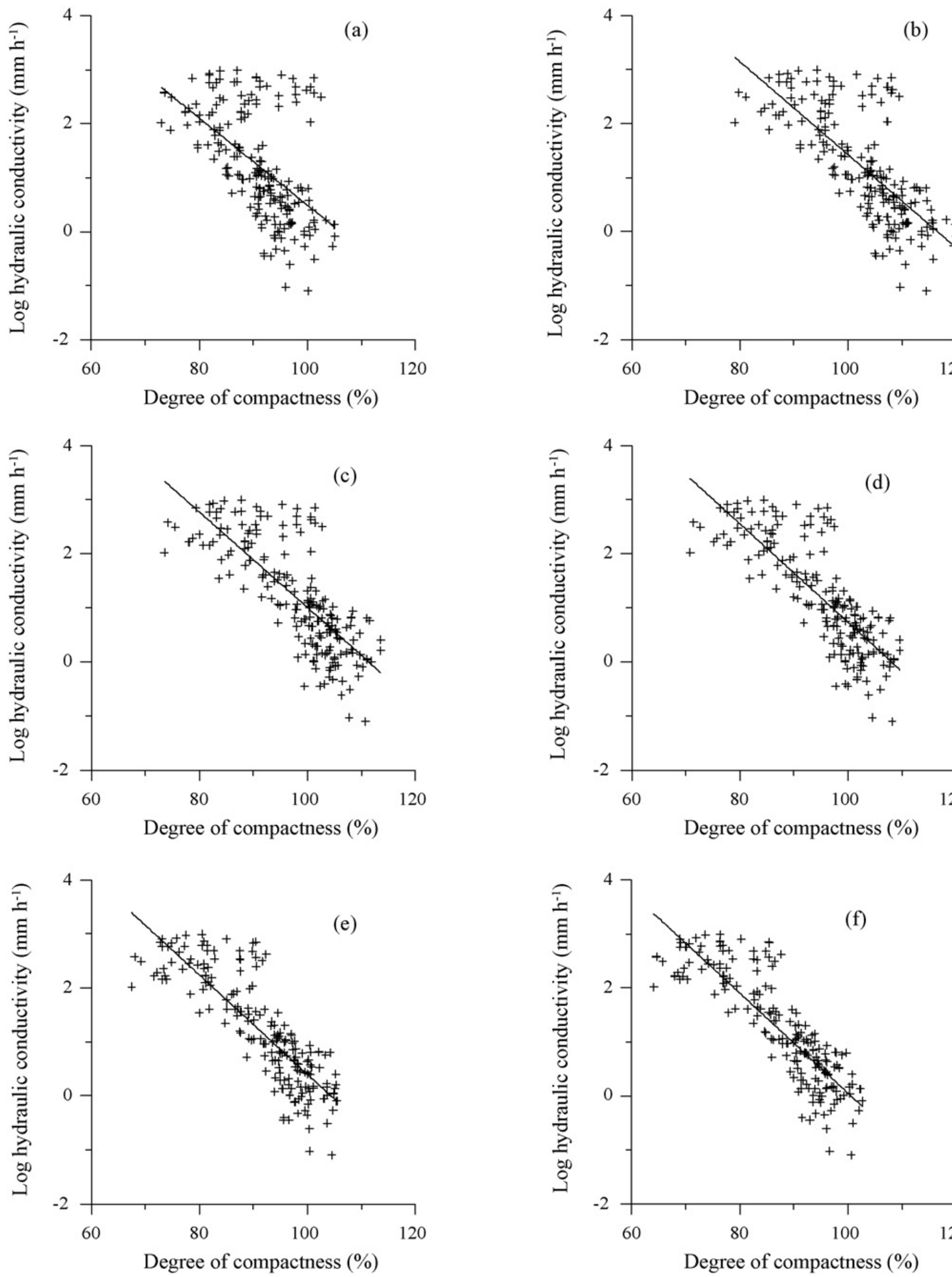

Fig. 5. Hydraulic conductivity (log $K_{\theta s}$) as function of degree of compactness (DC) calculated on the basis of BD_{ref} Proctor (a), BD_{ref} 200 kPa dist (b), BD_{ref} 200 kPa undist (c), BD_{ref} 400 kPa undist (d), BD_{ref} 800 kPa undist (e) and BD_{ref} 1600 kPa undist (f), for soils from southern Brazil.

for BD_{ref} 1600 kPa undist and BD_{ref} 800 kPa undist is nearly the same as between BD_{ref} 800 kPa undist and BD_{ref} 400 kPa undist, whereas the distance between BD_{ref} 400 kPa undist and BD_{ref} 200 kPa undist is smaller. Consequently, when using undisturbed samples from no-till soils the load in the reference test should be at least 400 kPa. It must be further studied, whether this conclusion also applies to annually loosened soil layers or to reference tests where disturbed soil samples are used. According to Suzuki (2005) the use of BD_{ref} 1600 kPa undist was promising for soil compaction studies in no-till soils. Another alternative is a Proctor test with relatively high energy.

The load or energy level used in the reference test should not be higher than necessary either. The reason is as follows. The difference in bulk density in field soils between the loosest state (for instance immediately after ploughing) and the state after normal field traffic is smallest in coarse-textured soils and increase with the clay content. This increase with the clay content is, in relative terms, still greater for the DC-values, since the BD_{ref}-values decrease with the clay content. Consequently, the difference in DC-value between the loosest state with a very low penetration resistance and a more dense state with a high penetration resistance is considerably smaller in a coarse-textured than in a fine-textured soil. At DC-values near 100 (BD-values near BD_{ref}) there are only small differences in penetration resistance between soils irrespective of the method used to determine BD_{ref}, but at lower DC-values the differences between soils can be large. This is important, since the penetration resistance is a factor frequently determining the optimum or critical soil density. From this point of view, the load in the reference test should be relatively low, so that DC-values on both sides of 100 occur in the soils under normal field

Table 5
Equations for estimating soil macroporosity (Mac) based on the degree of compactness (DC) calculated on the basis of BD_{ref} Proctor, BD_{ref} 200 kPa dist, BD_{ref} 200 kPa undist, BD_{ref} 400 kPa undist, BD_{ref} 800 kPa undist and BD_{ref} 1600 kPa undist, for different clay content ranges, for soils from southern Brazil

Range of clay content[a] (g kg^{-1})	Equation	r^2	Probability
BD_{ref} Proctor			
68-103	Mac = 0.5242 − 0.0048DC	0.64	<0.0001
211-338	Mac = 0.6269 − 0.0059DC	0.68	<0.0001
339-721	Mac = 0.4998 − 0.0046DC	0.50	<0.0001
BD_{ref} 200 kPa dist			
68-103	Mac = 0.5245 − 0.0042DC	0.64	<0.0001
211-338	Mac = 0.6225 − 0.0053DC	0.72	<0.0001
339-721	Mac = 0.5497 − 0.0048DC	0.57	<0.0001
BD_{ref} 200 kPa undist			
68-103	Mac = 0.5187 − 0.0043DC	0.61	<0.0001
211-338	Mac = 0.5433 − 0.0049DC	0.46	<0.0003
339-721	Mac = 0.6080 − 0.0058DC	0.55	<0.0001
BD_{ref} 400 kPa undist			
68-103	Mac = 0.5263 − 0.0045DC	0.62	<0.0001
211-338	Mac = 0.5927 − 0.0056DC	0.57	<0.0001
339-721	Mac = 0.6474 − 0.0065DC	0.64	<0.0001
BD_{ref} 800 kPa undist			
68-103	Mac = 0.5335 − 0.0047DC	0.63	<0.0001
211-338	Mac = 0.6084 − 0.0061DC	0.62	<0.0001
339-721	Mac = 0.6622 − 0.0070DC	0.70	<0.0001
BD_{ref} 1600 kPa undist			
68-103	Mac = 0.5356 − 0.0049DC	0.64	<0.0001
211-338	Mac = 0.6134 − 0.0064DC	0.64	<0.0001
339-721	Mac = 0.6522 − 0.0072DC	0.73	<0.0001

[a] The clay content range was established based on texture of the studied soils, namely sandier Alfisols in the first group, medium texture Ultisols in the second group, and clayey Ultisols and Oxisols in the third group.

conditions. However, as discussed above, this leads to less well-defined values of BD_{ref}. The best compromise seems to be that the load in the reference test is such that the DC-values in the field soils are as close to 100 as possible, rarely exceeding this value.

The final choice of load in the reference test should be made with respect to typical load values applied by farm machinery. These loads are often between 100 and 200 kPa (Carpenedo, 1994; Silva et al., 2000), but are up to 600 kPa for grain loaders (Carpenedo, 1994). In forest harvesting, Horn et al. (2004) measured values from 400 to 600 kPa applied by tree harvesters. Even higher values may occur, but the field traffic only applies short-time loading, sometimes when the soil is relatively dry and resistant. This suggests that a suitable load in a reference test for no-till soils is in the 400–1600 kPa range.

The regression equations of BD_{ref} against clay content were highly significant, whereas against clay plus silt the coefficients were lower but still significant, except to BD_{ref} 200 kPa dist – Intern (Fig. 2, Table 4). The angular coefficients of the different equations were similar, except for the equation for Proctor test that had a higher angular coefficient.

Table 6
Estimation of the hydraulic conductivity ($\log K_{\theta s}$) based on the degree of compactness (DC) using as BD_{ref} the Proctor test, BD_{ref} 200 kPa dist, BD_{ref} 200 kPa undist, BD_{ref} 400 kPa undist, BD_{ref} 800 kPa undist and BD_{ref} 1600 kPa undist

BD_{ref}	Equation	r^2	Probability
Proctor	$\log K_{\theta s}$ = 8.55607 − 0.08067DC	0.28	<0.0001
200 kPa dist	$\log K_{\theta s}$ = 10.03505 − 0.08613DC	0.53	<0.0001
200 kPa undist	$\log K_{\theta s}$ = 9.83809 − 0.08838DC	0.59	<0.0001
400 kPa undist	$\log K_{\theta s}$ = 9.83951 − 0.09113DC	0.65	<0.0001
800 kPa undist	$\log K_{\theta s}$ = 9.60378 − 0.09208DC	0.70	<0.0001
1600 kPa undist	$\log K_{\theta s}$ = 9.31182 − 0.09262DC	0.73	<0.0001

Table 7
Estimation of the hydraulic conductivity ($K_{\theta s}$) based on the degree of compactness (DC) for a soil macroporosity of 0.10 m^3 m^{-3} for different range of clay content, using as BD_{ref} the Proctor test, BD_{ref} 200 kPa dist, BD_{ref} 200 kPa undist, BD_{ref} 400 kPa undist, BD_{ref} 800 kPa undist and BD_{ref} 1600 kPa undist

BD_{ref}	Range of clay content (g kg^{-1})					
	68-103		211-338		339-721	
	DC (%)	$K_{\theta s}$ (mm h^{-1})	DC (%)	$K_{\theta s}$ (mm h^{-1})	DC (%)	$K_{\theta s}$ (mm h^{-1})
Proctor	88	28.84	89	23.99	87	34.67
200 kPa dist	101	21.38	98	38.90	94	87.10
200 kPa undist	97	18.20	90	75.86	87	141.25
400 kPa undist	95	15.14	88	66.07	84	151.36
800 kPa undist	92	13.49	83	91.20	80	173.78
1600 kPa undist	89	11.75	80	79.43	77	151.36

The lower the clay content, the higher the degree of compactness to reach the limit of 0.10 m^3 m^{-3} macroporosity. However, this limit is based on the requirement for adequate soil aeration, and can be regarded just as a rough rule of thumb, most applicable to regularly tilled, medium-textured soils. The actual value varies with soil texture. Gebhardt et al. (2006) state that the macropores are predominantly textural pores that persist even after high loads in coarse-textured soils. However, as discussed by Håkansson (2005), many of the macropores in coarse-textured soils are poorly interconnected and do not contribute very much to the gas exchange. Therefore, for adequate aeration, a larger macroporosity than 0.10 m^3 m^{-3} is required in these soils. In clay soils, the continuity of the macropore system is better and a lower macroporosity than 0.10 m^3 m^{-3} is often sufficient. In no-till soils the continuity of the macropore system gradually improves, and this explains why a lower macroporosity is required than in annually loosened soils. Even though the largest and least resistant pores under no-tillage tend to be deformed into pores of smaller diameter, the macropore system is more resistant and the soil can support larger loads (Beutler et al., 2006).

If the pore diameter reduced by compaction, water and gas fluxes are decreased (Horn, 2003). Under saturated conditions the water flow mainly occurs in the macropores. Therefore, a correlation between $K_{\theta s}$ and macroporosity is likely (Mesquita and Moraes, 2004).

Changes in soil hydraulic and aeration properties and in the configuration of the root system caused by soil compaction may reduce the nutrient uptake by the plants, and this may affect the environment. For example, N losses to the ground water and to the atmosphere may be greater in compacted than in uncompacted soil (Lipiec and Stepniewski, 1995). Destruction of inter- and intra-aggregate pores results in reduced aeration and water infiltration, increased soil strength of the compacted soil, worsening of pore functions and reduced root development. This may induce a more pronounced horizontal flux of water, which may cause soil erosion (Horn et al., 1995).

The range of $K_{\theta s}$ according to clay content verified in this study is, in general, moderately slow (0.6–2 mm h^{-1}), according to the classification of Anon. (1990). This author presented seven classes to indicate hydraulic conductivity, going from extremely slow (<0.06 mm h^{-1}) to very rapid (>20 mm h^{-1}).

Table 8 indicates that wheat has been more sensitive to compaction than soybean and black beans. Soybean reached maximum yield at a higher degree of compactness than black beans. However, as discussed by Håkansson (2005) there are many complications when comparing the sensitivity of different crops to compaction, particularly when comparing crops with different growing seasons. Then the difference between crops may be

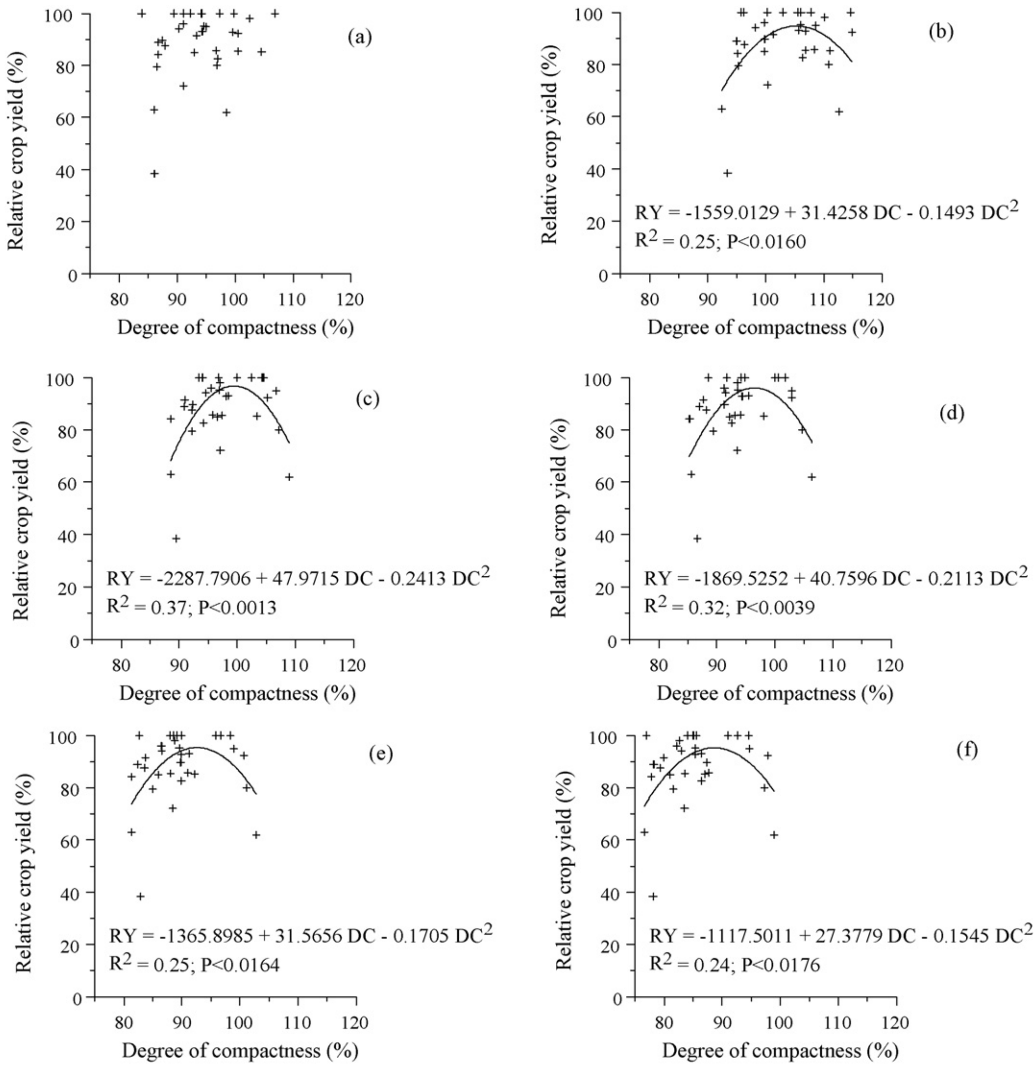

Fig. 6. Relative yield (RY) of soybean as a function of degree of compactness (DC) calculated on the basis of BD_{ref} Proctor (a), BD_{ref} 200 kPa dist (b), BD_{ref} 200 kPa undist (c), BD_{ref} 400 kPa undist (d), BD_{ref} 800 kPa undist (e) and BD_{ref} 1600 kPa undist (f), for soils from southern Brazil.

caused by differences in climatic conditions between the seasons causing differences for instance in crop establishment or in risk of poor soil aeration rather than by differences in sensitivity to compaction as such. Soybean and black beans were grown here as summer crops and wheat as a winter crop.

A low degree of compactness reduces the root-to-soil contact, whereas a high degree of compactness reduces soil aeration and increases penetration resistance with a negative effect on root growth and development (Suzuki, 2005). Thus, crop growth is negatively affected by soil compaction, but the highest yields are not obtained in a very loose soil (Arvidsson and Håkansson, 1991).

The greatest crop yield is usually reached with a DC-value between 80 and 90% (Beutler et al., 2005; Lipiec et al., 1991; Carter, 1990; Håkansson, 1990). However, the exact value depends on the method used to determine BD_{ref}. Using a Proctor test, Carter (1990) observed that a DC-value from 77.5 to 84% presented a relative yield larger or equal to 95%, and Beutler et al. (2005) observed that the optimum DC-value for soybean was 80% for an Oxisol of medium texture. Using a uniaxial test with disturbed samples and a load of 200 kPa, Håkansson (1990) observed a mean maximum yield of spring barley in 100 compaction experiments on various soils in Sweden at a DC-value around 87%, Lipiec et al. (1991) observed for two soils that the barley leaf area index and yield decreased when the DC-value in the plough layer exceeded approximately 88% for a soil with 60 g kg^{-1} clay and 680 g kg^{-1} silt, and 91% for a soil with 70 g kg^{-1} clay and 150 g kg^{-1} silt.

The optimum DC-value has been 4–14% lower when using a Proctor test than when using a uniaxial test with a load of 200 kPa dist (Table 9). This is understandable from the data in Fig. 1 showing that the former test in most soils results in higher values of BD_{ref} than the latter test. Consequently, when reporting

Table 8
Estimated degree of compactness (DC) based on the highest relative crop yield for soybean, black bean and wheat, using as BD_{ref} the Proctor test, BD_{ref} 200 kPa dist, BD_{ref} 200 kPa undist, BD_{ref} 400 kPa undist, BD_{ref} 800 kPa undist and BD_{ref} 1600 kPa undist

BD_{ref}	DC (%)		
	Soybean	Black bean	Wheat
Proctor	[a]	90	95
200 kPa dist	105	102	102
200 kPa undist	99	97	95
400 kPa undist	96	95	90
800 kPa undist	95	90	85
1600 kPa undist	90	85	80

[a] Not determined.

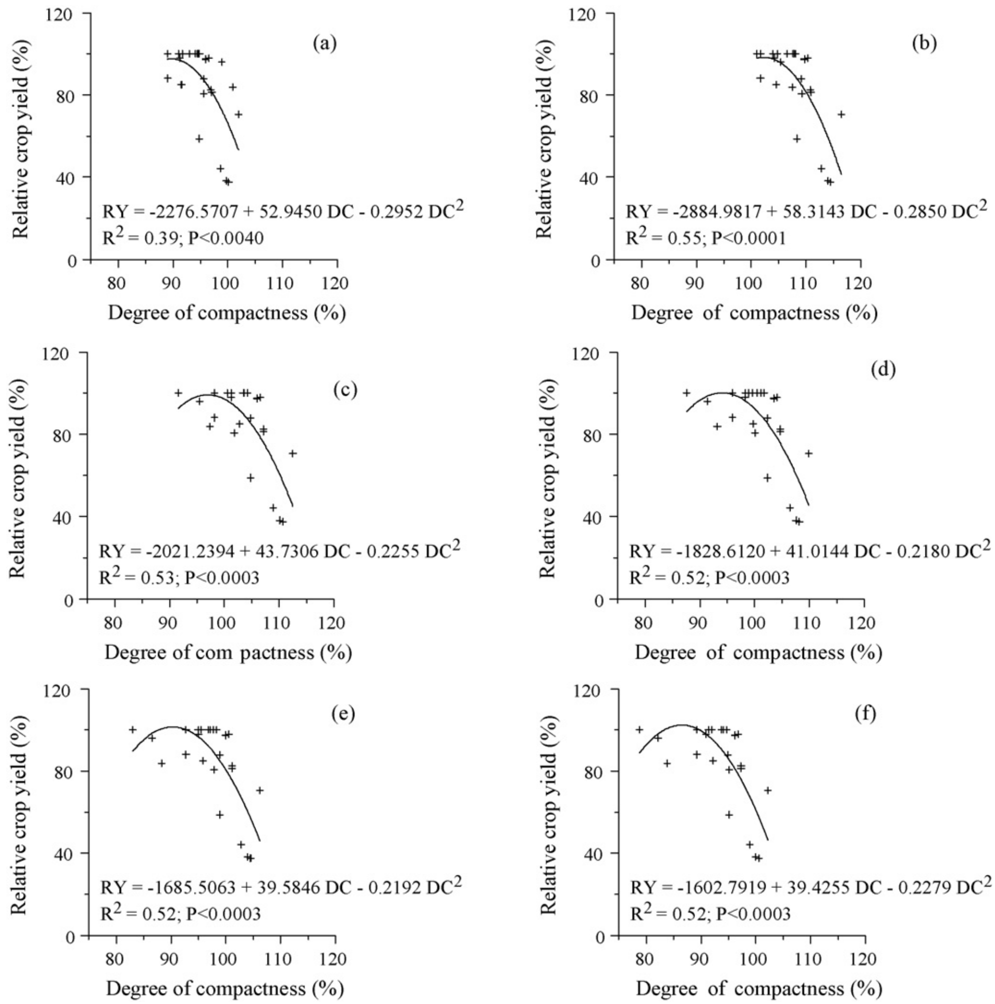

Fig. 7. Relative yield (RY) of black bean as a function of degree of compactness (DC) calculated on the basis of BD_{ref} Proctor (a), BD_{ref} 200 kPa dist (b), BD_{ref} 200 kPa undist (c), BD_{ref} 400 kPa undist (d), BD_{ref} 800 kPa undist (e) and BD_{ref} 1600 kPa undist (f), for soils from southern Brazil.

DC-values, the kind of reference test used must be specified. Unfortunately, the slope of the regression lines for the Proctor test and for the uniaxial tests in Fig. 1 are not parallel, indicating that the difference in BD_{ref} between the two types of tests depends on soil texture. This must be considered when comparing the usefulness of various types of reference tests.

The degree of compactness restricting macroporosity to $0.10\ m^3\ m^{-3}$ is usually lower than the degree of compactness restricting plant growth. While this topic needs further study, it is evident that under no-tillage a network of biopores and other continuous and stable macropores allows proper crop growth and yield, as demonstrated by the equations estimating critical bulk density as functions of least limiting water range and restrictions to root growth. No-tillage soil with high penetration resistance may still have greater corn yield than conventional tillage, when biopores are present in the former (Silva et al., 2004).

Our data show that ecological properties, such as aeration estimated from macroporosity or hydraulic conductivity, are primarily affected by soil compaction and these in turn affect plant development. This leads to conclude that when plant growth is affected, many ecological properties are also negatively affected.

The BDc-values indicate conditions critical or restrictive to crop growth or development. The BD_{ref}-values, on the other hand, may be considered just as bulk density values seldom exceeded in the field soils, but they make it possible to establish critical DC-values both for crop growth and for soil quality, and these values are not necessarily the same. Most soil properties and processes are likely to be more closely related to the degree of compactness than to bulk density.

Although BDc and BD_{ref} are quantified independently, and the first considers the crop as indicator while the second the soil as indicator, these two values are interrelated. If a soil reaches BDc and this is adequately estimated, the corresponding DC-value should also be critical to plant growth. The advantage of using the degree of compactness is that different soils may be compared, while the use of BDc may make a comparison among soils erroneous.

While the use of BD_{ref} 1600 kPa undist is a possibility for soil compaction studies in no-till soils, there were large differences in DC-values at BDc LLWR in soils with different clay content, due to different slopes in equations for estimating BDc LLWR and BD_{ref} 1600 kPa undist from clay content. When observing the data distribution in Fig. 3a, there are three data points for a soil with low clay content that contributed to decreasing the slope of BD_{ref} 1600 kPa undist as a function of clay content. Thus, more soils, particularly coarse-textured ones, should be studied to check this slope.

When determining the degree of compactness, it is necessary to pay regard also to the time and method to establish the bulk density in the field, particularly in swelling/shrinking soils. In such

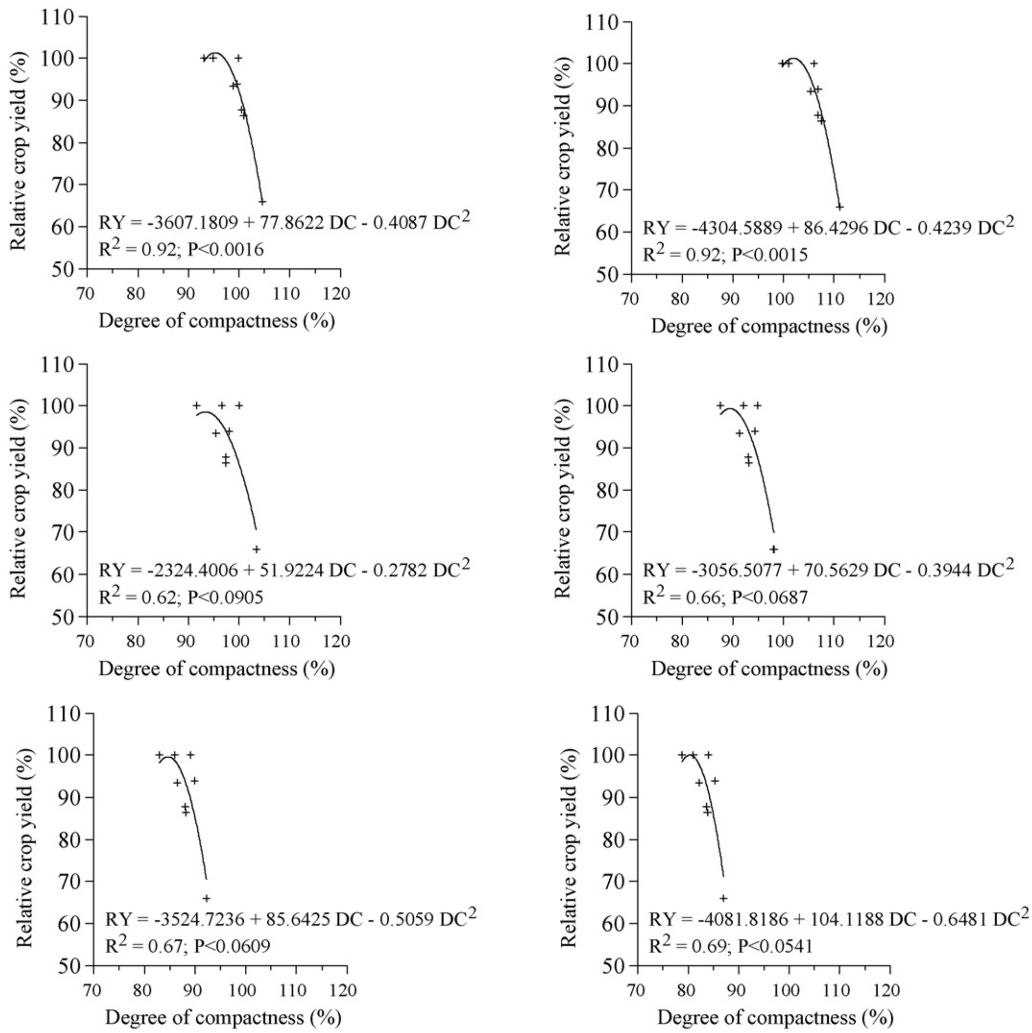

Fig. 8. Relative yield (RY) of wheat as a function of degree of compactness (DC) calculated on the basis of BD_{ref} Proctor (a), BD_{ref} 200 kPa dist (b), BD_{ref} 200 kPa undist (c), BD_{ref} 400 kPa undist (d), BD_{ref} 800 kPa undist (e) and BD_{ref} 1600 kPa undist (f), for soils from southern Brazil.

Table 9
Degree of compactness (DC) for selected clay content, based on the BD_c LLWR, comparing disturbed and undisturbed soil samples compacted with Proctor test and uniaxial compression, for soils from southern Brazil

Clay content[a] (g kg^{-1})	DC (%)					
	Disturbed soil samples		Undisturbed soil samples			
	Proctor	Uniaxial compression test				
	Standard test	200 kPa	200 kPa	400 kPa	800 kPa	1600 kPa
103	95	109	101	99	96	93
338	94	104	98	95	91	87
721	91	95	91	87	81	76

[a] Upper limit of clay content for texture classes presented in Table 5.

soils, reversible variations in bulk density of the upper soil layers during the season due to variations in water content can amount to 10% and more, and the reversible part of the BD-changes should not be reflected in the DC-values. Therefore, as discussed by Håkansson and Lipiec (2000), the bulk density used to calculate a DC-value must be tied to a standardised moisture situation, with field capacity being the most recommendable. This can be achieved by always carrying out the field sampling at this situation. A correction of the values to this situation might be an alternative, but it may be difficult to find a relevant correction method. The technique for the sampling may also influence the BD-values. For instance, when traditional core sampling was compared with frame sampling using a 0.5 m^2 frame, Håkansson (1990) typically found a 4% greater bulk density in the plough layer by the former method than by the latter method.

5. Conclusion

Using vertical uniaxial compression with a load of 200 kPa on disturbed or undisturbed samples in the reference test generates low values of reference bulk density and high values of degree of compactness (higher than 100% in many cases). The standard Proctor test generates higher values of reference bulk density, which are similar to those in a uniaxial test with a load of 1600 kPa for soils with low clay content but lower for soils with high clay content.

The critical bulk density based on the least limiting water range (using 0.10 $m^3 m^{-3}$ air-filled porosity and 2 MPa penetration resistance as critical values) does not necessarily restrict root growth or crop yield under no-tillage, since field investigations led to higher restrictive bulk density values. The restrictive values should be adjusted both with respect to soil texture and tillage system. Nevertheless, a critical value based on the least limiting water range is an alert that soil physical conditions are not optimal and that restrictive density affecting roots and yield has almost been reached.

A uniaxial load greater than 800 kPa is promising to determine reference bulk density for no-tillage soils, with values of degree of compactness almost always below 100%.

Independently of the method used for its determination, the reference bulk density is highly correlated to the clay Content; thus, pedotransfer functions may be established to estimate the former based on the latter.

Soil ecological properties, like aeration estimated from macroporosity and hydraulic conductivity, are affected before compaction restricts plant growth and yield.

Advances in establishing critical values of degree of compactness for crop growth and yield have been made. The degree of compactness is an efficient parameter to identify soil compaction affecting crops, but there are still unanswered questions, mainly related to reference bulk density such as the effects of clay mineralogy and organic matter content. The effect of compaction on ecological properties must also be further considered.

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