ELSEVIER

Soil & Tillage Research 56 (2000) 197–204

Soil & Tillage Research

www.elsevier.com/locate/still

Maximum compactibility of Argentine soils from the Proctor test; The relationship with organic carbon and water content

A. Aragón[a], M.G. García[a], R.R. Filgueira[a,*], Ya.A. Pachepsky[b]

[a]*Areas Manejo y Conservación de Suelos y Física Aplicada, Facultad de Ciencias Agrarias y Forestales,*
Universidad Nacional de La Plata, 1900 La Plata, Argentina
[b]*USDA-ARS Hydrology Laboratory, Beltsville, MD, USA*

Received 14 October 1999; received in revised form 5 June 2000; accepted 28 June 2000

Abstract

Soil compaction is recognized as an increasingly challenging problem for the agricultural, horticultural and forest production in many climatic regions. The Proctor test provides a standardized method to study compactibility of disturbed soils over a range of soil water contents. The objectives of our study were: (a) to determine values of the critical water content for compaction and maximum bulk density from Proctor compaction curves for soils different in their properties; (b) to study the correlation between the maximum bulk density and readily available soil properties. Thirty soil samples were taken from six different locations in Argentina between 58 and 64°W and 34 and 38°S. The degree of saturation at maximum bulk density varied from 73.2 to 96.8%. Comparison of our data with data of two studies in USA showed that relationships between the maximum bulk density and the critical water content were similar to these studies. However, the slope of the relationship between the maximum bulk density and the organic carbon content was 50% less in our study as compared with the two others. The maximum bulk density was highly correlated with the organic carbon content and the silt content, the determination coefficient of the multiple linear regression, r^2, was 0.88. © 2000 Elsevier Science B.V. All rights reserved.

Keywords: Soil; Compaction; Proctor test; Organic carbon content; Water content

1. Introduction

Soil compaction presents problems for soil and crop management in agriculture, horticulture, and forestry in all climatic regions (Soane and van Ouwerkerk, 1994; Hakansson and Voorhees, 1998). Excessive compaction causes such undesirable effects as a decrease in water infiltration, an increase in runoff, and a restriction of root development, which can lead to reduction in crop yields and soil quality (Unger and Kaspar, 1994; Schafer et al., 1992). In many agricultural soils the problem arises because fields are often trafficked and tilled when soils are in a condition prone to compaction due to wetness (Spoor, 1997; Gabriels et al., 1998). Soil compaction becomes a regional problem in Argentina (Quiroga et al., 1999).

The Proctor test provides a widely accepted procedure to study compactibility of disturbed soils over a range of soil water contents under a standardized dynamic load (Hillel, 1980). This test has long been applied to predict stability of road and building foundations. The Proctor test has been also employed to characterize resistance of agricultural soils to compaction (Soane et al., 1972; Morin and Todor, 1977;

---

[*] Corresponding author. Tel.: +54-221-4833658;
fax: +54-221-4252346.
E-mail address: filgueira@infovia.com.ar (R.R. Filgueira).

PII: S0167-1987(00)00144-6

De Kimpe et al., 1982; Felton and Ali, 1992; Pecorari et al., 1993; Wagner et al., 1994; Aragón et al., 1996; Thomas et al., 1996; Ekwue and Stone, 1997, 1995; Zhang et al., 1997). In these studies, dependencies of soil bulk density on soil water content were obtained. Parameters to compare compactibility of soils were the maximum soil bulk density (ρ_{MBD}) under Proctor test and the critical water content (θ_{CWC}) at which this bulk density was reached. The agronomic importance of these parameters is elucidated by the work of Wagner et al. (1994) who have found the maximum tillage-induced breakdown occurring at water contents close to θ_{CWC}. Regional relationships between θ_{CWC} values and plastic limit were found in studies of tropical soils (Morin and Todor, 1977; Carter and Bentley, 1991). Work of De Kimpe et al. (1982) showed the relationship between soil water retention at low matric potential and θ_{CWC}. Another agronomic usefulness of MBD is in expressing soil bulk density on a relative basis which is of interest in soil physical quality evaluation (i.e., Darusman et al., 1991).

Several research groups attempted to relate soil compactibility, as measured with the Proctor test, to readily available soil parameters and management practices. Those studies were focused on relationships between Proctor compactibility parameters, soil organic matter and soil texture. Thomas et al. (1996) used the Proctor test to compare maximum compactibilities of some Kentucky soils (USA) with various management histories including no-tillage, conventional tillage, and continuous sod. A negative correlation was found between the maximum compactibility and the amount of soil organic carbon content (OCC) in this study. Aragón et al. (1996) found that both ρ_{MBD} and θ_{CWC} values correlated with OCC values in soils from different locations in the Buenos Aires Province, Argentina. Ekwue and Stone (1995) and Felton and Ali (1992) also reported significant correlation between organic matter contents and ρ_{MBD}. Felton and Ali (1992) found that the addition of organic matter to B-horizon soils leads to an increase in the porosity and the water retention, and to a decrease in the bulk density determined by Proctor test. Thomas et al. (1996) applied a linear regression to relate the ρ_{MBD} to the OCC, whereas Pecorari et al. (1993) advocated the use of the linear regression of OCC vs. the reciprocal of the ρ_{MBD}. Soane (1990) reviewed effects of the organic matter in soil compactibility and concluded that an increase in the organic matter content reduced compactibility because of the increase in resistance to deformation and/or the increase in elasticity. Zhang et al. (1997) found that the effectiveness of organic matter in reducing soil compactibility was dependent on soil texture and organic matter composition. Working with data on soils from 19 states of the USA, Wagner et al. (1994) derived a non-linear equation to predict θ_{CWC} from the OCC, clay and sand contents. These results show that a description of qualitative and quantitative effects of organic matter and texture on the soil compactibility may lead to a better understanding of factors controlling the compactibility of the soils from a region.

Values of ρ_{MBD} and θ_{CWC} are correlated if obtained from the Proctor test applied to a range of soils. Hillel (1980, p. 383) has shown that the soil bulk density ρ_{b} (Mg/m^3), the soil water content θ (m^3/m^3) and the degree of saturation of soil, $S=\theta/\theta_{\mathrm{s}}=V_{\mathrm{w}}/V_{\mathrm{pore}}$, with θ_{s} the water content at saturation, are related by the following equation:

$$\frac{1}{\rho_{\mathrm{b}}}=\frac{1}{\rho_{\mathrm{s}}}+\frac{\theta}{S\rho_{\mathrm{w}}} \qquad (1)$$

where ρ_{s} and ρ_{w} are bulk densities of soil solids and pore water, respectively. At the CWCs in the Proctor test, Eq. (1) yields

$$\frac{1}{\rho_{\mathrm{MBD}}}=\frac{1}{\rho_{\mathrm{s}}}+\frac{\theta_{\mathrm{CWC}}}{S_{\mathrm{CWC}}\rho_{\mathrm{w}}} \qquad (2)$$

where S_{CWC} is the degree of saturation at CWCs. Hillel (1980, p. 383) suggested that the value of the S_{CWC} might be approximately 80% in all soils. Should this hypothesis be true, Eq. (2) should be valid for a wide range of soils with $1/\rho_{\mathrm{s}}$ as the intercept. Wagner et al. (1994) found the value of $S_{\mathrm{CWC}}=76.9\%$ from data on 39 soils using a non-linear optimization method.

This study was a part of a project having an ultimate goal to improve the understanding of soil compaction phenomenon in Argentinean condition. The specific objectives of this study were: (a) to determine values of the CWC for compaction and MBD from Proctor compaction curves for soils different in their properties; (b) to find the correlation between ρ_{MBD} and OCC; (c) to observe the variability in values of the saturation degree at maximum compaction, and evaluate the applicability of Eq. (2) with the same value of

S_{CWC} over the wide range of soils; (d) to compare our results with other available data.

2. Materials and methods

2.1. Data acquisition

Soil samples were taken in Azul, La Plata, General Pinto, Tandil, Neuquen, and Santa Rosa locations. Table 1 contains characteristics of the locations. The total number of samples was 30. Soil samples were manually crushed while slightly moist, dried at room temperature and humidity and subsequently sieved trough a 4.8 mm screen.

The standard Proctor method (ASTM, 1992) was applied. Subsamples of about 2.5 kg were spray-moisturized in order to reach eight different water contents. Following the method, amounts of soil from these homogenized wet subsamples were compacted in three layers in a compaction chamber, volume 0.911×10^{-3} m^3. Each layer received 25 blows of a 2.5 kg falling hammer from 0.305 m height. The energy density was 593.7 kJ/m^3. The weight of the wet compacted soil in the chamber was determined. Then the samples were dried in an oven at 105°C for 24 h, and weighed again to estimate the moisture content and dry bulk density. Soil texture was determined using the Bouyoucos (1951) hydrometer method. Soil OCCs were measured in subsamples of the original sample with the method of Walkley (1947). Duplicate samples were used for all determinations.

2.2. Data analysis

Inspection of relationships between bulk densities and water contents showed that all the dependencies had a typical shape with two well-expressed quasi-linear intervals Hillel (1980, p. 383). Bulk densities increased with increasing water content when the water content was below the CWC, and decreased with the increase in water content above the CWC. Therefore, piecewise linear approximation of the dependencies was used to estimate the MBD and the CWC as the interception point of the two straight lines

$$\rho_{\mathrm{b}} = \begin{cases} b_1(\theta - \theta_{\mathrm{CWC}}) + \rho_{\mathrm{MBD}}, & \theta < \theta_{\mathrm{CWC}} \\ b_2(\theta_{\mathrm{CWC}} - \theta) + \rho_{\mathrm{MBD}}, & \theta \geq \theta_{\mathrm{CWC}} \end{cases} \tag{3}$$

where ρ_{b} is the bulk density, Mg/m^3, θ is the gravimetric water content, 100 kg/kg, b_1 and b_2 are slopes of the linear dependencies of the BD on the WC before and after reaching the MBD value, respectively. This equation was fitted to the data on each sample using the Marquardt algorithm of non-linear optimization to minimize the root mean square error (Jandel, 1995). Values of ρ_{MBD} and θ_{CWC} were estimated together with the b_1 and b_2 values. Standard errors of the ρ_{MBD} and θ_{CWC} values were estimated along with the average values. The degree of saturation, S_{CWC}, at maximum compaction was estimated for every sample by inverting Eq. (2) and using estimated values of ρ_{MBD} and θ_{CWC},

Table 1
Characterization of sampling locations

Location (ID)	Province	Longitude (W)	Latitude (S)	Mean annual temperature (°C)	Average annual precipitation (mm)	Sampled soils (FAO classification)[a]	Typical land use
Azul (Az)	Buenos Aires	59°50′	36°42′	13.8	890	Haplic Phaeozem	Rotation of conventional tillage and pasture
La Plata (LP)	Buenos Aires	57°50′	34°55′	16.0	1050	Luvic Phaeozem and Vertic Phaeozem	Horticulture and conventional tilled fields
General Pinto (GP)	Buenos Aires	62°15′	34°25′	15.7	780	Haplic Phaeozem	Rotation of conventional tillage and pasture
Tandil (Ta)	Buenos Aires	59°22′	37°10′	13.3	850	Luvic Phaeozem	Rotation of conventional tillage and pasture
Neuquen (Nq)	Neuquen	68°00′	38°30′	12.0	125	Eutric Fluvisol	Orchards under irrigation
Santa Rosa (SR)	La Pampa	64°19′	36°37′	15.5	580	Eutric Regosol	Rotation of conventional tillage and pasture

[a] FAO/UNESCO (1994) classification.

and values of ρ_s of 2.65 Mg/m^3 and ρ_w of 1.00 Mg/m^3. Standard errors of the linear regression coefficients and the significance of differences between slopes and intercepts were estimated according to (Dowdy and Wearden, 1985). The one way ANOVA with multiple comparison option (Jandel, 1995) test was run to test the hypothesis of no difference between our data set and data sets of other authors. The significance level of 0.05 was used in statistical comparisons.

3. Results and discussion

The observed ranges of variation for all soil properties were relatively large. The OCC ranged from 0.27 to 6.20%, the gravimetric CWC from 15.0 to 43.1%, the MBD from 1.17 to 1.74 Mg/m^3, and the S_{CWC} from 73.2 to 96.8%. Data in Table 2 and in Fig. 1 show general trend of reduction in the MBD with increase in the OCC and that of reduction in the MBD with increase in the CWC.

Table 3 shows the results of testing the hypothesis of no differences between data from works of Thomas et al. (1996), Wagner et al. (1994), and this study. Our data have a higher mean value of OCC and a wider range of OCC as compared with the other two sets. Data of this work have also a wider range of the CWC values and the lower mean value of the MBD.

Regression equations derived to relate ρ_{MBD} values to OCC values are shown in Table 4 for the data

Table 2
Site characterizations and Proctor test results

Site ID and depth range (m)	Land use	Soil	Texture (100 kg/kg)			OCC (100 kg/kg)	CWC (100 kg/kg)	MBD (Mg/m^3)	Saturation degree at CWC (%)
			Sand	Silt	Clay				
Az 0–0.20	Pasture	Haplic Phaeozem	47	28	25	4.58	33.5	1.29	83.0
Az 0–0.20	Crop	Haplic Phaeozem	43	37	20	2.70	28.3	1.46	92.9
Az 0–0.20	Crop	Haplic Phaeozem	39	40	21	3.20	26.1	1.48	87.2
Az 0–0.15	Pasture	Haplic Phaeozem	39	40	21	2.55	26.0	1.44	82.0
Az 0.15–0.30	Pasture	Haplic Phaeozem	45	28	27	1.31	20.4	1.66	88.9
GP 0–0.20	Crop	Haplic Phaeozem	59	26	15	1.33	16.6	1.65	73.2
GP 0–0.20	Pasture	Haplic Phaeozem	59	26	15	1.93	23.0	1.53	83.3
LP 0–0.05	Crop	Luvic Phaeozem	27	50	23	3.07	29.1	1.43	90.4
LP 0.05–0.10	Crop	Luvic Phaeozem	25	51	24	3.01	30.2	1.37	85.7
LP 0.10–0.20	Crop	Luvic Phaeozem	27	50	23	2.75	28.4	1.42	86.9
LP 0.20–0.30	Crop	Luvic Phaeozem	27	48	25	2.71	28.0	1.43	87.0
LP 0.30–0.40	Crop	Luvic Phaeozem	25	48	27	2.15	25.0	1.52	89.1
LP 0–0.20	Pasture	Luvic Phaeozem	31	56	13	6.20	43.1	1.17	90.3
LP 0–0.20	Crop	Luvic Phaeozem	27	58	15	2.41	29.1	1.44	91.8
LP 0–0.20	Horticulture	Luvic Phaeozem	36	42	22	2.01	26.4	1.44	83.3
LP 0–0.20	Crop	Luvic Phaeozem	27	52	21	1.74	26.4	1.44	83.3
LP 0–0.20	Pasture	Luvic Phaeozem	31	50	19	2.85	30.7	1.34	83.2
LP 0–0.20	Crop	Vertic Phaeozem	29	46	25	1.52	24.9	1.44	78.5
LP 0.20–0.40	Crop	Vertic Phaeozem	25	52	23	0.92	25.0	1.47	82.5
LP 0–0.20	Pasture	Luvic Phaeozem	25	52	23	2.14	26.0	1.46	84.5
LP 0–0.20	Crop	Luvic Phaeozem	25	52	23	2.57	28.0	1.43	87.0
LP 0–0.20	Crop	Luvic Phaeozem	26	51	23	1.66	28.4	1.45	90.9
LP 0–0.20	Crop	Vertic Phaeozem	28	50	22	1.41	28.2	1.48	94.5
LP 0–0.20	Pasture	Luvic Phaeozem	28	49	23	4.04	35.6	1.29	89.5
Ta 0–0.20	Pasture	Luvic Phaeozem	49	38	13	6.10	34.0	1.28	84.2
Ta 0–0.20	Crop	Luvic Phaeozem	43	42	15	4.82	27.6	1.46	91.0
Nq 0–0.20	Orchard	Eutric Fluvisol	25	56	19	0.63	28.3	1.5	96.8
Nq 0–0.20	Orchard	Eutric Fluvisol	76	15	9	0.27	15.0	1.74	76.0
SR 0–0.20	Pasture	Eutric Regosol	59	32	9	0.80	19.2	1.57	73.2
SR 0–0.20	Crop	Eutric Regosol	65	28	7	0.58	18.6	1.66	80.0

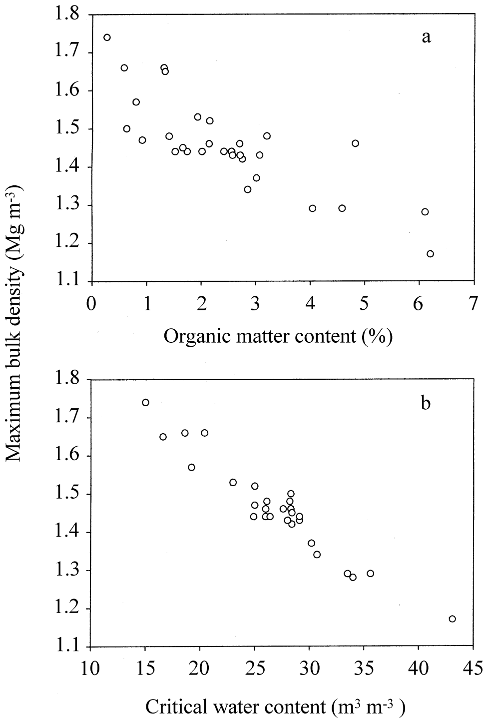

Fig. 1. Dependencies of the MBD from the Proctor test on (a) the soil organic matter content, and (b) the CWC.

from works of Thomas et al. (1996), Wagner et al. (1994) and this study. Wagner et al. (1994) used the same energy level in the Proctor test as we did in the present work, whereas Thomas et al. (1996) used somewhat different setup. Despite the different level of energy used in the Proctor test by Thomas et al. (1996), the resulting linear regression equations were rather similar (Table 4) to those obtained with the data set of Wagner et al. (1994). However, the determination coefficients were quite different; the lowest values were obtained with data from the work of Wagner et al. (1994). It is interesting to mention that data of Thomas et al. (1996) and our data sets were collected across smaller regions than data used by Wagner et al. (1994). Thomas et al. (1996) grouped soil samples by county and found a significant increase in determination coefficients. The values of the determination coefficients r^2 were in the range from 0.85 to 0.98 in their study after the grouping. The negative slope of the equation (reduction of the ρ_{MBD} per unit increase in percentage of OCC) obtained from our data is ca. 50% less than in the other two sets. This suggests that the effects of the organic matter on soil compactibility may have regional differences which depend on soil variables

Table 3
Results of the ANOVA to test the independence of OCCs, CWCs for compaction and MBDs in three different data sets[a]

Data source	Number of data sets	OCC (100 kg/kg)				CWC (100 kg/kg)				MBD (Mg/m^3)			
		Mean	Minimum	Maximum	Range	Mean	Minimum	Maximum	Range	Mean	Minimum	Maximum	Range
Thomas et al. (1996)	36	1.858 b	0.80	3.50	2.70	21.03 b	14.7	29.0	14.3	1.588 b	1.39	1.82	0.43
Wagner et al. (1994)	39	1.151 c	0.14	3.13	2.99	16.97 c	8.0	26.0	18.0	1.684 c	1.46	1.99	0.53
This work	30	2.465 a	0.27	6.20	5.93	26.97 a	15.0	43.1	28.1	1.458 a	1.17	1.74	0.57

[a] Mean values in each column followed by different letters are significantly different according to the Tukey's test.

Table 4
Intercepts (a), slopes (b), and determination coefficients r^2 for linear relationships of MBD and the reciprocal of the MBD with soil OCC[a]

Data source	Number of data sets	$(1/\rho_{\mathrm{MBD}}) = a + b\,\mathrm{OCC}$			$\rho_{\mathrm{MBD}} = a + b\,\mathrm{OCC}$		
		a	b	r^2	a	b	r^2
Thomas et al. (1996)	36	0.526±0.010	0.057±0.005	0.79	1.845±0.027	−0.138±0.014	0.75
Wagner et al. (1994)	39	0.540±0.012	0.050±0.009	0.47	1.850±0.034	−0.145±0.026	0.46
This study	30	0.611±0.012	0.032±0.004	0.70	1.619±0.026	−0.065±0.009	0.66
All three	105	0.554±0.006	0.046±0.003	0.69	1.779±0.017	−0.109±0.008	0.62

[a] The ± sign separates estimates of parameters from estimates of their standard errors.

other than OCC. Model studies of Zhang et al. (1997) show that the composition of soil organic matter along with the total amount is also an important factor in results of the Proctor test.

Comparison of using the ρ_{MBD} and its reciprocal to relate with OCC showed that the reciprocal model improved the determination coefficients in all data sets (Table 4). Pecorari et al. (1993) used the reciprocal equation to model the relationship between ρ_{MBD} and OCC in soils of the Pampas region in Argentina. These authors found equation $(1/\rho_{\mathrm{MBD}}) = 0.0389\,\mathrm{OCC} + 0.617$ for 23 samples with the OCC ranging from 1 to 3.2%. The slope and estimates obtained in the present work (Table 4) were close to those of Pecorari et al. (1993), and different from the other two sets in accordance with the above mentioned possibility of regional differences in ρ_{MBD}–OCC dependencies. The determination coefficient in the Pecorari et al. (1993) work was $r^2 = 0.429$ which is lower than the value of 0.70 obtained in the present work. One possible explanation of the differences in correlation coefficients is that the soils in the Pecorari et al. (1993) study were sampled across a much broader region of Argentina than in our study. A similar difference in correlation coefficients (Table 4) and size of regions sampled was found between data of Wagner et al. (1994) and of Thomas et al. (1996).

Wagner et al. (1994) suggested using soil texture parameters along with the OCC values to estimate the MBD. This suggestion appeared to be applicable to our data. Fig. 2 shows the joint effect of the soil silt content and the OCC on the ρ_{MBD}. The increase in silt content reduces soil compactibility with the same organic matter contents. A linear regression of ρ_{MBD} with both silt contents and OCC as independent variables had the equation

$$\rho_{\mathrm{MBD}} = 1.766 - 0.00598\,\mathrm{Silt} - 0.0158\,\mathrm{OCC}$$

and the value of the determination coefficient $r^2 = 0.88$ which is much higher than the value 0.66 found for regression of ρ_{MBD} on OCC only. Including clay content or sand content in the equations did not improve the determination coefficient. Using silt contents along with OCC values to estimate θ_{CWC} resulted in the equation

$$\theta_{\mathrm{CWC}} = 10.1 + 0.239\,\mathrm{Silt} + 2.669\,\mathrm{OCC}$$

with the determination coefficient $r^2 = 0.86$.

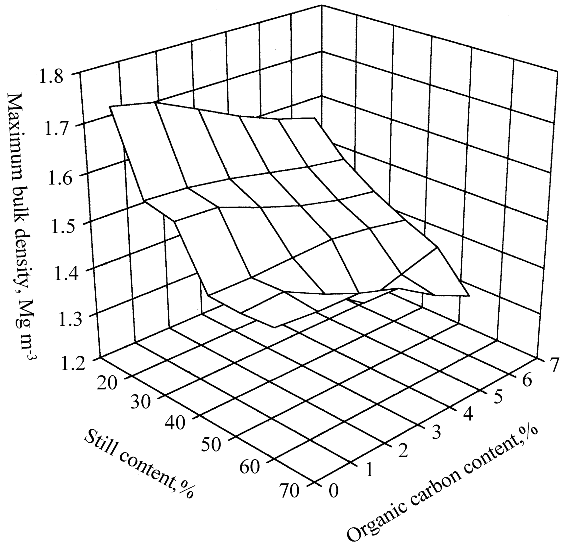

Fig. 2. Dependence of the MBD from the Proctor test on silt content and OCC in studied soils.

Relatively high determination coefficient between the MBD and soil organic matter and silt may partly be related to the wide range of organic matter contents and silt contents obtained in the regional sampling. For the same soil type the correlation may be lower, and land use may be an important factor modifying the MBD values. For example, data in Table 2 indicate that Luvic Phaeozem under crops has the MBD range from 1.37 to 1.45 Mg/m^3 in the depth range 0–0.30 m. This range is much narrower than the one observed across the sampling region. Within this group of samples, the determination coefficient of the regression of the organic matter content vs. MBD is only 0.53 whereas for the whole region it is 0.65.

Relationships between ρ_{MBD} and θ_{CWC} are summarized in Table 5. A strong negative correlation between these parameters was found. This was observed in earlier studies (Aragón et al., 1996; Wagner et al., 1994). Although the soil samples were taken in different regions, they all showed similar slopes and intercepts and high correlation coefficients. This similarity represents an interesting avenue to explore. Using the reciprocal of ρ_{MBD} as suggested by Hillel (1980, p. 383) resulted in an improvement in determination coefficients. Wagner et al. (1994) determined S_{CWC} to be in the range from 73.9 to 79.8% at 95% probability level. Applying Eq. (2) to data of this

Table 5
Intercepts (*a*), slopes (*b*) and determination coefficients r^2 for linear regressions of the CWC vs. MBD values and their reciprocals[a]

Data source	Number of data sets	$\rho_{\mathrm{MBD}} = a + b\,\theta_{\mathrm{CWC}}$			$(1/\rho_{\mathrm{MBD}}) = a + b\,\theta_{\mathrm{CWC}}$		
		a	*b*	r^2	*a*	*b*	r^2
Thomas et al. (1996)	36	2.152±0.042	−0.027±0.002	0.84	0.4032±0.0164	0.0109±0.0008	0.86
Wagner et al. (1994)	39	2.151±0.031	−0.027±0.002	0.87	0.4358±0.0099	0.0095±0.0006	0.89
This work	30	2.009±0.032	−0.020±0.001	0.92	0.4248±0.0146	0.0099±0.0005	0.93
All three	105	2.087±0.016	−0.024±0.001	0.91	0.4308±0.0063	0.0097±0.0063	0.93

[a] The ± sign separates estimates of parameters from estimates of their standard errors.

work gave values of S_{CWC} in the range from 73.2 to 96.8% at the same probability level. This may be related to the presence of soils with high OCC in our data set.

The probability of reaching CWCs during periods when the machinery has to be in fields depends on the climate of a location. Table 2 shows that saturation degrees at CWC are relatively high, and close to 100%. Data of Table 1 show that the precipitation varies widely across the region under study. Combining soil water balance with estimates of saturation degrees at CWCs is needed to evaluate the potential risk of soil compaction.

The Proctor test results should be viewed as components of soil compactibility studies. Hillel (1980) discusses the Proctor test as the one important for engineering decisions on using soil for construction purposes and as a tractable surface for vehicles. Both trafficability and workability of soils were found related to the Proctor test results (De Kimpe et al., 1982; Wagner et al., 1994). Soane (1990) has suggested that the compactibility of agricultural soils should be characterized in terms other than density, e.g. porosity and permeability. Measuring penetration resistance presents yet one more way to characterize soil compactibility. Soil components, and in particular, soil organic matter may affect different indexes of compaction in different ways. Soane (1990) has noted that tests employing an impact loading (e.g. Proctor) generally indicate that increases of organic matter result in a reduction in compactibility, whereas no differences in compression indices may be obtained from continuous axial compression tests where water is allowed to drain (Larson et al., 1980; Wulfsohn et al., 1998). Zhang et al. (1997) found no consistency in the relationship between the amount of added organic matter and the penetration resistance, although an increase in MBD was observed when peat was added to soils. The complexity of the phenomenon of soil compaction warrants using a combination of soil mechanical characteristics to assess soil trafficability, workability, and plant growth restrictions as related to compaction.

4. Conclusions

Negative correlation was observed between MBDs and OCCs, and between MBDs and CWCs. The correlation between estimated and measured ρ_{MBD} was significantly improved by adding to OCC the linear dependence on silt content, in our study. Using reciprocals of ρ_{MBD} improved the correlation. The accuracy of the ρ_{MBD} and θ_{CWC} estimates from the OCC and texture parameters seems to be high enough to use this estimation for predictive purposes.

Acknowledgements

We thank the Universidad Nacional de La Plata, the Consejo Nacional de Investigaciones Científicas y Técnicas (CONICET) and the Fundación Campodónico La Plata for financial support. We are grateful to two anonymous reviewers for their insightful comments.

References

Aragón, A., García, M.G., Nico, A.I., Filgueira, R.R., 1996. Compactabilidad de suelos; influencia de la capacidad de retención de agua y variables conexas. IV Congreso Argentino y II Internacional de Ingeniería Rural, Neuquén, Argentina. Memorias 2, pp. 707–712 (in Spanish).

ASTM, 1992. Annual Book of ASTM Standards. American Society for Testing and Materials, Philadelphia, PA.

Bouyoucos, G.J., 1951. A recalibration of the hydrometer method for making mechanical analyses of soils. Agron. J. 43, 434–438.

Carter, M., Bentley, S.P., 1991. Correlations of Soil Properties. Pentech Press, London.

Darusman, L.R., Stone, D.A., Whitney, K.A., Janssen, K.A., Long, J.H., 1991. Soil properties after twenty years of fertilization with different nitrogen sources. Soil Sci. Soc. Am. J. 55, 1097–1100.

De Kimpe, C.R., Bernier-Cardou, M., Jolicoeur, P., 1982. Compaction and settling of Quebec soils in relation to their soil–water properties. Can. J. Soil Sci. 62, 165–176.

Dowdy, S., Wearden, S., 1985. Statistics for Research. Wiley, New York.

Ekwue, E.I., Stone, R.J., 1995. Organic matter effects on the strength properties of compacted agricultural soils. Trans. Am. Soc. Agric. Eng. 38, 357–365.

Ekwue, E.I., Stone, R.J., 1997. Density–moisture relations of some Trinidadian soils incorporated with sewage sludge. Trans. Am. Soc. Agric. Eng. 40, 317–323.

FAO/UNESCO, 1994. World Reference Base for Soil Resources. ISSS, ISRIC, FAO, Rome.

Felton, G.K., Ali, M., 1992. Hydraulic parameter response to incorporated organic matter in the B horizon. Trans. Am. Soc. Agric. Eng. 35, 1153–1160.

Gabriels, D., Horn, R., Villagra, M.M., Hartmann, R., 1998. Assessment, prevention, and rehabilitation of soil structure caused by soil surface sealing, crusting, and compaction. In: Lal, R., Blum, W.H., Valentine, C., Stewart, B.A. (Eds.), Methods for Assessment of Soil Degradation/Advances in Soil Science. CRC Press, Boca Raton, FL, pp. 129–165.

Hakansson, I., Voorhees, W.B., 1998. Soil compaction. In: Lal, R., Blum, W.H., Valentine, C., Stewart, B.A. (Eds.), Methods for Assessment of Soil Degradation. CRC Press, Boca Raton, FL, pp. 167–179.

Hillel, D., 1980. Fundamentals of Soil Physics. Academic Press, New York, 413 pp.

Jandel, 1995. SigmaStat for Windows, Version 2.0 and SigmaPlot for Windows, Version 2.03.

Larson, W.E., Gupta, S.C., Useche, R.A., 1980. Compression of agricultural soils from eight soil orders. Soil Sci. Soc. Am. J. 44, 450–547.

Morin, W.J., Todor, P.C., 1977. Laterites and lateritic soils and other problem soils of the tropics. USIAA, A10/csd 3682. Government Print Office, Washington, DC.

Pecorari, C., Andriulo, A., Ausilio, A., 1993. Aptitud Físico-mecánica de los suelos para el laboreo. II. Efectos de la textura y de la materia orgánica sobre la densidad aparente máxima de algunos suelos de la región pampeana Argentina. Informe Técnico INTA No. 281, 16 pp. (in Spanish).

Quiroga, A.R., Buschiazzo, D.E., Peinemann, N., 1999. Soil compaction as related to management practices in the semi-arid Argentine pampas. Soil Till. Res. 52, 21–28.

Schafer, R.L., Johnson, C.E., Koolen, A.J., Gupta, S.C., Horn, R., 1992. Future research needs in soil compaction. Trans. ASAE 35, 1761–1770.

Soane, B.D., 1990. The role of organic matter in soil compactibility: a review of some practical aspects. Soil Till. Res. 16, 179–201.

Soane, B.D., van Ouwerkerk, C. (Eds.), 1994. Soil Compaction in Crop Production. Elsevier, Amsterdam.

Soane, R.D., Campbell, D.J., Herkes, S.M., 1972. The characterization of some Scottish arable topsoils by agricultural and engineering methods. J. Soil Sci. 23, 94–104.

Spoor, G., 1997. Benefits from traffic control. Landwards 52, 2–5.

Thomas, G.W., Haszler, G.R., Blevins, R.L., 1996. The effects of organic matter and tillage on maximum compactability of soils using the Proctor test. Soil Sci. 161, 502–508.

Unger, P.W., Kaspar, T.C., 1994. Soil compaction and root growth: a review. Agron. J. 86, 759–766.

Wagner, L.E., Ambe, N.M., Ding, D., 1994. Estimating a Proctor density curve from intrinsic soil properties. Trans. Am. Soc. Agric. Eng. 37, 1121–1125.

Walkley, A., 1947. A critical examination of a rapid method for determining organic carbon in soils. Effect of variations in digestion conditions and of inorganic soil constituents. Soil Sci. 63, 251–263.

Wulfsohn, D., Adams, B.A., Fredlund, D.G., 1998. Triaxial testing of unsaturated agricultural soils. J. Agric. Eng. Res. 69, 317–330.

Zhang, H., Hartge, K.H., Ringe, H., 1997. Effectiveness of organic matter incorporation in reducing soil compactability. Soil Sci. Soc. Am. J. 61, 239–245.