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BULK DENSITIES OF GHANAIAN FOREST SOILS IN RELATION TO OTHER PHYSICO-CHEMICAL SOIL PARAMETERS

K. F. Salifu,

Faculty of Forestry, University of Toronto, 33 Willcocks St. Toronto, Ontario, Canada M5S 3B3
E-mail: k.salifu@utoronto.ca

W. L. Meyer & H. G. Murchison

Faculty of Forestry, Lakehead University, Thunder Bay, Ontario, Canada P7B 5E1

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SALIFU, K. F., MEYER, W. L. & MURCHISON, H. G. 2002. Bulk densities of Ghanaian forest soils in relation to other physico-chemical soil parameters. Prediction of soil bulk density (BD) requires taking several representative volumetric soil samples which is often laborious and difficult, particularly for wet and stony mineral soils. Alternative empirical models to predict BD under teak (*Tectona grandis*) plantations from physico-chemical soil properties, which are easier to obtain, are presented. Core samples were taken from the 0–20 cm (A-horizon) and 20–40 cm (B-horizon) soil layers from 28 soil pedons in Bosomoa, Tain II and Yaya forest reserves in The High Forest Zone of Ghana. Multiple linear regression techniques were used to develop statistical relationships to estimate BD for the A-horizon. The data were grouped according to their soil taxonomy classification. BD was negatively correlated with soil organic matter content (SOM) ($r = -0.85, p < 0.002$) and pH ($r = -0.77, p < 0.01$). Mean BDs of the A-horizon were 1.33 and 1.19 g cm^{-3} for Haplic Acrisols (BD_a) and Haplic Ferralsols (BD_f) respectively. The following predictive equations were derived for Haplic Ferralsols and Haplic Acrisols: $BD_f = 1.96 - 0.12\,pH + 0.03\,clay - 0.05\,SOM$ ($r^2 = 0.55$, $Se = 0.18$, $n = 18$) and $BD_a = 1.75 - 7.21\,Arcsin\,(SOM) - 0.17\,pH + 0.32\,ln\,(silt)$ ($r^2 = 0.92$, $Se = 0.05$, $n = 10$) (BD in g cm^{-3}, and clay, SOM and silt in per cent). In general, the models suggested that soil properties such as SOM, pH, silt and clay content can provide a reliable alternative to determine BD.

Key words: Bulk density - Ghana - Haplic Acrisols - Haplic Ferralsols - multiple regression - soil organic matter - soil texture - *Tectona grandis*

SALIFU, K. F., MEYER, W. L. & MURCHISON, H. G. 2002. Kaitan ketumpatan pukal tanah hutan Ghana dengan parameter fiziko-kimia tanih yang lain. Ramalan mengenai ketumpatan pukal tanih (BD) memerlukan pengambilan beberapa contoh volumetri tanih yang selalunya menggunakan banyak tenaga buruh dan sukar, terutama bagi tanih galian berbatu dan tanih galian basah. Model empirik alternatif untuk meramalkan BD di ladang jati (*Tectona grandis*) daripada ciri-ciri fiziko-kimia tanih yang lebih senang diperoleh, dibentangkan. Contoh-contoh teras diambil daripada lapisan tanih 0–20 cm (horizon A) dan 20–40 cm (horizon B) dari 28 pedon tanih di hutan simpan Bosomoa, hutan simpan Tain II dan hutan simpan Yaya di Zon Hutan Tinggi Ghana. Teknik regresi linear berganda digunakan dalam membangunkan kaitan statistik untuk menganggar BD horizon A. Data dikumpulkan berdasarkan pengelasan taksonomi tanihnya. BD berkorelasi secara negatif dengan kandungan bahan organik tanih (SOM) ($r = -0.85, p < 0.002$) dan pH ($r = -0.77, p < 0.01$). BD min horizon A masing-masing ialah 1.33 dan 1.19 g cm^{-3} bagi Haplic Acrisols (BD_a) dan Haplic Ferralsols (BD_f). Persamaan ramalan yang berikut diperoleh bagi Haplic Ferralsols dan Haplic Acrisols: $BD_f = 1.96 - 0.12$ pH $+ 0.03$ lempung $- 0.05$ SOM ($r^2 = 0.55$, Se = 0.18, n =18) dan $BD_a = 1.75 - 7.21$ Arcsin (SOM) $- 0.17$ pH $+ 0.32$ ln (lodak) ($r^2 = 0.92$, Se= 0.05, n =10) (BD dalam g cm^{-3}, sementara lempung, SOM dan lodak dalam peratus). Pada umumnya, model-model tersebut mencadangkan bahawa ciri tanih seperti SOM, pH, lodak dan lempung dapat memberi alternatif yang baik untuk menentukan BD.

Introduction

Generally, soil bulk density (BD) is defined as the weight of an oven-dried sample of undisturbed soil per unit or "bulk" volume. In this paper, BD is defined as the ratio of mass to bulk volume of soil particles < 2 mm plus pore space in a sample (Blake 1965). The mass is determined after drying the sample to constant weight at 105 °C and the volume is that as taken in the field. BD is an important soil index. It is required for converting water percentages by weight to content by volume, for calculating porosity when particle density is known, and for estimating the weight of a volume of soil too large to weigh conveniently (Blake 1965). In addition, BD is required to quantify the magnitude of the total nutrient pools stored in forest soils and is critical for nutrient budget and sustainability studies. As an index of soil compaction, BD has been found to correlate negatively with root density (Strong & La Roi 1985, Gale & Grigal 1986) and tree growth (Hamilton & Krause 1985, Froelich *et al.* 1986).

BD is often strongly correlated with soil organic matter content (SOM), soil texture (particle size distribution) and structure (aggregation) (Grigal *et al.* 1989, Huntington *et al.* 1989, Manrique & Jones 1991). For example, differences in BD between soils in the United States and Puerto Rico have been found to be primarily due to differences in texture (Manrique & Jones 1991). The BD of fine textured mineral soils may range from 1.0 to 1.3 g cm^{-3} and that of sandy soils from 1.3 to 1.7 g cm^{-3} (Brady 1990, Foth 1990). The BD of organic soils is usually much less than that of mineral soils and may be lower than 0.4 g cm^{-3} (Fonteno 1996).

Several techniques, such as the clod, core, excavation and radiation methods can be used to quantify BD (Blake 1965). However, the most common technique employed is the core method because of its convenience and simplicity compared with the others (Armson 1977). Problems with this technique include unknown compaction of soil sample during extraction, difficulty in sampling wet soils or soils with high coarse fragment levels or root content (Federer 1983), and poor BD estimation due to sample falling apart when cylinder is extracted from the profile. Furthermore, with this technique, several representative volumetric soil samples are required to estimate BD, which is often time consuming and laborious.

There is, hence, a need to explore alternative methods to estimate BD from more readily obtainable physico-chemical soil properties. Several procedures have been developed to predict BD based on soil texture and SOM. Shaffer (1988) predicted BD as a function of clay content of soils in Minnesota. Huntington *et al.* (1989) predicted BD for California soils as a function of the per cent carbon content. Tamminen and Starr (1994) estimated BD for Finnish soils using SOM as a predictor variable. Van Wambeke (1974) predicted BD for Oxisols based on the sand fraction. Jones (1983) used silt and clay contents to predict BD for soils with fragipans.

Quantitative data on BD of forest soils in Ghana is lacking. Most forest soils in Ghana are stony and it is difficult to estimate their BDs. This paper seeks to quantify and explain conceptual links between BD and other soil properties. With the understanding that developed models for specific locations will yield greater precision than universal equations (Harrison & Bocock 1981), we provide a method to estimate BD from physico-chemical soil properties that are easier to obtain.

Materials and methods

Description of study site

The study was conducted in the Bosomoa, Tain II and Yaya forest reserves which are located in The High Forest Zone of Ghana (Figure 1). Climatic and edaphic requirements of teak and a complete description of the study site are presented in Salifu and Meyer (1998) and Salifu (2001). The soils are Oxisols and are divided into two major soil groups: Savanna and Forest Ochrosols (Figure 1). Ancient rocks with considerable quartzite, granite and gneiss underlie the Ochrosols (Boateng 1966). They are usually red or reddish brown on summits and upper slopes of hills, orange brown or brown on middle slopes and yellow brown on lower slopes. They are well drained, fertile and are the most important soils in Ghana from the agricultural point of view (Boateng 1966). Savanna Ochrosols, referred to as Haplic Acrisols (Anonymous 1988), occur in Bosomoa (Figure 1). These soils are inherently deficient in phosphorus (P) and nitrogen (N). Despite this deficiencies they support excellent plant growth in the northern savanna zone (Boateng 1966). Forest Ochrosols, referred to as Haplic Ferralsols (Anonymous 1988), occur in Tain II and Yaya and are rich in SOM and worm casts that give the A-horizon a characteristic dark brown color. Below the A-horizon are ironstone concretions that give the soil a characteristic reddish brown color (Boateng 1966).

The High Forest Zone is divided into four broad ecological types: wet evergreen, moist evergreen, moist semi-deciduous and dry semi-deciduous (Hall & Swaine 1981). The zone consists of a heterogeneous collection of uneven-aged trees with multi-layered strata (Taylor 1960). Emergent trees may reach a height of up to 60 m. Some of the emergents include *Triplochiton scleroxylon, Ceiba pentandra, Melicia* *excelsa, Terminalia superba, Antiaris africana* and *Pycnanthus angolensis*. Ghana's most valuable timber species are found in this vegetation zone. Ground flora is sparse. Entwined throughout the stands are thick-stemmed lianas and creepers.

Field sampling and laboratory analysis

Data were collected from 28 soil pedons from Bosomoa, Tain II and Yaya forest reserves (Figure 1). Fourteen 32-ha rectangular compartments under similar management regimes were randomly selected from a group of 30 with the aid of a table of random digits for the study. The selection process resulted in five, six and three compartments at Bosomoa, Tain II and Yaya respectively. A compartment is a component of a forest management unit distinguished by a characteristic that is unique to that portion of the forest estate, identified for record keeping and for making management decisions. Compartments were each represented by one 20 × 20 m plot. Two soil pits were randomly located within each plot for BD sample collection. A complete description of sample design is given in Salifu (1997).

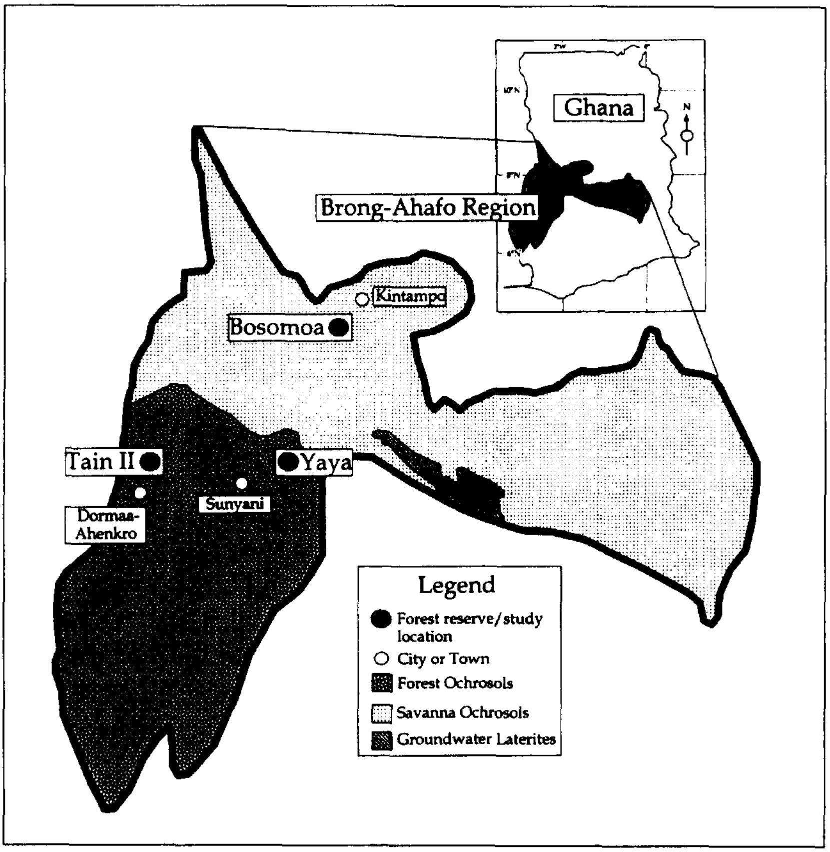

Figure 1 Study locations in the Brong-Ahafo Region of Ghana

Volumetric soil samples were collected from A-horizon (0–20 cm) and B-horizon (20–40 cm) depths using the core method (Blake 1965, Rowel 1994). To collect BD samples, the face of the soil horizon was cleaned with a knife and a sharpened cylinder of known volume (either a 50 cm^3 or 89.1 cm^3) was placed horizontally against the surface of the excavated pit. Then a protective metal cap was placed against the cylinder which was then hammered gently into the soil using a rubber mallet until the soil protruded about 3 mm of the cylinder end (Rowell 1994). The soil cylinder was then carefully dug free and soil extending beyond the open ends was trimmed flush. The soil core was finally pushed into a plastic bag and transported to the laboratory for analysis.

In the laboratory, the soil sample was dried at 105 °C and BD was estimated on measured soil mass inclusive of the < 2 mm coarse fragments according to the methods of Tamminen and Starr (1994). Specifically, BD was quantified as:

$$BD = \frac{M_s}{V_t - V_{cf}} \qquad (1)$$

where,

BD is soil bulk density (g cm^{-3}),

M_s is mass of soil < 2 mm fraction,

V_t is volume of sample tube and

V_{cf} is volume of coarse fragments determined according to Archimedes Principles.

Thus, V_{cf} was estimated by volume of liquid displaced by coarse fragments immersed in a cylinder. Particle size analysis was estimated by the pipette method (Anonymous 1979). Soil pH was determined potentiometrically in 0.01 M $CaCl_2$ solution using a soil to solution ratio of 1: 2.5 (Anonymous 1979). Organic matter content was estimated by loss on ignition (Ball 1964).

Statistical analysis

Statistical modelling of the relationship between BD and independent (predictor) variables was done using the backward elimination method (Neter *et al.* 1996). In this iterative method, the dependent variable (BD) was initially regressed on the full set of independent variables (SOM, pH, clay, silt, sand, N, Ca and V_{cf}).

After variable selection, the model was evaluated for goodness of fit by examining the residual statistics. These were assumed to be normally distributed over the range of independent variables and, hence, showed constant variance and no systematic variation. Graphical analysis was normally sufficient for this evaluation of residuals. Where assumptions of normality and homoscedasticity of residuals were not met, independent variables were transformed to obtain desired behaviour of residuals. SPSS version 6.1 was used for the regression analysis.

Results

Physico-chemical soil parameters for the two major soil groups, Haplic Acrisols and Haplic Ferralsols, are given in Table 1. The soil samples varied considerably in their SOM content. Haplic Acrisols had a lower mean SOM value (3.4%) compared with Haplic Ferralsols (8.6%). Similarly, the silt and clay percentages were lower for Haplic Acrisols (Table 1). Per cent clay increased by 120% in Haplic Ferralsols compared with Haplic Acrisols.

Data used to develop the models (Table 1) were compared with data from the B-horizon (data not presented). BD for Haplic Acrisols showed higher variability in the A-horizon (11.3%), decreased with increased depth, and was 5.5% in the B-horizon (20–40 cm depth). In contrast, BD for Haplic Ferralsols was least variable in the A-horizon (20%) and variability increased with depth in the B-horizon (31%). Haplic Acrisols in the A-horizon, with lower silt and clay percentages, had 11% more BD compared with Haplic Ferralsols.

Predicted models of BD are summarised in Table 2. Although the sample size was small for definitive evaluation, there were no reasons to assume the assumptions of normality for model 2 were not adequate (Figure 2A). Similarly, the assumptions of homoscedasticity of residuals in Figure 2B could be considered adequately associated with the small sample size. Similar plots were obtained for model 1 (plots not presented).

Table 1 Mean, range, coefficient of variation (CV%) and sample size (n) for BD, SOM, pH, silt and clay for the A-horizon of Haplic Ferralsols and Haplic Acrisols

Soil taxonomy classification	Forest reserves			Range			
		Variable[a]	Mean	Lower	Upper	CV (%)	n
Haplic Ferralsols	Tain II and Yaya	BD	1.19	0.79	1.67	20.17	18
		SOM	8.56	3.00	14.40	34.81	18
		pH	6.35	5.20	7.30	9.92	18
		silt	32.42	18.35	47.57	29.74	18
		clay	13.19	5.93	22.23	35.86	18
Haplic Acrisols	Bosomoa	BD	1.33	1.04	1.53	11.28	10
		SOM	3.39	1.80	6.60	42.77	10
		pH	5.95	5.08	7.06	10.92	10
		silt	13.41	9.50	22.55	26.40	10
		clay	5.97	0.64	11.78	63.99	10

[a] BD (g cm^{-3}), and SOM, silt and clay (%)

Table 2 Regression coefficients and related statistics for the relationship between BD and physico-chemical soil properties for Haplic Ferralsols (1) and Haplic Acrisols (2)

		Regression coefficients						Goodness of fit statistics		
		Independent variables								
Model	bo	Arcsin (SOM)	pH	Ln (SOM)	Clay	SOM	Ln (silt)	r^2	SE*	n
1	1.96^b	-	-0.12	-	0.03^c	-0.05^c	-	0.55^b	0.18	18
2	1.75^a	-7.21^b	-0.17^b	-	-	-	0.32^c	0.92^b	0.05	10

* SE = standard error of the estimate for the model, a = $p < 0.001$, b = $p < 0.01$, c = $p < 0.05$.
Blanks in the table represent variables that did not meet the criteria for backward inclusion in the model.

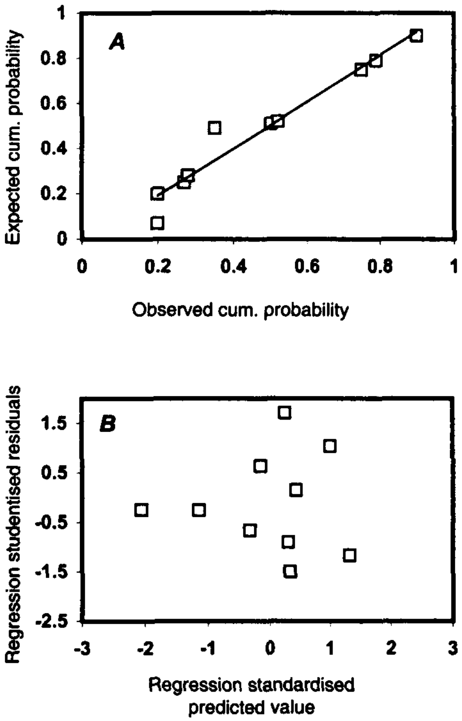

Figure 2 Normal probability plot of residuals (A) and Scatter plot of studentised residuals vs. standardised predicted values (B) for the relationship between BD and SOM, pH and silt for Haplic Acrisols at Bosomoa forest reserve in Ghana

Examination of the multiple regression models (Table 2) showed 55% of the variability in BD of Haplic Ferralsols (Model 1) could be accounted for by SOM, pH and clay. Similarly, BD for Haplic Acrisols was predicted from SOM, silt and pH (Model 2). BD was inversely related to SOM ($r = -0.85$, $p < 0.002$, Figure 3A), pH ($r = -0.77$, $p < 0.01$, Figure 3B) and silt ($r = -0.43$, $p < 0.22$, Table 3). The arcsin transformation of SOM and the natural log of silt improved the coefficient of determination, distribution of residuals (Figure 2) and the standard error of estimate for the models (Table 2). The predictor variables for Haplic Acrisols accounted for up to 92% of the variation in BD for the A-horizon. In addition, BD can be predicted for Haplic Acrisols using SOM ($r^2 = 0.71$, Figure 3A) or pH ($r^2 = 0.58$, Figure 3B) as independent predictor variables.

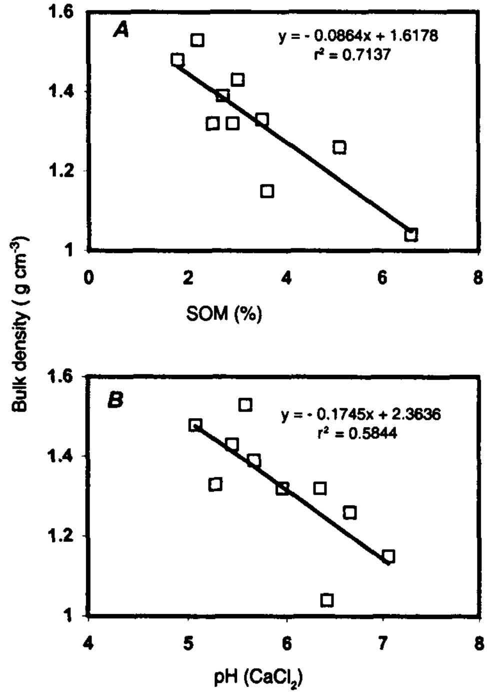

Figure 3 Relationship between BD and SOM (A) and pH (B) for Haplic Acrisols at Bosomoa forest reserve in Ghana

Table 3 Correlation coefficients of continuous variables with one another included in the prediction of BD for Haplic Acrisols (see Table 2)

	BD	SOM	pH	Silt
BD	1.000	- 0.8448	- 0.7645	- 0.4257
SOM	- 0.8448	1.000	0.5780	0.555
pH	- 0.7645	0.578	1.000	0.7082
Silt	- 0.4257	0.555	0.7082	1.000
Significance (2-tail)				
BD	.	0.002	0.010	0.220
SOM	0.002	.	0.080	0.096
pH	0.010	0.080	.	0.022
Silt	0.220	0.096	0.022	.

Number of observations =10 for all variables

Discussion

The BD values found in this study (1.0–1.5 g cm^{-3}) compared well with BD values reported in the literature for sandy soils (Brady 1990, Foth 1990). Studies have shown significant relationships between SOM, pH, clay and silt with BD (Jones 1983, Manrique & Jones 1991, Tamminen & Starr 1994). Grigal *et al.* (1989) and Tamminen & Starr (1994) have shown that BD is related to SOM in a non-linear fashion. We found, however, that the relationship between BD and SOM could be modelled by linear relationships (Figure 3A). The observed linear relationship between BD and SOM may be because SOM was confined to values $< 10\%$ for Haplic Acrisols and up to 14% for Haplic Ferralsols in our study (Table 1, Figure 3A). Clay contents of $\geq 7\%$ significantly improved prediction of BD in Finland (Tamminen & Starr 1994). The mean clay contents in this study were 13% for Haplic Ferralsols and 6% for Haplic Acrisols (Table 1) and could have contributed to the higher r^2 and lower standard error of estimate for the model obtained for Haplic Acrisols.

Independence among the predictor variables was examined using simple correlations (Table 3). Silt was correlated to pH ($p < 0.05$) and, hence, only one of these variables appeared in the model. Since pH is more strongly correlated with BD, it was the preferred variable. If, however, the partial correlation between BD and silt after adjusting for the inclusion of pH in the model is significant, silt will also appear in the model. This was the case in this study.

Higher BDs of Haplic Acrisols with soil depth is partly due to decreasing SOM content and to tillage practices that may cause relatively loose structure in the surface soil and compaction in the subsoil (Manrique & Jones 1991). Similarly, Salifu (1997) and Amponsah (1998) have found that increased BD with depth is associated with decreased SOM with depth under teak plantations in Ghana. SOM improves soil structure (Brady 1990). Thus, higher SOM at surface horizons improves crumb-structure that promotes soil aggregation and may lower BD in surface soils. In contrast, higher BD in lower depth strata is due to reduced SOM with depth associated with less aggregate formation in subsoil.

Furthermore, BD of Haplic Ferralsols decreases with depth as particle size increases and is partly due to the highly negative and significant correlation ($r = -0.97$, $p < 0.001$) between BD and volume of coarse fragments (Salifu 1997). In addition, declining BD with increasing soil depth can be due to historical vehicular traffic (Kimmins 1994). Generally, BD relates to the combined volume of solid and pore spaces in soil. Thus, soils with a high proportion of pore space to solid have lower BD than those that are more compact with less pore space. Consequently, any factor that influences pore space, such as tillage operations, scarification and use of heavy machinery in thinning operations, affects BD. Thus, plantation-thinning operations with heavy machinery can be the cause for the decreasing BD with depth.

The coarse fragment contents of the studied soils ranged from 0% in Haplic Acrisols to 75% in Haplic Ferralsols with a mean of > 20%. Higher variability of BD with depth for Haplic Ferralsols can be due to increasing errors in estimation of coarse fragment volume (Huntington *et al.* 1989). The positive correlation between BD and clay ($r = 0.51$, $p < 0.05$) in this study corroborates the results of Alexander (1980), Manrique and Jones (1991) as well as Tamminen and Starr (1994) but differs from that of Jones (1983) who found a negative correlation between BD and clay for fragipans.

The negative correlation between BD and pH is probably due to the higher Ca and base saturation (BS) of these soils (Salifu 1997, Salifu 2001). Interpretive significance can sometimes be derived from the signs and relative magnitudes of the coefficients of the independent variables from the correlation matrix (Table 3). Reliability of such interpretations is proportional to the contribution of the variable to regression (Alexander 1980). Thus, the negative correlation between BD and pH in this study was also likely due to the positive correlation ($p < 0.08$) between SOM and pH (Table 3). Moreover, higher pH means more biological activity and granular structure formation in A-horizon, which can lower BD since granular soil is much looser (Brady 1990).

The mean BD of the A-horizon were 1.33 g cm^{-3} for Haplic Acrisols and 1.19 g cm^{-3} for Haplic Ferralsols (Table 1). Differences in BD amongst soil groups are likely due to the differences in particle size distribution (Manrique & Jones 1991) and SOM content. In general, coarse fragments created large pore spaces in soil volume that might have resulted in a lower BD as occurred in this study for Haplic Ferralsols.

The percentage of C in SOM is relatively constant (Huntington *et al.* 1989). Walkley (1946) have estimated that a gram of SOM contains 0.58 g of carbon. Thus, Huntington *et al.* (1989) have used SOM or %C to predict BD and the variation in their models are similar ($r^2 = 0.72$–0.75). Moreover, SOM have often been used to estimate BD for use in quantification of soil carbon pools (Huntington *et al.* 1989). The coefficient of determination of our model for Haplic Acrisols using SOM as predictor variable ($r^2 = 0.71$) compares well with the reported BD indices above but that predicted from the joint contribution of SOM, pH and clay was higher ($r^2 = 0.92$), demonstrating significant joint contribution of predictor variables to the r^2. The high r^2 of the regression equations suggested that BD can be reliably predicted for Haplic Acrisols and for Haplic Ferralsols. For example, predicted BD index by the fitted equation for Haplic Acrisols was 1.325 (Table 2) compared with 1.330 estimated (Table 1).

Conclusions

A method for predicting BD of soils under teak plantations based on particle size information, SOM and pH is presented. The models suggest that BD can be reliably predicted from easily measured soil properties by the soil groups (Haplic Acrisols: $r^2 = 0.92$ and Haplic Ferralsols: $r^2 = 0.55$). The lower coefficient of determination of the model for Haplic Ferralsols may be due to errors associated with estimation of the coarse fraction. Results are consistent with published relationships between BD and the predictor variables (Grigal *et al.* 1989, Huntington *et al.*1989, Manrique & Jones 1991, Tamminen & Starr 1994). The models have weaknesses because they explicitly define in precise details the experiment that will support the hypothesis, or suggest modifications to them, but will likely yield greater precision in predicting BD at the study site and other locations with similar soil conditions than universal equations (Harrison & Bocock 1981).

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