Reprinted from the *Soil Science Society of America Journal*
Volume 62, no. 3, May–June 1998
677 South Segoe Rd., Madison, WI 53711 USA

Bulk Densities of Brazilian Amazon Soils Related to Other Soil Properties

Martial Bernoux,* Dominique Arrouays, Carlos Cerri, Boris Volkoff, and Claudy Jolivet

ABSTRACT

The results of this study provide the first baseline for predicting D_b from soil properties for soils across the Amazon basin. Bulk density values are needed to convert nutrient content and organic carbon (OC) content to weight of nutrient and OC per unit area; unfortunately, common field methods to measure D_b are limited with regard to reliable, complete, and uniform soil data. Much effort has been made in finding alternative solutions to predict D_b from soil properties. We hypothesized that D_b could be reliably estimated by multiple regression of OC, soil textural properties, and some chemical properties. Using the data of 323 soil horizons from the Brazilian Amazon basin, a stepwise multiple regression (SMR) procedure was developed to predict D_b from other soil properties. Multiple regression relationships were obtained for all the data, which were also partitioned by layer and then by main soil order: Latossolos (Oxisols, 62 horizons) and Podzólicos (Alfisols and Ultisols, 212 horizons). The SMR on all the data showed that clay content is the best predictor of D_b, accounting for 37% of the variation. Adding OC content increased the explained variance up to nearly 50%. Predictions of the models were improved when the data were partitioned by order and by horizon type. In the case of Latossolos (Oxisols), the use of OC and clay content as predictors increased the percentage of explained variation, reaching 71% using all layers and 79% for A horizons. The results of this study will provide a basis for estimating OC stocks in the Amazon basin.

ESTIMATING CONCENTRATIONS and fluxes of elements in soils requires the knowledge of soil D_b. Measurements of these parameters are commonly labor intensive and time consuming, particularly when surveying large areas of forest soils. Therefore, much effort has gone into evaluating predictive procedures from soil physical and chemical data.

Increasing attention to global warming, greenhouse effects, and environmental conditions in general has focused on the stocks of C in soil and their fluxes. The organic matter contained in the earth's soils is a large reservoir of C that can act as a sink or source of atmospheric CO_2 (Lugo and Brown, 1993). The world's mineral soils represent a large reservoir of C of about 1500 Pg C (Post et al., 1982; Eswaran et al., 1993; Batjes, 1996). The need for accurate estimates of this pool are the main concern, but their reliability depends on suitable data in terms of OC content and soil D_b. Commonly, D_b measurements are lacking, especially in tropical soils. Refining current estimates of the soil organic C pool requires better estimates of soil D_b.

Global or large-scale stock estimates (Sombroek et al., 1993; Moraes et al., 1995; Batjes, 1996) used OC content and mean or median values of D_b to calculate the total soil OC stocks for each map unit. Predictive equations (simple or multiple regressions) are generally developed within one specific soil unit (Huntington et al., 1989; Arrouays and Pélissier, 1994) and/or for a specific ecosystem (Grigal et al., 1989; Honeysett and Ratkowsky, 1989; Howard et al., 1995; Dupouey et al., 1997).

Numerous studies (Curtis and Post, 1964; Saini, 1966; Adams, 1973; Alexander, 1980; Federer, 1983; Grigal et al., 1989; Honeysett and Ratkowsky, 1989; Huntington et al., 1989; Federer et al., 1993; Arrouays and Pélissier, 1994) have shown the effect of OC on D_b in various soils. These researchers used measurements of OC content (or its square root or logarithmic term) to predict D_b. Stewart et al. (1970) and Vincent and Chadwick (1994) demonstrated that whole-soil D_b can be reliably predicted with rock fragments for gravelly soils. Using soil horizons covering a wide range of soil textural classes, Rawls (1983) showed that, together with the amount of OC, the particle-size distribution could be used for predicting the D_b of natural undisturbed soils. This researcher also noted that the residual errors (measured minus predicted D_b) varied systematically with depth or horizon. Jones (1983) found that increasing soil clay or silt + clay percentage decreases soil D_b determined at −33 kPa water pressure in soil layers described as fragipans.

Most of these studies were done in temperate areas and also concerned specific soils or ecosystems. As a result of their specificity, their predictive equations are probably unable to be used at larger scales.

Tropical soils represent at least 32% of the total mass of organic C stored in the soils of the world (Eswaran et al., 1993). Among tropical ecosystems, the Amazonian forest is known to play a major role in C sequestration and release (Cerri et al., 1994). However, global estimates of C storage in this ecosystem are few (Moraes et al., 1995) and accurate estimates of D_b are lacking.

Concerning Brazilian tropical soils, Kiehl (1979) and mainly Moraes (1991) showed relationships between clay content and soil D_b. However, these relations were not used in the first attempt to estimate C pools for the Brazilian basin (Moraes et al., 1995), assuming constant values for D_b (mean D_b by soil type).

A survey called RADAMBRASIL reported soil analyses for about 12 000 soil horizons representing 2559 soil profiles throughout the Amazon basin. Carbon and other soil properties were routinely measured but not D_b, as a result limiting the usefulness of this survey for estimating pools. This limitation could be eliminated if D_b could be accurately estimated from other routinely measured soil properties. If one wants to estimate C pools in an approach based on extrapolation of calcu-

M. Bernoux and C. Cerri, Centro de Energia na Agricultura-USP, Caixa Postal 96, 13400-970 Piracicaba, SP, Brazil; D. Arrouays and C. Jolivet, Institut National de la Recherche Agronomique, Unité de Science du Sol, SESCPF, 45160 Ardon, France; and B. Volkoff, ORSTOM, 32 Av. H. Varagnat, 93143 Bondy Cedex, France. Received 26 March 1997. *Corresponding author (mbernoux@mail.cena.usp.br).

Published in Soil Sci. Soc. Am. J. 62:743–749 (1998).

Abbreviations: CV, coefficient of variation; OC, organic carbon; SE, standard error; SMR, stepwise multiple regression.

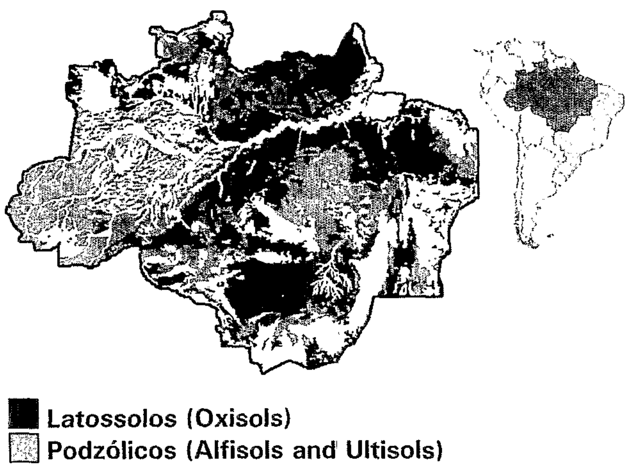

Fig. 1. Map of the legal Amazon basin showing the distribution of the two main soil divisions: Latossolos (Oxisols) and Podzólicos (Alfisols and Ultisols).

lated stock at a point location, it would be necessary to predict the D_b from other measured properties (a proxy variable) at the sampling location. Therefore, the aim of this study was to develop statistical relationships between D_b and other readily available soil characteristics in order to improve D_b predictions in Amazonian soils.

MATERIAL AND METHODS

Soils

According to the considerations developed by Jacomine and Camargo (1996), the two main divisions of the Brazilian soil classification, Latossolos (Oxisols) and Podzólicos (Ultisols and Alfisols), cover nearly 75% of the total area (Fig. 1) of the legal Amazon basin (Rodrigues, 1996). The remainder are distributed among 13 soil divisions, only two of which are >5% of the Amazon basin: Plintossolos (Inceptisols, Oxisols, and Alfisols) and Gleissolos (Entisols and Inceptisols), representing 7.4 and 5.3%, respectively.

Table 1. List of soil properties available in the data base and used in predictive equations.

Symbol	Variable information
D_b	Soil bulk density (Blake, 1965), in weight per volume ($Mg\ m^{-3}$).
DEPTH	Average depth of sampled soil horizon (cm).
OC	Organic C by dichromate oxidation are (% [w/w] of the soil fraction <2 mm; Walkley and Black, 1934).
GRAVEL	Fraction of the bulk soil >2 mm (% [w/w] of the bulk soil).
CLAY	Clay content (particles <2 μm), after dispersion with sodium hexametaphosphate (% [w/w] of the soil fraction <2 mm; Day, 1965).
SAND	Sand content (0.05–2-mm particles) (% [w/w] of the soil fraction <2 mm; Day, 1965).
PHW	pH measured in water (1:1).
PHK	pH measured in KCl 1 M (1:1).
FE	Free Fe oxides extractable using sodium dithionite (Deb method, Jackson, 1958; % of Fe_2O_3 [w/w] of the soil fraction <2 mm).
S	Sum of exchangeable bases ($S = Ca^{2+} + Mg^{2+} + Na^{+} + K^{+}$), Ca and Mg extracted with KCl 1 *M* at pH 7 in the proportion 1:10 (soil/solution), K and Na extracted with HCl 0.05 *M* ($cmol_c\ kg^{-1}$) of soil fraction <2 mm; Vettori, 1969).
CEC	Total cation-exchange capacity, $CEC = S + Al^{3+} + H^{+}$, S see above, Al and H determined after extraction with KCl 1 *M* ($cmol_c\ kg^{-1}$ of soil fraction <2 mm; Vettori, 1969).

The Brazilian Latossolos correspond to well-drained Oxisols in the U.S. soil taxonomy, and the FAO–UNESCO soil map legend identifies them as Ferralsols. The Podzólicos belong to the Alfisols (when eutrofic) and to the Ultisols (when dystrofic) orders of the soil taxonomy, and most of them fall into the Acrisols, Nitosols, and Lixisols (Luvisols) of the FAO–UNESCO map legends (Van Wanbeke, 1992). Most Alfisols, Ultisols, and Oxisols belong to low-activity clay soils. Ultisols usually occupy younger geomorphic surfaces than Oxisols, with which they are often associated in landscapes (Moraes et al., 1996). These soils are thick mineral soils, often >2 m deep.

Database for Calculation

The regressions between soil D_b and other soil parameters were investigated utilizing data from the Brazilian Amazon

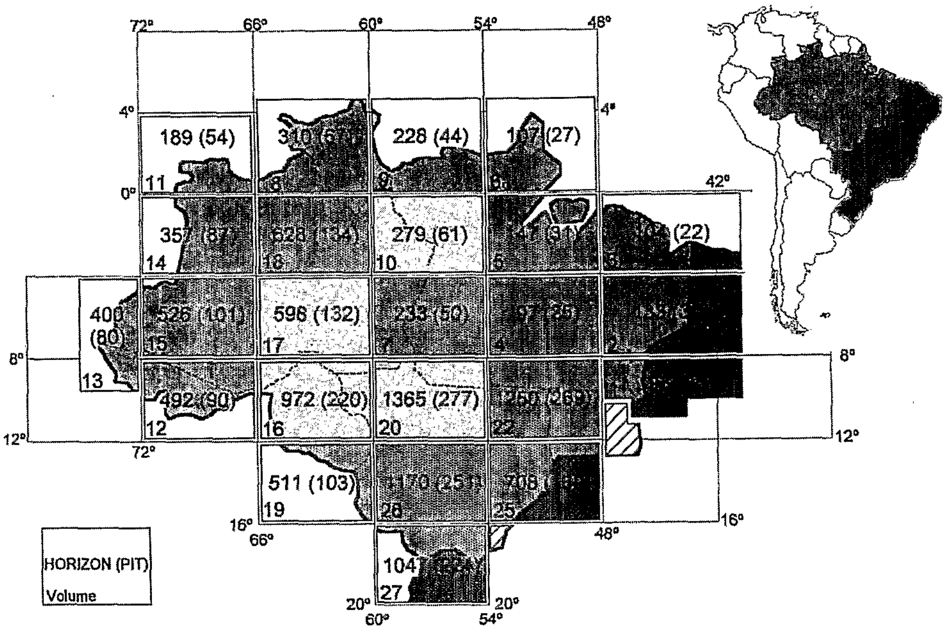

Fig. 2. Localization of the area surveyed by the RADAMBRASIL project. Extent of the area described in each volume, number of the horizon analyzed and, in brackets, number of the corresponding pit.

basin. A database was constructed from soil profile information for soils pits surveyed by the RADAMBRASIL project carried out from 1973 to 1982 (Ministério das Minas e Energia, 1973–1982). The RADAMBRASIL project was carried out in the entire Brazilian Amazon (Fig. 2) and included surveys of geology, geomorphology, vegetation, soils, and land use. The soil survey had the main objective of identifying, delimiting, and localizing the various soil classes that occur in this region. Several laboratories participated in the soil survey and subsequent analyses, but only one (Centro de Estudos de Solos da ESALQ/USP, Piracicaba, Brazil) reported values of soil D_b (paraffin clod method, Blake, 1965). Reported results include other physicochemical soil properties (Table 1) such as C concentrations (Walkley–Black method, Walkley and Black, 1934) and particle-size analysis (pipette method, Day, 1965). The RADAMBRASIL project reported D_b determinations directly in only four volumes (Vol. 10, 16, 17, and 20) corresponding to 323 horizons (Fig. 2), which were stored in the data base. The number of measured D_b values for the Latossolos and the Podzólicos were 62 and 212, respectively. The remainder were spread among the other soil divisions, with numbers of samples too small to be representative.

Table 1 is a list of soil properties available in the data base and a brief description of the laboratory procedures. Complete description can be found in RADAMBRASIL reports (Ministério das Minas e Energia, 1973–1982) or in the specific references indicated in Table 1.

Data Analysis

Descriptive statistics and multiple linear regression analyses using a least-square criterion method were performed with the Statistica package for use on a personal computer (Statsoft, 1996). Multiple linear regression analyses were performed on all the data and subgroups according to soil classification and horizon type. The procedure used was a stepwise linear regression, which allowed independent variables to be individually added or deleted from the model at each step of the regression, and therefore evaluation of changes in the R^2 value. A multiple linear regression method was used because it is a practical tool that furnishes direct quantitative results, and also because the data set was not adapted to spatial analysis such as geostatistics due to lacking or imprecise geographic coordinates.

In the linear regressions, only parameters with statistical significance at the 0.01 level were considered for computing predictive equations and reporting results. Standard error (SE) of the estimates and percentage of the variance explained, through R^2 values, were used as a means to evaluate reliability of the models. The input variables were chosen because they are known to influence D_b (OC and soil texture) or because they are easily obtained (pH).

RESULTS AND DISCUSSION

The 323 soil horizons covered a wide range of soil textural classes. Both clay and sand fractions ranged from a few percentage points to >90% (Table 2). All chemical properties, except pH measurements, had a coefficient of variation (CV) >40%. The OC contents ranged from 0.04 to 12.16%, and had a CV of 126.9%. According to Wilding and Drees (1983), OC is one of the most variable soil properties, with a magnitude of variability that generally increases with increasing scale factor from pedons (<10%) to polypedons (20–30%) to mapping units (30–70%). Therefore, it is not surprising to find a CV of 126.9% at the continental scale. The legal Amazon basin is about 5 000 000 km^2. Manrique and Jones (1991), at a similar scale, (Continental USA, Hawaii, Puerto Rico, and some other countries) found CVs for OC ranging from 87 to 200% for various soil orders. However, in our study this high CV of OC is mainly due to a few high OC contents.

Descriptive statistics of soil properties for Latossolos (Oxisols) and Podzólicos (Alfisols and Ultisols) are reported in Table 3. The B horizons were more clayey than A horizons, contained higher free Fe oxide contents and had lower nutrient and OC contents. Podzólicos (Alfisols and Ultisols) were more stony and less clayey (clay content significantly different at the 0.001 level) than Latossolos (Oxisols), but both orders had similar levels of cation-exchange capacity, free Fe oxides, and OC.

Mean D_bs were 1.15 and 1.17 Mg m^{-3} for Latossolos (Oxisols) and Podzólicos (Alfisols and Ultisols), respectively. Manrique and Jones (1991), studying nine orders of U.S. taxonomy, found mean values of D_b ranging from 1.2 (Oxisols) to 1.5 Mg m^{-3} (Alfisols and Ultisols), with associated CVs of 16.6 and 13.3%, respectively. Coefficients of variation for D_b were 9.7% for Latossolos (Oxisols) and 10.6% for Podzólicos (Alfisols and Ultisols), consistent with the findings of Moraes et al. (1995) at the same scale: 7% for the Podzólicos (Alfisols and Ultisols) and 13% for the yellow dystrophic Latossolos (Oxisols) of the Amazon basin.

Stepwise multiple regression on all the data showed that clay content is the best predictor of D_b, accounting for 37% of the variation (Table 4). Adding OC content increased the explained variance up to nearly 50%. Adding pH, determined in water, as a third variable and sand content as a fourth variable led to an explained variance of 56%. After the first four steps, no other variable was significant at the 0.01 level nor further reduced the SE of estimates. Using logarithmic or squared terms for OC did not improve the predictions. The final best predictive equation for all the data was:

Table 2. Descriptive statistics for all the data (n = 323).†

	D_b	DEPTH	OC	GRAVEL	CLAY	SAND	PHW	PHK	FE	S	CEC
Mean	1.18	53.5	0.93	5.16	38.84	38.89	4.36	3.89	3.18	1.46	6.96
Median	1.17	45.0	0.56	1.20	36.60	37.10	4.30	3.80	2.59	0.47	5.35
Min	0.74	1.5	0.04	0.00	3.90	1.60	3.00	3.00	0.00	0.11	0.58
Max	1.58	160.0	12.16	93.50	90.70	91.90	6.50	5.70	12.00	28.75	31.45
SD‡	0.14	41.5	1.18	12.13	18.26	21.88	0.65	0.43	2.57	3.54	4.99
CV§, %	11.9	77.5	126.9	235.1	47.0	56.3	14.9	11.1	80.8	41.2	71.7

† See Table 1 for complete description of the variables.
‡ Standard deviation.
§ Coefficient of variation (SD/mean).

Table 3. Descriptive statistics by soil order and horizon.†

	D_b	DEPTH	OC	GRAVEL	CLAY	SAND	PHW	PHK	FE	S	CEC
				Latossolos (Oxisols), A horizon (n = 26)							
Mean	1.14	21.08	1.63	1.01	47.62	42.20	3.67	3.68	2.94	0.58	8.69
Median	1.17	16.25	1.39	0.20	46.60	40.85	3.65	3.70	2.30	0.53	8.12
Min	0.81	1.50	0.43	0.00	16.50	5.80	3.00	3.20	0.50	0.15	3.07
Max	1.37	52.50	4.40	7.70	83.90	77.90	4.40	4.00	11.80	1.48	15.65
SD‡	0.13	14.87	0.99	1.98	21.90	23.79	0.31	0.23	2.90	0.35	3.52
				Latossolos (Oxisols), B horizon (n = 36)							
Mean	1.15	86.94	0.51	2.51	54.92	36.51	4.26	3.98	3.46	0.31	4.75
Median	1.13	81.25	0.44	0.25	57.20	33.65	4.30	4.00	2.60	0.27	4.15
Min	0.93	25.00	0.10	0.00	23.30	4.60	3.90	3.30	0.52	0.11	2.19
Max	1.36	157.50	1.28	32.50	90.70	66.70	5.00	4.60	12.00	0.64	10.28
SD	0.11	33.80	0.31	5.95	20.15	21.35	0.28	0.24	3.23	0.14	1.98
				Podzólicos (Alfisols and Ultisols), A horizon (n = 88)							
Mean	1.19	14.56	1.65	6.41	27.69	49.17	4.01	3.74	2.50	1.35	8.30
Median	1.18	10.00	1.11	1.50	27.60	51.90	3.90	3.70	2.09	0.73	6.94
Min	0.74	2.50	0.12	0.00	3.90	9.50	3.00	3.10	0.08	0.25	0.93
Max	1.56	45.00	12.16	93.50	61.60	85.50	5.90	5.50	7.97	8.42	25.57
SD	0.13	10.21	1.78	16.22	12.58	19.18	0.60	0.44	1.81	1.65	5.25
				Podzólicos (Alfisols and Ultisols), B horizon (n = 124)							
Mean	1.15	77.59	0.40	7.61	44.86	34.10	4.70	4.03	3.57	0.67	4.65
Median	1.14	71.25	0.33	1.85	43.85	35.55	4.60	3.90	2.98	0.42	4.20
Min	0.92	15.00	0.12	0.00	19.50	6.30	3.60	3.40	0.27	0.11	0.58
Max	1.47	160.00	1.68	74.40	76.80	77.90	6.50	5.70	11.01	4.19	11.37
SD	0.12	35.09	0.24	13.48	14.08	15.98	0.61	0.46	2.21	0.70	1.94

† See Table 1 for complete description of the variables.
‡ Standard deviation.

$$D_b = 1.52(\pm0.05) - 0.0038(\pm0.0004)\ \text{clay} - 0.050(\pm0.005)\ \text{OC} - 0.045(0.008)\ \text{pH} + 0.0010(\pm0.0003)\ \text{sand} \quad (R^2 = 0.56)$$

The effect of soil textural classes on the residual errors was tested. Five textural classes were considered according to the simplified Brazilian classification (Prado, 1996, p. 58): clay >60% (very clayey, n = 43), 35% < clay <60% (clayey, n = 134), clay <35% and sand <15% (silty, n = 7), sand > clay + 70% (sandy, n = 14), and the remaining (medium, n =125). Predicted D_b was not significantly (0.001 level) different from measured D_b for all classes, except for sandy soils. In this last case, predicted values (mean 1.34 Mg m^{-3}) systematically underestimated observed values (mean 1.43 Mg m^{-3}). Sandy layers corresponded with soils classified as Areias Quartzosas (Psamments). A specific SMR for the sandy soils showed that D_b was best predicted using OC and sand content:

$$D_b = 0.0181(\pm0.0003)\ \text{sand} - 0.08(\pm0.02)\ \text{OC} \quad (R^2 = 0.66)$$

Then an SMR was conducted on all the data after suppression of the sandy layers (Table 5). The first three predictors were clay content, OC, and pH as for all the data. Sand content did not add any significant contribution. The gravel content, however, was then significant.

Table 4. Results of the stepwise multiple regressions for all the data (323 horizons).†

Intercept	CLAY	OC	PHW	SAND	SE‡	R^2
1.352§	−0.0045				0.11	0.369
1.398	−0.0047	−0.042			0.10	0.498
1.606	−0.0046	−0.051	−0.047		0.09	0.542
1.524	−0.0038	−0.050	−0.045	0.0010	0.09	0.558

† See Table 1 for complete description of the variables.
‡ Standard error of estimate.
§ All parameters have statistical significance at 0.001 level.

Results from Table 5 show that textural characteristics have a major effect on D_b in these soils. This is probably due to the low levels of OC that are generally observed in tropical soils. Predictions of D_b using soil textural components have been conducted on soils and horizons having a low level of OC: fragipan horizons (Jones, 1983), 30- to 50-cm layers of glaciofluvial soils in Finland (Heinonen, 1977), Brazilian tropical soils (Moraes, 1991; Kiehl, 1979), various U.S. soils (Rawls [1983] with mean OC = 0.66%; Shaffer [1988] with mean organic matter = 2.59%), and soils with high stone contents (Stewart et al., 1970; Vincent and Chadwick, 1994). On the other hand, D_b has been frequently related to OC in soils storing large amounts of organic matter (Grigal et al., 1989; Huntington et al., 1989; Arrouays and Pélissier, 1994; Howard et al., 1995).

Data were partitioned into two subsets according to horizon type: A horizons (mean OC = 1.68%) on the one hand and B + C horizons (mean OC = 0.43%) on the other hand (Table 5). A SMR was conducted on each subset. The influence of OC on D_b variation decreased with soil depth. The OC variation explained 33.5% of the variance in A horizons and only a few percentage points in the other layers. The pH values played an increasingly significant role in predicting D_b as soil depth increased. In the literature, relationships between D_b and pH measurements are few. Shaffer (1988) observed that pH showed its highest correlation with D_b for 0- to 15-cm soil layers, but gave no explanation. Dupouey et al. (1997), for superficial layers under temperate forest, gave a predictive equation for D_b based on OC, pH in water, and gravel content. In deeper layers, texture or other properties play an increasingly

Table 5. Results of the stepwise multiple regression for all the data except the sandy soils (309 horizons).†

Regression equations						SE‡	R^2
			All horizons (n = 309)				
Intercept	CLAY	OC	PHW	GRAVEL	CEC		
1.324	−0.0040					0.10	0.316
1.369	−0.0042	−0.040				0.09	0.459
1.580	−0.0040	−0.050	−0.047			0.09	0.513
1.615	−0.0040	−0.055	−0.057	0.0014**		0.09	0.530
			A horizon (n = 121)				
Intercept	OC	CLAY	GRAVEL	PHW			
1.241	−0.046					0.10	0.335
1.331	−0.042	−0.0030				0.09	0.484
1.322	−0.050	−0.0026	0.0021**			0.09	0.511
1.526	−0.056	−0.0028	0.0028	−0.048		0.08	0.566
			B horizon (n = 174) + C horizon (n = 14)				
Intercept	CLAY	PHW	OC	CEC	PHK		
1.396	−0.0051					0.09	0.477
1.681	−0.0051	−0.062				0.08	0.559
1.722	−0.0048	−0.069	−0.048**			0.08	0.568
1.739	−0.0047	−0.076	−0.087**	0.005**		0.08	0.589
1.678	−0.0048	−0.111	−0.112	0.006	0.058**	0.08	0.604

** Significant at the 0.01 probability level. All other parameters significant at 0.001.
† See Table 1 for complete description of the variables.
‡ Standard error of estimate.

significant role in controlling D_b as OC is a minor component as soil depth increases. The use of pH as an input variable is justified by the fact that pH is commonly determined at low cost. No direct physical link exists between D_b and pH, but nevertheless, as pH is linked in these soils to the total exchangeable capacity, exchangeable Al hydroxyl, clay (content and nature), and Fe oxides, this could explain the role played by pH in these regressions. Dupouey et al. (1997) hypothesized that increasing pH values would be related with increasing Ca level, and this, in turn, would result in more stable soil aggregates and therefore a higher soil porosity (i.e., lower D_b). However, this must be moderated for tropical soils, which have low level of exchangeable bases.

When considering subsets based on soil classification and horizon type, the use of OC and clay content as predictors increased the percentage of explained variance. In the case of Latossolos (Oxisols), the explained variation in D_b reached 71% using all layers and 79% for A horizons (Table 6). Clay alone also gave good results and could be considered as an alternative for estimating D_b when OC measurements are lacking. When suppressing OC and clay contents in the SMR, another set of variables (sand contents, cation-exchange capacity, and Fe oxide contents) also gave good results, increasing R^2 values and decreasing SE. But the general usefulness of these last equations is doubtful, as Fe oxide measurements are commonly sparse.

Manrique and Jones (1991) found that the square root of OC could be used to predict D_b for Oxisols: $D_b = 1.396 - 0.185 \sqrt{OC}$ ($R^2 = 0.24$ and $n = 173$). Very similar results were obtained with the Latossolos (Oxisols) when testing this regression: $D_b = 1.287 - \sqrt{0.154\ OC}$ ($R^2 = 0.25$ and $n = 62$). Using the model given by Manrique and Jones (1991) led to a mean overestimation of only 0.08 for the predicted D_b. These consistent results show that studies based on large amounts of data and scales improve the general usefulness of the predictive equations.

Concerning the Podzólicos (Alfisols and Ultisols), clay and OC contents explained 47% of the variation in D_b. Variations in D_b were less related to clay content

Table 6. Results of the stepwise multiple regression for the Latossolos (Oxisols).†

Intercept	CLAY	OC	SAND	CEC	FE	SE‡	R^2
			All horizons (n = 62)				
1.376§	−0.0044					0.08	0.590
1.404	−0.0040	−0.048				0.07	0.709
1.013			0.0044	−0.013	0.015	0.06	0.757
			A horizon (n = 26)				
1.371	−0.0048					0.09	0.614
1.419	−0.0037	−0.061				0.06	0.786
1.166			0.0030	−0.017		0.08	0.711
1.096			0.0037	−0.018	0.016**	0.06	0.809
			B horizon (n = 36)				
1.392	−0.0044					0.07	0.628
1.001			0.0041			0.07	0.622
1.037			0.0043	−0.022**	0.019	0.06	0.754

** Significant at the 0.01 probability level. All other parameters significant at 0.001.
† See Table 1 for complete description of the variables.
‡ Standard error of estimate.

Table 7. Results of the stepwise multiple regression parameters for Podzólicos (Alfisols and Ultisols).†

Regression equations						SE‡	R^2
			All horizons (n = 212)				
Intercept	CLAY	OC	PHW	GRAVEL			
1.338	−0.0045					0.10	0.326
1.394	−0.0051	−0.037				0.09	0.469
1.625	−0.0046	−0.046	−0.055			0.09	0.542
1.669	−0.0045	−0.053	−0.067	0.0015**		0.08	0.568
			A horizon (n = 88)				
Intercept	OC	SAND	DEPTH	CLAY	PHW		
1.265	−0.044					0.11	0.358
1.133	−0.041	0.0026				0.10	0.492
1.054	−0.035	0.0030	0.003**			0.09	0.542
1.172	−0.030	0.0019**	0.004	−0.0031**		0.09	0.588
1.355	−0.032	0.0021**	0.005	−0.0035**	−0.046**	0.08	0.626
			B horizon (n = 124)				
Intercept	CLAY	PHW	PHK				
1.421	−0.0060					0.09	0.491
1.718	−0.0056	−0.068				0.08	0.602
1.662	−0.0056	−0.099	0.050**			0.08	0.615

** Significant at the 0.01 probability level. All other parameters significant at 0.001.
† See Table 1 for complete description of the variables.
‡ Standard error of estimate.

for Podzólicos (Alfisols and Ultisols) than for Latossolos (Oxisols), 33 and 59% of explained variance, respectively. Adding OC in the model improved the R^2 value by a similar level for both orders, suggesting that OC contents have a similar importance in controlling D_b for both soils. The inclusion of both pH and gravel content in the model improved the prediction of D_b for the Podzólicos (Alfisols and Ultisols), reaching 57% of the variance explained (Table 7). Partitioning the Podzólicos (Alfisols and Ultisols) data by horizon type led to results similar to those inferred for Latossolos (Oxisols) concerning OC content.

All these results suggest that an estimate of the SE of predicting D_b throughout the Amazon basin would fall within 5 to 10% of the predicted values. The SE of the estimate and R^2 values are lower for the Podzólicos (Alfisols and Ultisols) than for the Latossolos (Oxisols) This is certainly due to the higher CV of the soil properties used as predictors in the SMR for the Podzólicos (Alfisols and Ultisols). For the Latossolos (Oxisols) OC exhibits a CV of about 60%, whereas it reaches 108% for the A horizons of the Podzólicos (Alfisols and Ultisols). The same trend is encountered for the pH values, with CVs ranging from 6 to 8.5% for the Latossolos (Oxisols) and between 11 and 15% for the Podzólicos (Alfisols and Ultisols). Regarding the textural properties, there is no marked difference in the CVs for the clay, sand, and gravel content, but in the case of the gravel content, the range of the extremes is 93.5 for the Podzólicos (Alfisols and Ultisols), whereas it is only 32.5 for the Latossolos (Oxisols). This general trend of CV and range of the soil properties being higher for the Podzólicos (Alfisols and Ultisols) is certainly due to the higher homogeneity of the Brazilian soil division Latossolos (Oxisols), which had a more restrictive definition than the Podzólicos (Alfisols and Ultisols) division.

CONCLUSION

A computer model is now used for a wide range of applications, e.g., environmental risk assessment, agricultural systems, and global environmental change. Many of these models require soil D_b values that are commonly lacking. To partly overcome this problem, the need exists to develop mathematical expressions, called *pedotransfer functions*, to estimate D_b from other soil properties. The strong point of this study is the development of such functions with high R^2 values, showing that D_b can be reliably predicted from other basic soil properties, such as OC, texture, and pH. The results of this large-scale study provide the first baseline for predicting D_b for soils of the whole Amazon basin. The SE associated with predicted D_b for the Latossolos (Oxisols) and the Podzólicos (Alfisols and Ultisols) was between 0.06 and 0.11 Mg m^{-3}. The error due to D_b estimation that could be expected if total OC was calculated based on calculated stock at point locations would be <10% of the final result. This reliability can be considered as satisfactory for such a continental scale. The results of this study will provide a basis for estimating OC stocks in the Amazon basin using information available in the RADAMBRASIL soil survey.

ACKNOWLEDGMENTS

Research support was provided, in part, by the Fundação de Amparo a Pesquisa do Estado de São Paulo (FAPESP) with contracts 94/6046-0 and 95/1451-6, and by the Fundação Coordenacão de Aperçoamento de Pessoal de Nível Superior (CAPES-MEC) with Grant no. 2129/95.

REFERENCES

Adams, W.A. 1973. The effect of organic matter on the bulk and true densities of some uncultivated podzolic soils. J. Soil Sci. 24:10–17.
Alexander, E.B. 1980. Bulk densities of California soils in relation to other soil properties. Soil Sci. Soc. Am. J. 44:689–692.
Arrouays, D., and P. Pélissier. 1994. Modeling carbon storage profiles in temperate forest humic loamy soils of France. Soil Sci. 157: 185–192.
Batjes, N.H. 1996. Total carbon and nitrogen in the soils of the world. Eur. J. Soil Sci. 47:151–163.
Blake, G.H. 1965. Particle density. p. 371–373. *In* C.A. Black et al. (ed.) Methods of soil analysis. Part. 1. Agron. Monogr. 9. ASA, Madison, WI.
Cerri, C.C., M. Bernoux, and G.J. Blair. 1994. Carbon pools and fluxes in Brazilian natural and agricultural systems and the implication

for the global CO_2 balance. p. 399–406. *In* Trans. Int. Congr. Soil Sci. 15th, Acapulco, Mexico. 10–17 July 1994. Vol. 5a. ISSS, Vienna.

Curtis, R.O., and B.W. Post. 1964. Estimating bulk density from organic matter content in some Vermont forest soils. Soil Sci. Soc. Am. Proc. 28:285–286.

Day, P.R. 1965. Particle fractionation and particle-size analysis. p. 545–567. *In* C.A. Black et al. (ed.) Methods of soil analysis. Part. 1. Agron. Monogr. 9. ASA, Madison, WI.

Dupouey, J.L., A. Thimonier, and P. Behr. 1997. Variations de la densité des sols des hêtraies du nord-est de la France en relation avec leurs caractéristiques physico-chimiques. Etudes Gestion Sols 4:43–51.

Eswaran, H., E. Van Den Berg, and P. Reich. 1993. Organic carbon in soils of the world. Soil Sci. Soc. Am. J. 57:192–194.

Federer, C.A. 1983. Nitrogen mineralization and nitrification: Depth variation in four New England forest soils. Soil Sci. Soc. Am. J. 47:1008–1014.

Federer, C.A., D.E. Turcotte, and C.T. Smith. 1993. The organic fraction–bulk density relationship and the expression of nutrient content in forest soils. Can. J. For. Res. 23:1026–1033.

Grigal, D.F., S.L. Brovold, W.S. Nord, and L.F. Ohmann. 1989. Bulk density of surface soils and peat in the north central United States. Can. J. Soil Sci. 69:895–900.

Heinonen, R. 1977. Towards "normal" soil bulk density. Soil Sci. Soc. Am. J. 41:1214–1215.

Honeysett, J.L., and D.A. Ratkowsky. 1989. The use of ignition loss to estimate bulk density of forest soils. J. Soil Sci. 40:299–308.

Howard, P.J.A., P.J. Loveland, R.I. Bradley, F.T. Dry, D.M. Howard, and D.C. Howard. 1995. The carbon content of soil and its geographical distribution in Great Britain. Soil Use Manage. 11:9–15.

Huntington, T.G., C.E., Johnson, A.H. Jonhson, T.G. Sicama, and D.F. Ryan. 1989. Carbon, organic matter, and bulk density relationships in a forested Spodosol. Soil Sci. 148:380–386.

Jackson, M.L. 1958. Soil chemical analysis. Prentice-Hall, Englewood Cliffs, NJ.

Jacomine, P.K.T., and M.N. Camargo. 1996. Classificação pedológica nacional em vigor. p. 675–689. *In* V.H. Alvarez et al. (ed.) O solo nos grandes domínios morfoclimáticos do Brasil e o desenvolvimento sustentado. SBCS-UFV, Viçosa, Brazil.

Jones, C.A. 1983. Effect of soil texture on critical bulk densities for root growth. Soil Sci. Soc. Am. J. 47:1208–1211.

Kiehl, J.E. 1979. Manual de edafologia. Ceres Ltda., São Paulo, Brazil.

Lugo, A.E., and S. Brown. 1993. Management of tropical soils as sinks or souces of atmospheric carbon. Plant Soil 149:27–41.

Manrique, L.A., and C.A. Jones. 1991. Bulk density of soils in relation to soil physical and chemical properties. Soil Sci. Soc. Am. J. 55:476–481.

Ministério das Minas e Energia. 1973–1982. Projeto RADAMBRASIL, programa de integração nacional. Levantamento de recursos naturais. Vol. 1–27. Ministério das Minas e Energia, Rio de Janeiro.

Moraes, J.L. 1991. Conteúdos de carbono e nitrogênio e tipologia de horizontes nos solos da Bacia Amazônica. M.S. thesis. Univ. of São Paulo, Piracicaba, Brazil.

Moraes, J.L., C.C. Cerri, J.M. Melillo, D. Kicklighter, C. Neill, D.L. Skole, and P.A. Steudler. 1995. Soil carbon stocks of the Brazilian Amazon basin. Soil Sci. Soc. Am. J. 59:244–247.

Moraes, J.L., C.C. Cerri, B. Volkoff, and M. Bernoux. 1996. Soil properties under Amazon forest and changes due to pasture installation in Rondônia, Brazil. Geoderma 70:63–81.

Post, W.M., W.R. Emmanuel, P.J. Zinke, and A.G. Stangenberger. 1982. Soil carbon pools and world life zones. Nature (London) 298:156–159.

Prado, H. 1996. Manual de clasificação de solos do Brasil. 3rd ed. FUNEP, Jaboticabal, Brazil.

Rawls, W.J. 1983. Estimating soil bulk density from particle size analysis and organic matter content. Soil Sci. 135:123–125.

Rodrigues, T.E. 1996. Solos da Amazônia. p. 19–60. *In* V.H. Alvarez et al. (ed.) O solo nos grandes domínios morfoclimáticos do Brasil e o desenvolvimento sustentado. SBCS-UFV, Viçosa, Brazil..

Saini, G.R. 1966. Organic matter as a measure of bulk density of soil. Nature (London) 210:1295–1296.

Shaffer, M.J. 1988. Estimating confidence bands for soil–crop simulation models. Soil Sci. Soc. Am. J. 52:1782–1789.

Sombroek, W.G., F.O. Nachtergaele, and A. Hebel. 1993. Amounts, dynamics and sequestrations of carbon in tropical and subtropical soils. Ambio 22:417–426.

StatSoft. 1996. STATISTICA for Windows. StatSoft, Tulsa, OK.

Stewart, V.I., W.A. Adams, and H.H. Abdulla. 1970. Quantitative pedological studies on soils derived from Silurian mudstones. II. The relationship between stone content and the apparent density of the fine earth. J. Soil Sci. 21:248–255.

Van Wanbeke, A. 1992. Soils of the tropics: Properties and appraisal. McGraw-Hill, New York.

Vettori, L. 1969. Método de análise de solo. Boletim Técnico 7. Equipe de Pedologia e Fertilidade do Solo, Rio de Janeiro.

Vincent, K.R., and O.A. Chadwick. 1994. Synthesizing bulk density for soils with abundant rock fragments. Soil Sci. Soc. Am. J. 58:455–464.

Walkley, A., and I.A. Black. 1934. An examination of the Degtjareff method for determining soil organic matter and a proposed modification of the chromic titration method. Soil Sci. 37:29–38.

Wilding, L.P. and L.R. Drees. 1983. Spatial variability in pedology. p. 83–116. *In* L.P. Wilding et al. (ed.) Pedogenesis and soil taxonomy. I: Concepts and interactions. Elsevier, New York.