SOIL PHYSICS

Calculating the Effect of Soil Organic Matter Concentration on Soil Bulk Density

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Soil bulk density (ρ_b) is required to estimate, evaluate, and calculate many physical soil properties and processes and is essential to convert data from weight-based to volume- and area-related data. One of the dominating factors changing ρ_b is the soil's organic matter (SOM) concentration that alters the soil's compressibility; ρ_b is an important soil structure attribute. Currently, no parameter for characterizing soil compactness giving directly comparable values for all soils is available. Therefore, our aim was to develop a general approach to calculate the effect of SOM concentration on ρ_b that would be universally valid for soils different in their genesis, compaction, and type of land use. To describe the effect of SOM on ρ_b mathematically, we used a nonlinear regression model that was parameterized and validated using published data from experiments where SOM concentration was the main ρ_b–affecting factor (long-term fertilization and proctor experiments, wetlands, reclaimed soils, and volcanic soils). To obtain a standardized parameter describing the present compaction status of a site, we introduced the standardized bulk density $s\rho_b$. Mathematically, $s\rho_b$ is the intercept parameter of the used nonlinear regression model, and ranged between 0.7 and 2.1 Mg m^{-3} and was very simple to estimate. Another distinct advantage of this novel concept is that only one representative pair of ρ_b and SOM has to be known to calculate $s\rho_b$ as well as the bulk densities corresponding to other SOM concentrations measured on the site. This concept might also be helpful for identifying similar universal approaches to standardize the effect of other ρ_b affecting parameters (e.g., texture, soil depth, tillage regime), however, reassessed from the SOM effect.

Abbreviations: OM, organic matter; ρ_b, bulk density; RMSE, root-mean-square error; RC, relative compaction; SD, standard deviation; SE, standard error; SOC, soil organic carbon; SOM, soil organic matter; $s\rho_b$, standardized bulk density.

Soil bulk density is defined as the mass of an oven-dry sample of undisturbed soil per unit bulk (wet) volume (ISSS Working Group, 1998). This parameter is required to estimate, evaluate, and calculate many physical soil properties, such as porosity, water retention, heat capacity, and compressibility. Finally, ρ_b is the essential base to convert data from weight-based to volume- and area-related data. Consequently, much work has been done to calculate the effect of various influencing factors on ρ_b. Whereas soil texture (Rawls, 1982; Gosselink et al., 1984; Tamminen and Starr, 1994; Ball et al., 2000), water content (Mosaddeghi et al., 2000; McNabb et al., 2001), tillage (Dao, 1996; Thomas et al., 1996; Franzluebbers et al., 2000), traffic (von Ow et al., 1996; McNabb et al., 2001; Krzic et al., 2004), cropping system (McLay et al., 1992; Quiroga et al., 1999; Shaver et al., 2002), and soil depth (Gosselink et al., 1984; Tamminen and Starr, 1994) affect ρ_b, one of the most dominating factors changing ρ_b is the SOM concentration (Gosselink et al., 1984; Heuscher et al., 2005). A simple way to calculate the effect of SOM concentration or soil organic carbon (SOC) concentration (SOM = 1.724SOC) on ρ_b is by using the empirical model as given in Eq. [1a] and [1b]. Although it is well known that the conversion factor between SOC and SOM isn't constant, we used the standard factor of 1.724 because a significant relationship between the SOM concentration of soil and the C concentration of SOM is not known from the literature. Also Rühlmann et al. (2006), who calculated the particle density of soils covering the whole range from organic matter-free mineral substrates to organic soils, found that the SOM concentration of soil and the C concentration of SOM were noncorrelated.

$$\rho_b = a_{SOM} + b_{SOM} SOM \qquad [1a]$$

$$\rho_b = a_{SOC} + b_{SOC} SOC \qquad [1b]$$

where ρ_b is given in Mg m^{-3}, SOM and SOC in g kg^{-1}, and a_{SOM}, b_{SOM}, a_{SOC}, and b_{SOC} are coefficients.

Whereas the Intercept a corresponds to the theoretical bulk density of the organic-matter-free mineral soil, the Slope b is the expression of the SOM effect on ρ_b. If soils highly different in SOM concentration are included in the analysis, the relationship between ρ_b and SOM concentration becomes

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curvilinear (Gosselink et al., 1984; Tamminen and Starr, 1994; Bockheim et al., 2003). Therefore, it is clear that the different Slopes b of Eq. [1] (–0.0007 to –0.0133 on SOM basis or –0.001 to –0.023 on SOC basis) given in the studies of Asmus et al. (1987), Körschens (1988), Ekwue (1990), Soane (1990), Pfefferkorn and Körschens (1991), Kahle et al. (1993), Thomas et al. (1996), Zhang et al. (1997), Quiroga et al. (1999), Aragón et al. (2000), Ball et al. (2000), Diaz-Zorita and Grosso (2000), and Calhoun et al. (2001) may be caused mainly by different SOM ranges of the single data sets. The respective Intercepts a ranged between 1.34 and 2.07, and relating all given intercepts to the corresponding slopes showed a positive correlation. However, this relation was only weak (R^2 = 0.37, n = 44, data not shown).

Besides the general high temporal and spatial variability of the parameters SOC and ρ_b (Körschens, 1988), our assumption was that the weakness of this relation may result from two facts: (i) a linear model as shown in Eq. [1] is increasingly not able to describe optimally curvilinear relationships if the range of the independent variable (SOM or SOC) of the given data set increases; and (ii) if the range of the independent variable (SOM or SOC) of the given data set becomes relatively narrow the confidence interval of the estimated parameters (slope and intercept) increases and consequently, the estimate becomes uncertain. Therefore, we used a nonlinear model to describe the effect of SOM on ρ_b.

However, a number of other factors affects the soil's bulk density as mentioned above. Thus, soils very similar in SOM concentration may have extreme different bulk densities. Finally, ρ_b is an important soil structure and quality attribute, and according to Håkansson and Lipiec (2000), there is a need to identify a parameter for its characterization that gives directly comparable values for all soils. Therefore, our aim was to develop a general approach to calculate the effect of SOM concentration on ρ_b that is universally valid for soils different in their genesis, type of land use, and precompaction stress.

MATERIAL AND METHODS

Regression Model to Calculate the Effect of Soil Organic Matter Concentration on Soil Bulk Density

We used the regression model given in Eq. [2] to calculate the effect of SOC concentration on soil bulk density because the relationship between these basic soil properties is nonlinear as mentioned above.

$$\rho_b = a\exp(-bSOC) \quad [2]$$

where ρ_b is given in Mg m^{-3} and SOC in g kg^{-1}.

Here, the intercept term a represents the theoretical bulk density of the organic-matter-free mineral soil. The slope term exp(–bSOC) is the expression for the nonlinear relation between SOC and ρ_b. Our assumption was that, similar to the intercept–slope relation as mentioned regarding Eq. [1], the Coefficients a and b of this nonlinear approach (Eq. [2]) will also be interrelated. To test this assumption, we used Eq. [3].

$$a = c + db \quad [3]$$

where the Coefficient c represents the value of the maximum theoretical bulk density of the organic-matter-free mineral soil.

Inserting Eq. [3] into Eq. [2] produces Eq. [4] which has three coefficients:

$$\rho_b = (c + db)\exp(-bSOC) \quad [4]$$

where ρ_b is given in Mg m^{-3} and SOC in g kg^{-1}.

To fit these three coefficients to measured values, we used the Solver Add-In module of Microsoft Excel 2000 by minimizing the root-mean-square error (RMSE; Eq. [5]) between the calculated ρ_b [$\rho_{b(c)}$] and measured ρ_b [$\rho_{b(m)}$]:

$$\mathrm{RMSE} = \sqrt{\frac{1}{n}\sum_{i=1}^{N}[\rho_{b(c)_i} - \rho_{b(m)_i}]^2} \quad [5]$$

where RMSE is given in Mg m^{-3} and N is the number of data points.

For statistical analyses, STATISTICA 6.1 was used.

Data Sets

To analyze the relationship between SOC and ρ_b, we used published data of soils covering a wide range of SOC concentration (2.6–574.2 g kg^{-1}) as well as ρ_b (0.03–2.0 Mg m^{-3}), (Table 1).

We divided the data in five main groups: arable, proctor, reclaimed, volcanic, and wetland soils. The data of arable soils were derived from long-term fertilization experiments. The advantage of using such data is that according to the *ceteris paribus* principle applied in long-term experiments, only a limited number of factors—the different fertilization treatments—were changed, whereas other ρ_b–affecting factors (e.g., crop rotation and tillage regime) remained constant. The soils compacted by a proctor test were called 'proctor soils'. We included this group because it should exemplarily represent the upper border of the possible range of soil's ρ_b. Therefore, we did not consider that the detailed experimental conditions (applied stress, water control) of the proctor experiments as described by Thomas et al. (1996), Smith et al. (1997), Aragón et al. (2000), and Krzic et al. (2004) differed. The group of reclaimed soils comprises soils derived from open cast mining. Usually, these soils are also relatively compacted but in a significantly lesser extent compared with proctor soils. In contrast to the proctor and reclaimed soils, volcanic soils and wetland soils were exemplarily used to represent the lower border of the possible range of soil's ρ_b.

To extract the exclusive effect of SOC on ρ_b, the soil's degree of compaction affected by factors such as vegetation, management system, traffic, soil depth, precompaction stress, and time of sampling should be quite comparable within a given dataset. Therefore, we subdivided the data of each single literature source according to sampling area, sampling depth and sampling time, respectively, if this differentiation was accounted for (Table 1).

A separate data set was derived from 115 soil samples of Ap horizons from 17 German long-term experiments (Brandenburg, Saxony, Saxony Anhalt, and Thuringia) having highly contrasting soil textures (Table 2).

These data were used to analyze the effect of soil texture on ρ_b. To exclude site-typical effects of previous crop and tillage techniques on ρ_b, the soil samples were uniformly compacted before measuring ρ_b (Körschens and Waldschmidt, 1995). The soil samples were taken by a soil corer, dried at 105°C, and sieved to 2 mm. Following, soil material was filled into an apparatus (six replications) were it was compacted into a 0.1 L core cutter by 100 fall cycles with 0.1 m height of fall. Finally, the weight of the 0.1 L soil material was estimated. The land use in all these experiments was arable cropping. Different long-term application rates of nitrogen fertilizer and farmyard manure has led to the varying SOC concentrations in the Ap horizons of these sites as reported by Körschens (1997).

Table 1. Characteristics of sites (Parameterization data set).

Data group†/ Source Nr.‡	Location	Site attribute	Soil organic carbon content, g kg^{-1} Mean ± SD	Min	Max	Bulk density, Mg m^{-3} Mean ± SD	Min	Max	N¶
ARAB/1	Denmark, Ascov	Arable land	11.9 ± 1.3	10.7	13.2	1.60 ± 0.03	1.57	1.64	3
			5.0 ± 1.0	4.4	6.1	1.61 ± 0.04	1.57	1.65	3
ARAB/2	Germany, Bad Lauchstädt	Arable land	32.2 ± 9.8	18.8	48.4	1.45 ± 0.08	1.31	1.56	10
ARAB/3	Germany, Dikopshof	Arable land	12.1 ± 0.6	11.2	12.8	1.50 ± 0.03	1.46	1.53	12
ARAB/4	Germany, Gross Kreutz	Arable land	6.8 ± 1.0	5.4	8.0	1.58 ± 0.03	1.54	1.62	5
ARAB/5	Germany, Hohenheim	Arable land	10.3 ± 1.1	8.8	11.9	1.48 ± 0.07	1.39	1.60	12
ARAB/6	India, Jabalpur	Arable land	5.5 ± 0.7	4.2	6.4	1.66 ± 0.04	1.58	1.72	8
ARAB/7	India, Ludhiana	Arable land	5.3 ± 0.8	4.0	6.2	1.64 ± 0.03	1.59	1.68	8
			13.6 ± 2.6	11.2	17.8	1.32 ± 0.02	1.28	1.34	5
ARAB/8	India, New Dehli	Arable land	5.5 ± 0.8	4.3	6.9	1.44 ± 0.03	1.39	1.47	11
ARAB/9	India, New Dehli	Arable land	10.5 ± 2.6	8.3	15.2	1.60 ± 0.06	1.52	1.67	7
			7.7 ± 1.1	6.5	9.9	1.66 ± 0.02	1.63	1.70	7
			4.7 ± 0.4	4.2	5.2	1.74 ± 0.04	1.67	1.78	7
ARAB/10	Sweden, Järna	Arable land	26.1 ± 1.2	24.5	28.1	1.21 ± 0.04	1.16	1.25	8
			26.3 ± 1.9	24.1	29.5	1.11 ± 0.03	1.08	1.15	8
ARAB/11	Sweden, Ultuna	Arable land	20.1 ± 7.6	10.4	35.8	1.29 ± 0.10	1.11	1.43	14
			17.0 ± 3.6	12.1	23.7	1.31 ± 0.06	1.19	1.41	14
ARAB/12	UK, Rothamsted	Grass land	19.0 ± 11.3	7.1	32.7	1.34 ± 0.17	1.12	1.50	5
ARAB/13	USA, Morrow Plots	Arable land	16.6 ± 3.1	13.2	19.4	1.37 ± 0.06	1.31	1.45	4
ARAB/14	USA, Sandborn Field	Arable land	13.7 ± 4.6	5.2	23.4	1.25 ± 0.10	1.13	1.45	12
PROC/15	Argentine	Arable land	24.7 ± 14.9	2.7	62.0	1.46 ± 0.12	1.17	1.74	30
PROC/16	Canada	Forest	23.1 ± 12.0	6.2	46.0	1.46 ± 0.18	1.07	1.75	25
PROC/17	South Africa	Forest	20.1 ± 14.0	2.6	57.7	1.68 ± 0.21	1.21	2.00	35
PROC/18	USA	Arable land	18.5 ± 6.5	8.2	34.7	1.59 ± 0.10	1.39	1.82	36
REC/19	Canada	Artificially-eroded	42.1 ± 10.9	17.3	55.1	1.16 ± 0.09	1.05	1.37	12
			23.6 ± 13.7	8.1	42.9	1.40 ± 0.12	1.21	1.59	12
			27.3 ± 12.1	10.1	44.9	1.20 ± 0.14	0.99	1.43	12
			10.6 ± 4.4	6.7	18.5	1.48 ± 0.05	1.40	1.54	12
REC/20	USA	Minelands chronosequence	12.8 ± 7.7	3.7	24.1	1.61 ± 0.05	1.53	1.67	6
			8.7 ± 4.5	3.2	16.2	1.58 ± 0.10	1.42	1.67	8
			15.1 ± 9.4	5.2	27.3	1.37 ± 0.20	1.18	1.59	6
			5.6 ± 3.2	2.9	11.5	1.49 ± 0.15	1.24	1.64	6
VOL/21	Alaska	Volcanic ash deposits	65.1 ± 46.3	9.0	138.0	0.62 ± 0.20	0.33	0.80	7
VOL/22	Chile	Volcanic ash deposits	91.8 ± 26.7	51.0	139.0	0.49 ± 0.07	0.42	0.60	9
VOL/23	Chile	Volcanic ash deposits	45.1 ± 23.6	17.8	59.1	1.00 ± 0.21	0.86	1.24	3
VOL/24	Costa Rica	Inceptisol, Ultisol	22.5 ± 6.6	15.0	31.0	0.77 ± 0.04	0.72	0.81	4
VOL/25	Hawaii	Tephra deposits/lava flow	75.4 ± 47.4	40.6	145.0	0.69 ± 0.24	0.44	1.00	4
VOL/26	Hawaii	Volcanic ash deposits	206.3 ± 43.7	158.0	280.0	0.41 ± 0.04	0.36	0.48	6
VOL/27	Italy	Tephra-derived soils	65.0 ± 60.2	14.0	184.0	0.74 ± 0.17	0.48	0.99	7
VOL/28	New Zeeland	Volcanic deposits	35.9 ± 19.5	10.2	59.2	0.82 ± 0.24	0.55	1.10	5
WET/29	Alaska	Peat land-Forest	349.1 ± 173.7	5.0	520.0	0.29 ± 0.39	0.03	1.40	27
WET/30	USA	Peat land-Forest	505.8 ± 72.4	278.4	574.2	0.14 ± 0.05	0.03	0.25	46
WET/31	USA	Relict deltaic march	204.5 ± 78.6	116.0	301.6	0.18 ± 0.09	0.08	0.29	8
WET/32	USA	Constructed salt marsh	7.9 ± 4.0	4.1	13.8	1.18 ± 0.19	1.00	1.39	5
WET/33	USA	Freshwater created marsh	55.6 ± 7.9	40.5	70.8	0.74 ± 0.17	0.58	1.16	13
WET/34	USA	Freshwater marsh	110.3 ± 42.8	63.6	188.7	0.28 ± 0.08	0.13	0.38	10
WET/35	USA	Salt marsh	68.0 ± 47.2	16.2	163.6	0.66 ± 0.30	0.23	1.14	10
WET/36	USA	Salt marsh	102.7 ± 57.1	38.3	241.9	0.36 ± 0.14	0.13	0.57	10
WET/37	USA	Sawgrass march	425.8 ± 26.1	380.0	455.0	0.06 ± 0.01	0.05	0.09	10
			445.1 ± 33.6	385.0	478.0	0.09 ± 0.01	0.06	0.10	10
WET/38	USA	Sawgrass march	435.8 ± 17.3	400.0	455.0	0.06 ± 0.01	0.05	0.07	8
			453.1 ± 29.3	395.0	478.0	0.09 ± 0.01	0.07	0.10	8
WET/39	USA	Sawgrass march	413.8 ± 18.3	378.0	431.0	0.07 ± 0.01	0.05	0.09	8
			451.8 ± 16.4	420.0	473.0	0.09 ± 0.01	0.06	0.11	8
WET/40	USA	Sedge meadow	116.6 ± 91.2	31.0	357.3	0.67 ± 0.22	0.27	1.03	12
ARAB§			14.7 ± 9.0	4.0	48.4	1.42 ± 0.19	1.08	1.78	171
PROC§			21.3 ± 12.3	2.6	62.0	1.56 ± 0.18	1.07	2.00	126
REC§			20.4 ± 15.1	2.9	55.1	1.38 ± 0.19	0.99	1.67	74
VOL§			81.8 ± 65.0	9.0	280.0	0.65 ± 0.22	0.33	1.24	45
WET§			312.5 ± 192.8	4.1	574.2	0.29 ± 0.32	0.03	1.40	193

† ARAB = arable soils (long-term experiments), PROC = proctor soil, WET = wetland soil, REC = reclaimed soils of open cast mining, VOL = volcanic soil.

‡ 1) Schjønning et al., 1994; 2) Kahle et al., 1992; 3) Dhein and Mertens, 1955; 4) Asmus et al., 1987; 5) Michael and Djurabi, 1964; 6) Singh et al., 2007; 7) Hati et al., 2007; 8) Masto et al., 2007; 9) Rudrappa et al., 2006; 10) Pettersson et al., 1992; 11) Kirchmann et al., 1994; 12) Ekwue, 1990; 13) Odell et al., 1984; 14) Anderson et al., 1990; 15) Aragón et al., 2000; 16) Krzic et al., 2004; 17) Smith et al., 1997; 18) Thomas et al., 1996; 19) Izaurralde et al., 1998; 20) Akala and Lal, 2001; 21) Hart, 1988; 22) Huygens et al., 2005; 23) Antilen et al., 2003; 24) Veldkamp and O'Brien, 2000; 25) Kurtz et al., 2001; 26) Scowcroft et al., 2004; 27) Vacca et al., 2003; 28) Tomer et al., 1999; 29) Hartshorn et al., 2003; 30) D'Amore and Lynn, 2002; 31) Hatton et al., 1983; 32) Craft et al., 1999; 33) Harter and Mitsch, 2003; 34) Morse et al., 2004; 35) Pennings et al., 2002; 36) McKee et al., 2006; 37) White and Reddy, 1999; 38) White and Reddy, 2000; 39) White and Reddy, 2001; 40) Werner and Zedler, 2002.

§ Soil group related data.

¶ N = number of sampled treatments (ARAB) or number of sampled locations per site (PROC, REC, VOL, WET), respectively.

Table 2. Characteristics of sites (Texture data set).

	Soil organic carbon content, g kg^{-1}			Bulk density, Mg m^{-3}						
	Mean ± SD	Minimum	Maximum	Mean ± SD	Minimum	Maximum	N†	Clay‡	Silt§	Sand¶
								g kg^{-1}		
Bad Lauchstädt	19.3 ± 4.4	9.5	24.0	1.43 ± 0.04	1.38	1.50	9	193	694	113
Bad Salzungen	7.7 ± 0.6	7.2	8.3	1.52 ± 0.02	1.50	1.54	3	98	225	683
Bernburg	15.3 ± 0.6	14.6	15.8	1.50 ± 0.02	1.49	1.52	3	149	644	206
Dewitz	8.1 ± 1.1	6.7	9.1	1.57 ± 0.02	1.55	1.59	6	89	334	578
Etzdorf	22.6 ± 0.6	21.9	23.5	1.38 ± 0.01	1.37	1.39	8	211	758	31
Gross-Kreutz	6.1 ± 1.7	4.7	9.5	1.69 ± 0.04	1.63	1.73	7	43	162	792
Halle	16.8 ± 1.5	12.6	18.6	1.52 ± 0.03	1.45	1.56	13	117	315	569
Lauterbach	37.4 ± 2.8	34.2	39.7	1.26 ± 0.02	1.24	1.27	3	149	512	339
Liebertwolkwitz	12.4 ± 1.9	10.1	15.5	1.52 ± 0.03	1.49	1.58	6	102	488	410
Methau	14.7 ± 1.0	14.1	15.9	1.40 ± 0.01	1.39	1.40	3	161	725	115
Mösslitz	11.7 ± 0.3	11.3	11.9	1.49 ± 0.01	1.48	1.51	4	184	645	173
Müncheberg	6.0 ± 0.5	5.2	6.6	1.71 ± 0.02	1.68	1.74	8	31	217	753
Noitsch	10.8 ± 1.7	8.6	13.7	1.70 ± 0.05	1.59	1.81	16	71	248	681
Seehausen	10.2 ± 0.5	9.6	10.9	1.56 ± 0.02	1.53	1.58	7	81	450	469
Spröda	9.9 ± 0.8	8.7	11.3	1.64 ± 0.02	1.60	1.68	13	62	275	663
Straussfurt	31.2 ± 1.3	29.8	32.2	1.38 ± 0.02	1.35	1.40	3	186	774	40
Thyrow	4.8 ± 1.5	3.7	6.5	1.73 ± 0.02	1.71	1.75	3	27	142	831

† N = number of sampled treatments.
‡ clay: <2 μm.
§ silt: 2–63 μm.
¶ sand: 63–2000 μm.

RESULTS

Parameterization of the Model

The data listed in Table 1 were used to fit the Parameters *b*, *c*, and *d* of the regression model given in Eq. [4]. The data covered an extremely wide range of both SOC concentration (2.6–574.2 g kg^{-1}) and ρ_b (0.03–2.00 Mg m^{-3}), (Fig. 1a).

We presumed (i) that the fitted values of the Parameters *c* and *d* were independent on the site and (ii) that the value of Parameter *c* was very similar to that of the particle density of the mineral soil particles. Therefore, (i) we assumed that *c* and *d* should have a general validity for all sites and (ii) we set Parameter *c* to 2.684 (Mg m^{-3}) estimated by Rühlmann et al. (2006) as mean density of mineral soil particles appropriate for 170 soils different in origin, genesis, texture, and land use. In the following step, all data were simultaneously used for fitting the Parameters *d* and *b*. Whereas Parameter *d* was fitted as mean value valid for all 59 data sets (Table 1), the slope Coefficient *b* was separately fitted for each of the five main soils groups (arable, proctor, reclaimed, volcanic, and wetland soils). As a result of this procedure, the regression model reads as follows (Eq. [6]):

$$\rho_b = (2.684 - 140.943b)\exp(-bSOC) \qquad [6]$$

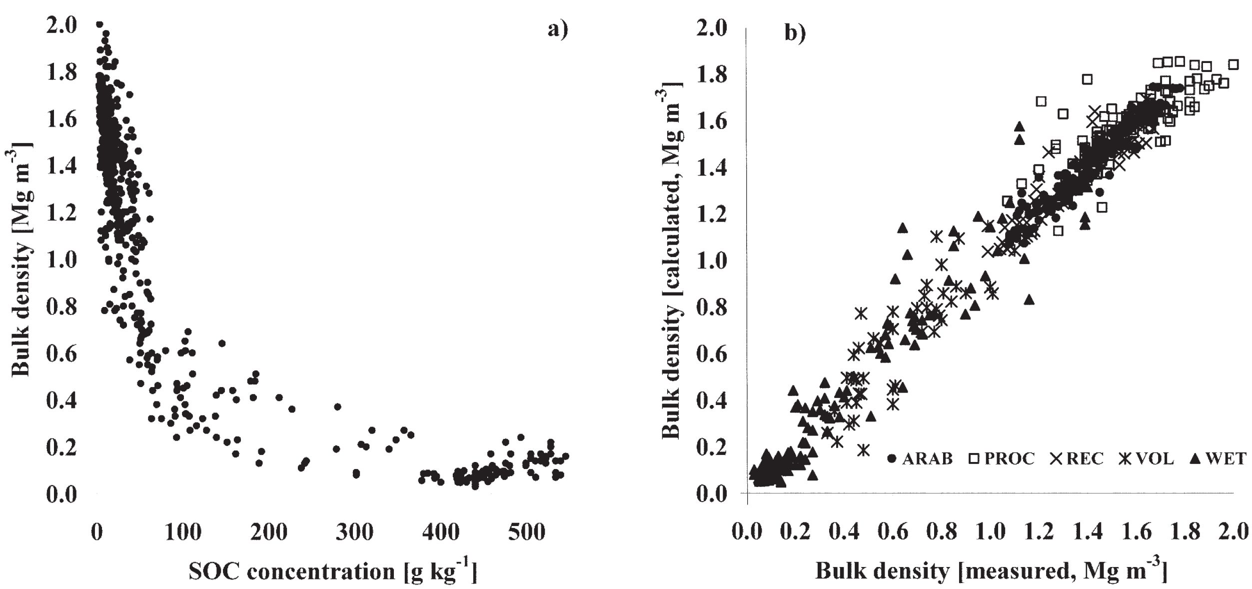

Fig. 1. Bulk density of soils as affected by (a) soil organic C concentration and (b) measured vs. calculated bulk density. Bulk density was calculated (b) by fitting Coefficient *b* separately for each soil group: arable (ARAB), proctor (PROC), reclaimed (REC), volcanic (VOL), and wetland soils (WET)

Table 3. Correlation matrix of the fitted Parameters *d* and *b*. (Parameter *b* was separately fitted for the five soil groups arable, proctor, reclaimed, volcanic, and wetland soils, respectively).

	d	b_{ARAB}	b_{PROC}	b_{REC}	b_{VOL}	b_{WET}
d	1.00	0.98	0.96	0.95	0.91	0.93
b_{ARAB}		1.00	0.94	0.93	0.89	0.91
b_{PROC}			1.00	0.92	0.87	0.89
b_{REC}				1.00	0.86	0.89
b_{VOL}					1.00	0.84
b_{WET}						1.00

where ρ_b is given in Mg m^{-3} and SOC in g kg^{-1}.

The fitted value of the Coefficient *d* was 140.943 (± 7.226) and that of the Coefficient *b* were 0.008 (± 3.5 10^{-4}), 0.006 (± 2.7 10^{-4}), 0.008 (± 3.4 10^{-4}), 0.010 (± 4.2 10^{-4}), and 0.008 (± 3.8 10^{-4}), (standard error in parentheses) for arable, proctor, reclaimed, volcanic, and wetland soils, respectively. All parameters were significant for a *p*-level < 10^{-3}. The regression function of the relationship between $\rho_{b(c)}$ and $\rho_{b(m)}$ (N = 609, Fig. 1b) was y = 0.900 (0.014) x + 0.080 (0.017), (SE in parenthesis); the estimates of R^2 and the overall RMSE (Mg m^{-3}) were 0.872 and 0.215, respectively. The correlation matrix of the fitted Parameters *d* and *b* is given in Table 3.

Since we estimated a high RMSE, we wanted to improve the quality of the performance of the model (Eq. [6]). To do this we calculated a site-specific value of the Coefficient *b* based on one representative measured pair of ρ_b and SOC concentration. We inserted this site-specific value of the Coefficient *b* in Eq. [6] and calculated then the ρ_b values corresponding to the single measured SOC concentrations. Because we utilized published data in this study, we could not use for example, a mixed soil sample to create a site-representative measured pair of ρ_b and SOC. Furthermore, it was also inappropriate to apply the mean values of ρ_b and SOC concentration, respectively, of a given data set for this purpose because the relationship between ρ_b and SOC concentration was identified to be nonlinear. Therefore, we first employed one arbitrarily selected measured pair of ρ_b and SOC concentration of a given data set to estimate the Coefficient *b*. Then, we calculated the ρ_b values corresponding to the remaining measured SOC values. This procedure was separately repeated for each data set whenever all measured data pairs acted once as predictor to estimate the Coefficient *b*. Consequently, we calculated *N*-1 values of ρ_b corresponding to each measured SOC value; here, *N* is the number of data pairs within a certain data set. Finally, all mean values of ρ_b calculated in this way and in each case corresponding to a certain measured SOC value were plotted against measured ρ_b values (Fig. 2).

Compared with the results shown in Fig. 1b, the performance of the model (Eq. [6]) was clearly improved by substituting the soil group related values of the Coefficient *b* for site-typical values. The regression function of the relationship between $\rho_{b(c)}$ and $\rho_{b(m)}$ (N = 609, Fig. 2) was y = 0.983 (0.006)x + 0.024 (0.007), (SE in parenthesis); R^2 for was raised from 0.872 to 0.977 and the overall RMSE was decreased from 0.215 to 0.09 Mg m^{-3}.

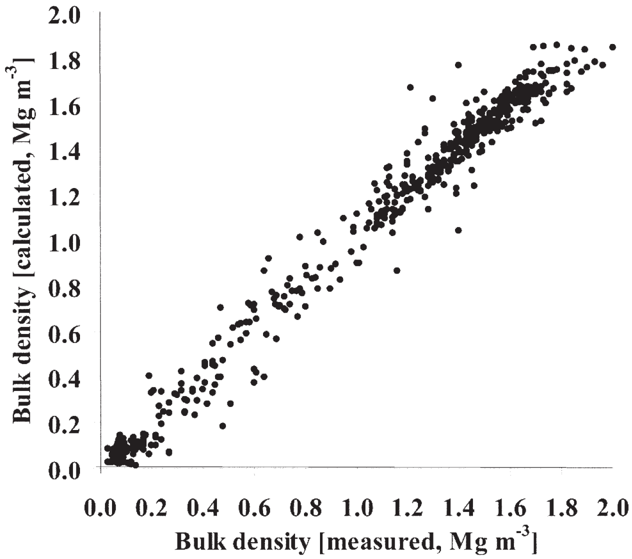

Fig. 2. Measured vs. calculated bulk density. Bulk density was calculated by fitting Coefficient *b* separately for each site.

The Concept of Standardized Bulk Density

The present compaction status of a certain soil is originated by a complex of factors as mentioned above. However, currently no parameter is available for characterizing soil compactness giving directly comparable values for all soils. The idea was to use the intercept term of Eq. [6] for this purpose. Because the intercept term is mathematically reassessed from the SOC effect, we called it the standardized bulk density $s\rho_b$ (Eq. [7]).

$$s\rho_b = 2.684\text{-}140.943b \qquad [7]$$

where ρ_b is given in Mg m^{-3}.

To show the difference of analyzing data based on ρ_b and on $s\rho_b$, we compared the corresponding means, standard deviations as well as maxima and minima of the five soil groups arable, proctor, reclaimed, volcanic, and wetland soils, respectively (Fig. 3a and 3b).

Whereas the soil group means of ρ_b differed significantly and corresponded to the soil group means of SOC concentration as given in Table 1, the range of the $s\rho_b$ soil group means became narrower. The highest $s\rho_b$ mean was estimated for the proctor soils (1.78 Mg m^{-3}); arable, reclaimed and wetland soils were characterized by a mean $s\rho_b$ around 1.60 Mg m^{-3} and volcanic soils showed the lowest mean $s\rho_b$ (1.28 Mg m^{-3}). In contrast to the wide range of the calculated ρ_b maxima (1.24–2.00 Mg m^{-3}, Fig. 3a), the $s\rho_b$ maxima of the five soil groups varied merely between 1.80 and 2.10 Mg m^{-3} (Fig. 3b) indicating a very similar upper border of soil compactness using the $s\rho_b$ concept.

The only free model Parameter *b* of the model (Eq. [6]) affects both the slope term and the intercept term of the function. We varied the Parameter *b* between 0.004 (upper bound) and 0.014 (lower bond) and created a nomogram to determine $s\rho_b$ corresponding to measured pairs of $s\rho_b$ and SOC concentration (Fig. 4).

Here, we assumed three soils identical in $s\rho_b$ (1.2 Mg m^{-3}) but different in SOC concentration (10–140 g kg^{-1}). The three asterisks, symbolizing the three data pairs (dotted lines),

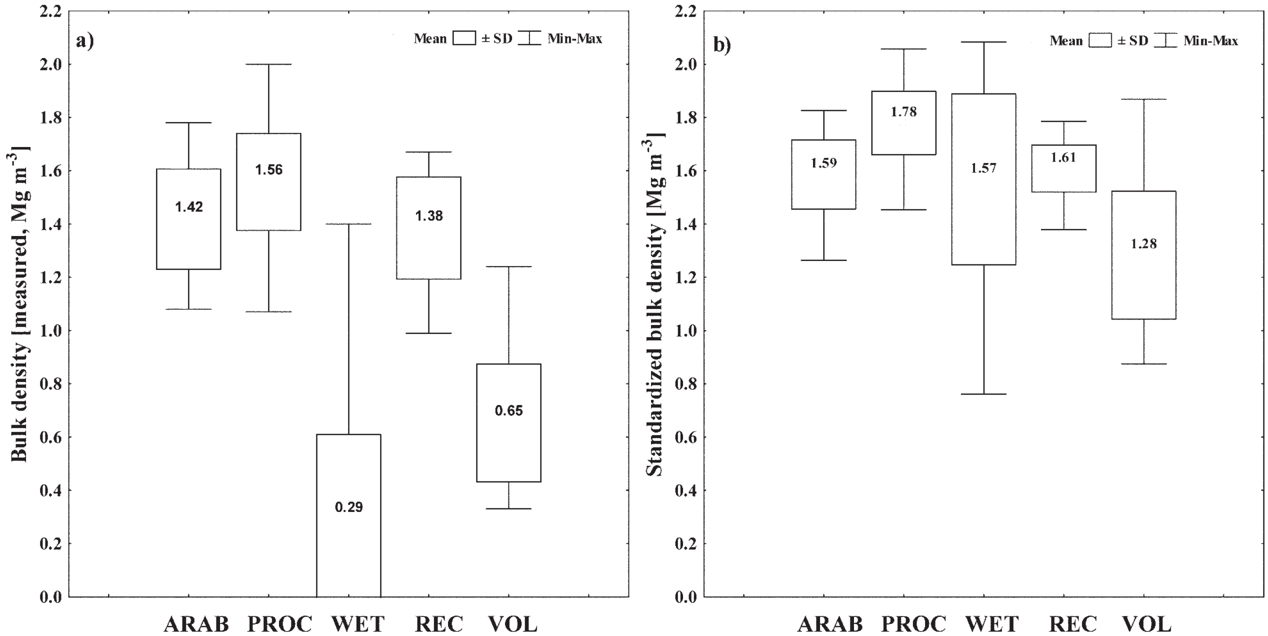

Fig. 3. Means, standard deviations and min-max values of each soil group: arable (ARAB, *N* = 163), proctor (PROC, *N* = 126), reclaimed (REC, *N* = 74), volcanic (VOL, *N* = 45), and wetland soils (WET, *N* = 193), respectively. Based on (a) bulk density and on (b) standardized bulk density.

were positioned on the curves which symbolize exemplarily the trend of the SOC affected change of ρ_b, each on a different level of soil compactness. For direct reading of the sρ_b values (1.3, 1.7, and 2.1 Mg m^{-3}), we have only to follow these curves to the corresponding intercepts as marked by dots.

Additionally, the nomogram provides information on the ratio $\Delta\rho_b$ /Δ SOC (Mg m^{-3}/g kg^{-1}). This ratio ranged in the interval of 0 < $\Delta\rho_b$ /Δ SOC < 0.012; the maximum effect of ΔSOC on $\Delta\rho_b$ was obtained for soils with SOC < 45 g kg^{-1} and a range of ρ_b between 0.6 and 2.1 Mg m^{-3}.

Effect of Soil Texture on ρ_b

Compared with the data used to parameterize the model (Table 1), the data employed to estimate the effect of soil texture on ρ_b were characterized by a relatively narrow range of SOM concentration and ρ_b (Table 2, Fig. 5).

Therefore, we expected a good fit of the model as shown in Fig. 2. The fitting procedure was the same as mentioned above—the only free model Parameter *b* was used to fit the model to the data. The Parameter *b* ranged between 0.006 and 0.008. The calculated regression function between $\rho_{b(c)}$ and $\rho_{b(m)}$ (Fig. 5) was y = 0.967 (0.017) x + 0.052 (0.026), (SE in parenthesis); with N = 115 and R^2 = 0.967. The overall mean RMSE estimated for the 17 data sets was 0.023 Mg m^{-3}. To estimate the effect of soil texture on the compactness of these soils, we related the mean ρ_b of each site to the corresponding clay concentration given in Table 2. We estimated a clear negative correlation between these two soil properties (Fig. 6a): y = 1.757 (0.038) x + 0.002 (3 10^{-4}), (SE in parenthesis); R^2 was 0.752.

However, a strong relationship was also observed between the soil texture and the SOC concentration (Körschens, 1980; Rühlmann, 1999). Therefore, the given relationship (Fig. 6a) may not be caused exclusively by soil texture effects but could be additionally affected by SOM concentration. To test this, we calculated the sρ_b values as described in Eq. [7] and related these to the corresponding clay concentrations (Fig. 6b). We estimated the range of sρ_b to be between 1.57 and 1.82 Mg m^{-3}. Similar to the relationship sρ_b vs. clay (Fig. 6a), we found a negative correlation between sρ_b and the clay concentration: y = 1.783 (0.027) x + 0.001 (2 10^{-4}), (SE in parenthesis); R^2 was 0.498. However, the slope of the relation between sρ_b and the clay concentration was only 50% of that between ρ_b and clay concentration.

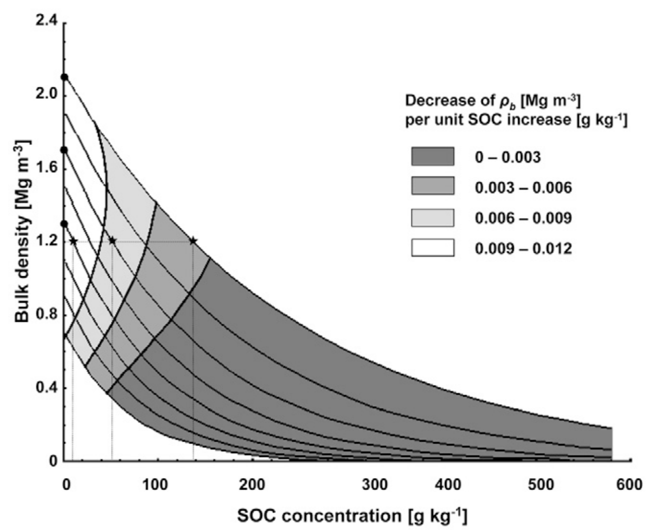

Fig. 4. Nomogram to determine the effect of soil organic C concentration on bulk density as generated using Eq. [6]. The asterisks, symbolizing three data pairs (dotted lines), were positioned on three of the eight curves which symbolize exemplarily the trend of the SOC affected change of ρ_b, each on a different level of soil compactness. For direct reading of corresponding sρ_b values (1.3, 1.7, and 2.1 Mg m^{-3}), follow these curves to the corresponding intercepts as marked by dots. The hatched areas provide information of the ratio $\Delta\rho_b$ /Δ SOC. The values for the Parameter *b* (Eq. [6]) corresponding to the upper bound (sρ_b = 2.1 Mg m^{-3}) and the lower bound (sρ_b = 0.7 Mg m^{-3}) are 0.004 and 0.014, respectively.

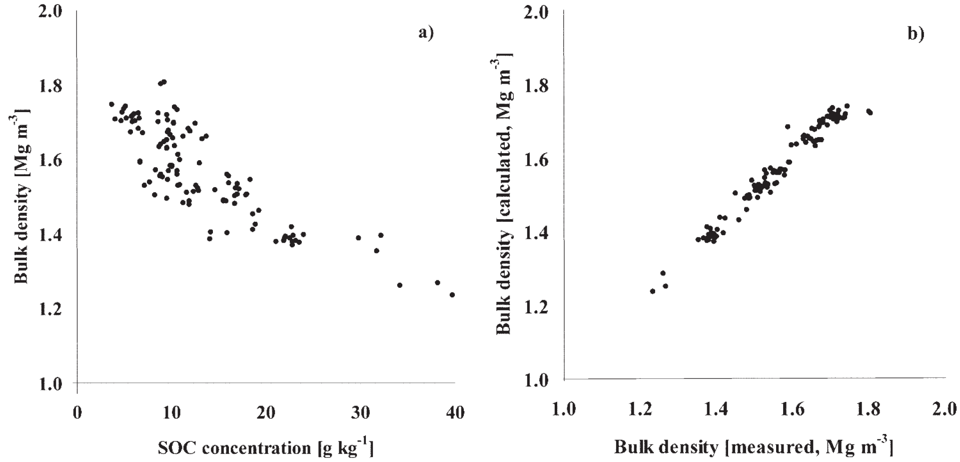

Fig. 5. Bulk density of soils as affected by (a) soil organic C concentration and (b) measured vs. calculated bulk density. (Texture data set).

DISCUSSION AND CONCLUSIONS

Selection of Data

Among a multitude of other factors, SOM concentration is the most dominating factor changing ρ_b (Gosselink et al., 1984; Heuscher et al., 2005). The SOM concentration of soils is a resultant measurement of the relationship between organic matter (OM) input and OM mineralization. Whereas the OM input into agro-ecosystems is relatively simply to manage– directly by applying different amounts of organic amendments and indirectly via changing the amount of crop and harvest residues by fertilizing or irrigating plants—the SOM mineralization processes are affected by a large complex of factors. Unfortunately, the SOM mineralization controlling factors like texture, hydrological site conditions, traffic intensity, and tillage system also have an effect on ρ_b. According to the multiple interrelations within this complex, the relationship ρ_b vs. SOM varies from site to site, and on a given site it may also vary over time. Therefore, it is a moot point to develop always novel site-specific approaches and solutions for this relationship. To make progress in this field, it is necessary to separate the effects of the single factors. However, and especially in the case of the relationship ρ_b vs. SOM, a precondition to separate this effect among diverse other interacting factors is to use appropriate data sets. A key strength of our analyses is that data was derived from long-term fertilization experiments. The advantage of using such data is that according to the *ceteris paribus* principle applied in such long-term experiments, only a limited number of factors—the different fertilization treatments—were changed, whereas the other ρ_b–affecting factors such as kind, depth, and frequency of tillage (similar machinery was employed) as well as cropping system remained constant. This results in a very similar degree of compaction of these soils on a given site. However, one disadvantage is that different fertilization strategies can change the SOM concentration of soils only in a relatively narrow range. In contrast, other data including a wide SOM range are in most cases also affected by differences in soil texture, tillage, or grown crops; these differences may cover the effect of SOM on ρ_b. Furthermore, data derived from soils having a highly contrasting degree of compactness was included in our analyses. This was necessary to determine whether the relationship ρ_b vs. SOM was overlaid by the particular soil compaction status. Consequently, data ranging from maximum compacted “proctor soils” to soils with very loose packing density like tephra-derived or permanently waterlogged soils were included in the analyses. A third aspect of selecting appropriate data was to include data derived from soils with very different mechanisms in building up their specific soil structure including soils with more or less disturbed soil structure such as reclaimed mine soils.

Effect of SOC Concentration on ρ_b

The use of this diverse data material allowed us to successfully parameterize a nonlinear model to describe the relationship ρ_b vs. SOC. The above-mentioned nomogram (Fig. 4) covers approximately the whole possible range of combinations between ρ_b and SOC and was generated using the model as given in Eq. [6]. The eight curves symbolize exemplarily the trend of SOC affected change of ρ_b, each on a different level of soil compactness. The upper curve shows the trend of maximum compacted, “proctor soils,” ranging from ρ_b = 2.1 Mg m^{-3} at minimum SOC concentration to ρ_b = 0.3 Mg m^{-3} at maximum SOC concentration. This upper boarder of ρ_b corresponded very well to the findings of Rawls (1982) and Heuscher et al. (2005) who documented for low SOC concentration mineral soils maximum values of ρ_b between 2.25 and 2.09 Mg m^{-3}, respectively. Regarding organic soils, McLay et al. (1992) analyzed the shrinkage behavior of New Zealand peat soils (≈ 470 g kg^{-1} SOC) depending on changes in water content and estimated a minimum specific

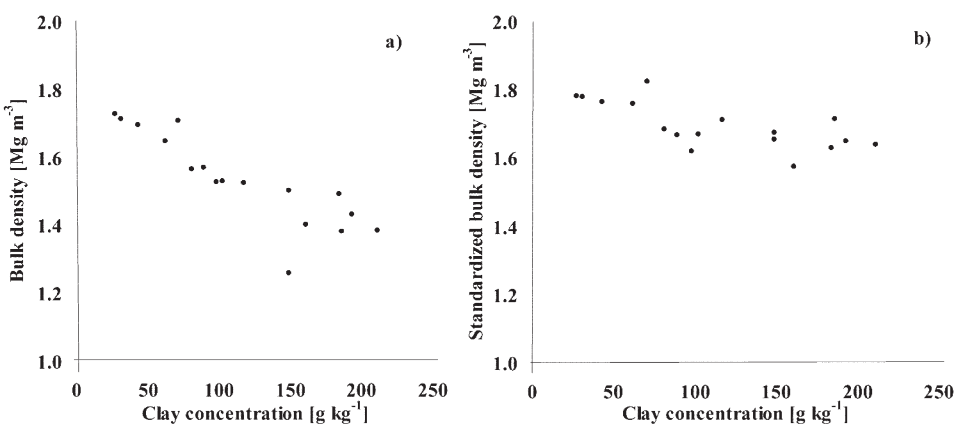

Fig. 6. (a) Bulk density of soils and (b) standardized bulk density as affected by clay concentration. (Texture data set).

volume of 1.67 m^3 Mg^{-1} corresponding to a maximum ρ_b = 0.60 Mg m^{-3}. At the other extreme, the lowest curve represents the minimum values of ρ_b existing under practical conditions as found in tephra-derived (e.g., allophanic andisols) and waterlogged (e.g., marshes) soils as given in Table 1.

To obtain a standardized parameter describing the present compaction status of a given site reassessed from the SOM effect, we introduced $s\rho_b$, the standardized bulk density. Mathematically, $s\rho_b$ is the intercept parameter of the model given in Eq. [6] and ranges between 0.7 and 2.1 Mg m^{-3}. Regarding the calculated $s\rho_b$ maxima (Fig. 3b), we estimated a very similar value (1.80–2.10 Mg m^{-3}) for all five soil groups arable, proctor, reclaimed, volcanic, and wetland soils, respectively. In contrast, the calculated $s\rho_b$ minima (Fig. 3b) were highest for proctor and reclaimed soils and lowest for volcanic and wetland soils, respectively. Additionally, our analyses showed that $s\rho_b$ is sensitive to soil texture (Fig. 5b). In agreement with the observations by Gupta and Larson (1979), Tamminen and Starr (1994), and Håkansson and Lipiec (2000), we found a significant negative relationship between the clay concentration and ρ_b. The possibility to distinguish between the texture effect on ρ_b and the interrelating SOM effect, allows the work of Rawls (1982) to be continued by being able to systematically determine the exclusive effect of soil texture classes on ρ_b.

Other approaches to quantify the compaction status of soils are also available. One of these approaches is that of the relative compaction (RC) where the observed ρ_b is related to a reference bulk density as obtained by a uniaxial compression test at a stress of 200 kPa (Håkansson and Lipiec, 2000). Kay et al. (1997) reported that RC, originally proposed as a measure of management-induced soil compaction, was sensitive to tillage effects but it was not significantly influenced by texture and SOC concentrations. However, the concept of RC allows directly to compare soils with similar SOC concentration because the magnitude of the theoretically possible compressibility decreases with increasing SOC concentrations (Fig. 4). In contrast, the $s\rho_b$ approach is applicable irrespective of the range of SOC concentration. Furthermore, $s\rho_b$ is very simple to estimate. According to the described relationship between the slope and the intercept parameter of the used model (Eq. [4] and [6]), for a given site, only one representative pair of $s\rho_b$ and SOC is required to calculate $s\rho_b$ and also the bulk densities corresponding to other SOC concentrations measured on this site.

In addition to the relationship between SOC and $s\rho_b$, the hatched areas of the nomogram presented in Fig. 4 provide information on the ratio $\Delta\rho_b$ /Δ SOC (Mg m^{-3}/g kg^{-1}). The maximum effect of ΔSOC on $\Delta\rho_b$ was obtained for soils with SOC < 45 g kg^{-1} and a range of ρ_b between 0.7 and 2.1 Mg m^{-3}. In the given SOC range, both higher and lower values of ρ_b are related to a decrease of the ratio $\Delta\rho_b$ /Δ SOC. In the case of compacted soils, this ratio might be decreased because the applied stress seems increasingly to limit the ability of SOM to act as spacer and adhesive bond between soil mineral particles. Regarding the loose-packed soils, for example, volcanic ashes, the decreasing ratio $\Delta\rho_b$ /Δ SOC may result from additional effects of cohesive forces and liquid bridges, as build by capillary forces (Yu et al., 2003). On the other hand, in waterlogged soils, the decreasing ratio $\Delta\rho_b$ /Δ SOC may result from buoyancy effects which neutralize those of gravity (Adams, 1973). Generally, rising SOC concentrations were related to a decreasing $\Delta\rho_b$ /Δ SOC ratio because this increase may be finally interpreted as a dilution of SOM by itself.

Our novel concept allows the effect of changes in SOC on ρ_b to be separated from all other ρ_b–affecting factors. The applicability of this model (Eq. [6]) to a wide variety of different soils indicates its high potential in regard to a universal validity. Presently, there is no evidence of interdependency between the slope–intercept relationship (Eq. [4] and [6]) and any non-SOM-related ρ_b–affecting factors. Therefore, all these other factors may be reflected in the soil compactness parameter $s\rho_b$ which is (i) reassessed from the SOM effect and (ii) directly related to the only free model parameter. The proposed concept of the $s\rho_b$ allows direct comparison of compactness of all soils included in this study. Finally, combining our new bulk density approach with a particle density one (Rühlmann et al., 2006) allows the straightforward calculation of the SOC effect on the total pore volume of soils.

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