Using Soil Physical and Chemical Properties to Estimate Bulk Density

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ABSTRACT

A stepwise multiple regression procedure was developed to predict oven-dried bulk density from soil properties using the 1997 USDA-NRCS National Soil Survey Characterization Data. The database includes both subsoil and topsoil samples. An overall regression equation for predicting oven-dried bulk density from soil properties (R^2 = 0.45, $P < 0.001$) was developed using almost 47 000 soil samples. Partitioning the database by soil suborders improved regression relationships (R^2 = 0.62, $P < 0.001$). Of the soil properties considered, the stepwise multiple regression indicated that organic C content was the strongest contributor to bulk density prediction. Other significant variables included clay content, water content and to a lesser extent, silt content, and depth. In general, the accuracy of regression equations was better for suborders containing more organic C (most Inceptisols, Spodosols, Ultisols, and Mollisols). Bulk density was poorly predicted for suborders of the Aridisol and Vertisol orders which contain little or no organic C. Although organic C was an important variable in the suborder analysis, water content explained most (>30%) of the variation in bulk density for Udox, Xererts, Ustands, Aquands, and Saprists. Relationships between bulk density with soil volume measured on oven-dried natural clods and bulk density with soil volume measured at field-moisture content and one-third bar were also determined (R^2 = 0.70 and 0.69, respectively; $P < 0.001$). Utilizing the regression equations developed in this study, oven-dried bulk density predictions were obtained for 71% of the 85 608 samples in the database without bulk density measurements. While improving on methods of previous analyses, this study illustrates that regression equations are a feasible alternative for bulk-density estimation.

Soil bulk density measurements are often required as an input parameter for models that predict soil processes. Such models often use bulk density measurements to account for horizon mass when aggregating soil data. Methods to measure bulk density are labor intensive and time-consuming. As a result, bulk density measurements are frequently missing from soil databases or have been measured using several different procedures. Thus, models have been developed to predict bulk density from soil physical and chemical data (Saini, 1966; Bernoux et al., 1998; Manrique and Jones, 1991; Calhoun et al., 2001; Rawls, 1983; Baumer, 1992). These studies have often focused on a specific or limited data set, and there are few published results concerning the relationship between bulk density measurement methods.

The objective of this study was to predict the oven-dried bulk density of samples in a database constructed from the USDA-NRCS National Soil Survey Characterization Data (Soil Survey Staff, 1997). This required determining the relationships between soil properties and bulk density as well as determining the relationships between bulk density measurement methods for the purpose of converting bulk density values measured at one-third bar and at field moisture content to oven-dried bulk density.

Since many soil textural and chemical properties are measured on a <2-mm mass basis (e.g., Fe content, cation exchange capacity, clay content, etc…), accounting for differences in mass between individual soil horizons is necessary to obtain a measurement representative of several horizons. The measured and predicted bulk density of the <2-mm soil fraction, horizon thickness, and course fragment volume were used to calculate a horizon mass estimate. Then a mass weighted average is used to aggregate soil property measurements. The statistical procedures and models for bulk density estimation are described in this paper.

MATERIALS AND METHODS

The National Soil Survey Characterization Data used in this study contains information for approximately 21 667 pedons and 136 000 samples from all 50 states, Puerto Rico, Virgin Islands, Trust Territories, and some foreign nations. The data set contains physical, chemical, engineering, mineralogical, and descriptive data for the pedons. Analytical procedures used to measure the soil physical and chemical properties are described in the Soil Survey Laboratory Investigations Report No. 42 (Soil Survey Staff, 1996).

Table 1 includes a list of soil properties evaluated in this paper and a brief description of their measurement procedure. To determine the relationships between bulk density and soil properties, multiple regression models were created using the procedure REG with a stepwise variable selection routine (SAS Institute, 1982). The soil properties listed in Table 1 were evaluated along with several calculated variables (Table 2). Variables in Table 2 were considered for multiple regression modeling because earlier studies have shown significant relationships between these variables and bulk density (Manrique and Jones, 1991; Calhoun et al., 2001; Rawls, 1983).

Using the stepwise selection routine, only variables with an F statistic that met the 0.999 significance level for entry were included into the regression equations (SLENTRY = 0.999). After a variable was added, all variables were examined and variables that did not produce an F statistic significant at the 0.001 probability level were deleted (SLSTAY = 0.001). According to Muller and Fetterman (2002), using these criteria for a stepwise modeling strategy provides a better approximation to the *all-possible-regressions* strategy, which requires fitting all possible models.

Oven-dried bulk density measurements present in the database were used as the dependent variable in the multiple

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Table 1. Description of parameters evaluated for inclusion in the simple and multiple regression models used in the estimation of bulk density.

Parameter name	Description
Bulk density, oven dry	Bulk density, <2-mm soil fabric, with soil volume measured by coating natural clods in plastic then weighing the oven-dried clod in air and water to obtain its volume by Archimedes' principle. Bulk density is calculated by dividing the weight of the oven dried clod by this volume. (g cm^{-3})
Bulk density, 1/3 bar	Bulk density, <2-mm soil fabric, with soil volume measured by coating natural clods in plastic then weighing the clod at one-third bar tension in air and water to obtain its volume by Archimedes' principle. Bulk density is calculated by dividing the weight of the oven-dried clod by this volume. (g cm^{-3})
Bulk density, field moisture content	Bulk density, <2-mm soil fabric, with soil volume measured by coating natural clods in plastic then weighing the clod at field moisture content in air and water to obtain its volume by Archimedes' principle. Bulk density is calculated by dividing the weight of the oven-dried clod by this volume. (g cm^{-3})
clay	Total clay content of the <2-mm fabric, the soil separate with <0.002-mm particle diameter, determined with the Kilmer and Alexander pipette method. Clay-size carbonate is included. (% weight)
silt	Total silt content of the <2-mm soil fabric, soil separate with 0.002- to 0.05-mm particle diameter, determined with the Kilmer and Alexander pipette method. (% weight)
sand	Total sand content of the <2-mm soil fabric, the soil separate with 0.05- to 2.0-mm particle diameter, determined by wet sieving. (% weight)
c_org	Organic C of the <2-mm soil fabric, determined by the Walkley–Black modified acid-dichromate $FeSO_4$ titration procedure. (% weight)
wc	Water content at −15 bar determined by placing a sample of <2-mm air-dried soil in a retainer ring on a cellulose membrane in a pressure membrane extractor. The membrane is covered with water to wet the sample by capillarity, and the sample is equilibrated at 15 bar tension. The gravimetric moisture content is determined. (% weight)
depth	Horizon sample depth, measured from soil surface to the midpoint of horizon. (cm)

Table 2. Description of calculated variables evaluated for inclusion in the multiple regression models used in the estimation of bulk density.

Variable Name	Description
w15cly	ratio of water content at −15 bar to clay content
wc^2	square of water content at −15 bar
wc^3	cube of water content at −15 bar
$clay^2$	clay content squared
$clay^3$	clay content cubed
$c\_org^{1/2}$	square root of organic C content
c_org^2	organic C content squared
c_org^3	organic C content cubed
$silt^2$	silt content squared
$silt^3$	silt content cubed
$sand^2$	sand content squared
$sand^3$	sand content cubed
siltplusclay	silt content + clay content

regression models. The regression models were then used to predict oven-dried bulk density values for samples in the database missing this measurement. The 50 904 samples in the database contain an oven-dried bulk density measurement and the 85 608 samples lack the measurement.

Before model development, the quality of the measurements in the database was assessed by setting limits for soil properties to eliminate suspect values. The following conditions resulted in deletion of the sample's data record:

- Missing values for soil properties used for model development
- Bulk density values <2.25 and >0.25 g cm^{-3}
- Organic C (c_org) values <100%
- Water content (wc) values <150%
- Individual clay, sand, or silt contents <100%
- Sum of clay, sand, and silt <106 or >94%

Establishing an acceptable range of 106 to 94% for the sum of clay, sand, and silt allows for a 2% error in each of the individual measurements of clay, sand, and silt content. Following quality control approximately 47 000 of the 50 904 samples that contain oven-dried bulk density measurement were available for model development.

Before model development, collinearity diagnostics for the independent variables were examined. Variables sand and siltplusclay were dropped from consideration because they are a linear combination of other variables. Since sand was dropped, $sand^2$ and $sand^3$ were also dropped. The ratio of water content at −15 bar to clay content (w15cly) was dropped from consideration because including this variable would exclude samples with clay contents of zero.

The data were subdivided into groups by suborder using taxonomic information contained in the database. Due to differences in clay content, organic C, and water content among soil suborders, partitioning the data by suborders reduced the variance of soil properties in the data sets with the goal of finding a range of soil property data for which a linear regression works well. Another advantage of this approach is that correlation of bulk density with other soil properties is probably more stable and consistent within groups of soils that have similar characteristics. Manrique and Jones (1991) have shown that partitioning data by suborders is beneficial for the purpose of predicting bulk density. Wösten et al. (2001) found that more accurate regression equations can be developed for groups in a database of measured soil hydraulic characteristics as compared with the database as a whole. Thus in this study, a regression equation was developed for each suborder.

Following model development, plots of studentized residuals for each suborder's regression equation were examined to identify possible outliers. In addition, plots of residual versus predicted values for each suborder were examined for patterns indicating an invalid fitted model. Collinearity diagnostics were examined again for each suborder. Suborders with a collinearity condition indices >14 and a proportion of variance >0.5 for two or more variables were presumed to have a collinearity problem. In these cases, one or more of these variables were deleted from the regression equation then the stepwise regression was repeated until the collinearity diagnostics no longer indicated a problem.

A relatively small number of samples (2115) in the database lack oven-dried bulk density measurements, but contain the one-third bar or field moisture content bulk density measurements described in Table 1. To determine relationships between these bulk density measurement methods, linear regression models were created using the procedure REG in SAS (SAS Institute, 1982).

RESULTS

Regression equations developed for each suborder are displayed in Table 3. The *P* values for all the models and independent variables are <0.001. The minimum number of samples required for a valid model was determined by multiplying the number of predictor variables (including the intercept) by ten (Muller and Fetterman, 2002). Suborder models lacking enough samples to meet this requirement were dropped from consideration and are not shown on Table 3. Cryids, Arents, Gypsids, Umbrepts, and Torrerts were suborders with enough samples to meet this requirement but are not shown on Table 3 because none of the parameters were significant predictors of bulk density. A possible explanation for the reason that Cryids, Umbrepts and Torrerts were unable to be modeled is that they had a low number of samples. Gypsids had plenty of samples (109) but the fact that they were unable to be modeled is not surprising since they are Aridisols. Suborders belonging to the Aridisol order have some of the lowest R^2 values compared with other suborders in Table 3. Arents lack diagnostic horizons because they have been mixed deeply by plowing, spading, or other methods by humans. Thus, they are likely to have large variations in bulk density due to the mechanical disturbance by humans. This is a probable reason that they were unable to be modeled. Figure 1 displays the resulting linear regression relationship of suborder model estimated oven-dried bulk density to measured oven-dried bulk density for all suborders.

A large number of samples in the database lack bulk density measurements and appropriate taxonomic information for suborder model prediction. To predict the bulk density of these samples, a multiple regression model was developed for all soils, regardless of taxonomic classification. The resulting equation, displayed in Table 3, is called the "all-soils" model. Figure 2 displays the resulting linear regression relationship of "all-soils" model estimated oven-dried bulk density to measured oven-dried bulk density.

Simple linear regression models were also developed between oven-dried bulk density and the other two bulk density measurement methods shown in Table 1. The relationship between the oven-dried and field moisture content bulk density measurements was:

$$(\text{Bulk density, oven dry}) = 0.54 + 0.697 \; (\text{Bulk density, field moisture content})$$

with an R^2 value of 0.70. This model was developed from 2473 samples. The high R^2 value of the model is somewhat surprising since field moisture content can vary; thus, one might expect clod volume and consequently field moisture content bulk density to vary significantly.

The relationship between the oven-dried and one-third bar bulk density measurements was:

$$(\text{Bulk density, oven dry}) = 0.37 + 0.839 \; (\text{Bulk density, 1/3 bar})$$

with an R^2 value of 0.69. The model was developed from 48 058 samples and shows that oven-dried bulk density is generally higher than one-third bar bulk density. Thus, clod volume is lower for oven-dried samples than for one-third bar samples due to the additional water loss and shrinkage on oven drying the soil clod. The *P* values for both models are <0.0001. The results show that both the field water content and one-third bar measurements are useful for predicting oven-dried bulk density.

Oven-dried bulk density values estimated from the regression models were added to the database. Where taxonomic information was available, the suborder models were utilized, and for samples lacking taxonomic classification, the "all-soils" model was used. For the relatively small number of samples in the database lacking a measurement for oven-dried bulk density but not one-third bar or field moisture bulk density, the regression equations displayed above were used to predict oven-dried bulk density. Since these equations yield an accurate prediction ($R^2 = 0.70$ and 0.69) of oven-dried bulk density, they were used instead of the suborder models or all-soils model.

DISCUSSION AND CONCLUSIONS

Results of this study show that oven-dried bulk density can be predicted from parameters such as organic C content, particle-size distribution, water content, and depth ($R^2 = 0.45$, Fig. 2). However, when the data were partitioned by suborders, bulk density prediction using the same parameters improved significantly ($R^2 = 0.62$, Fig. 1). Regression equations can also be used to accurately predict ($R^2 = 0.69$ and 0.70) oven-dried bulk density from other types of bulk density measurements.

Results show that organic C content and the square root of organic C content are strongly correlated to bulk density. Organic C content shows a negative relationship with bulk density, indicating bulk density decreases as organic C content increases. This result is consistent with published relationships between bulk density and soil properties (Federer et al., 1993; Saini, 1966; Manrique and Jones, 1991; Rawls, 1983). Organic C content alone explains 25% of the variation in bulk-density for all soil samples in the database (Fig. 3). The square root of organic C content alone, explains 33% of the variation in bulk-density (Fig. 4). Taking the square root of organic C content reduces the impact of extreme values. The same effect could be achieved by taking the logarithm of organic C; however, the square root was chosen since there are samples in the database with organic C contents of zero.

Partitioning the data by suborders resulted in development of regression equations for 48 suborders (Table 3). Oven-dried bulk density was poorly predicted ($R^2 < 0.40$) from soil properties for 13 suborders and relatively accurately predicted ($R^2 > 0.60$) for 14 suborders (Table 3). The quality of the regression models for suborders is affected by presence of organic C since organic C content is the best predictor of bulk density. Other parameters such as water content at −15 bar, clay content, silt content, and depth describe variation in bulk density, but not to the extent that organic C does. Thus, suborders

Table 3. Regression relationships between soil properties and oven-dried bulk density for suborders and all soils (all-soils model).

Suborder	Order	Intercept	c_org$^{1/2}$	c_org	c_org^2	c_org^3	wc	wc^2	wc^3	clay	clay^2	clay^3	depth	silt	silt^2	silt^3	IN†	R^2	N‡	RMSE§
Aqualfs	Alfisols	1.887	−0.176				−0.0029			0.0061		-9.08×10^{-7}		−0.0038			5	0.41	1895	0.130
Boralfs	Alfisols	1.784	−0.347														1	0.34	69	0.212
Cryalfs	Alfisols	1.746	−0.333				−0.0254			0.0194				−0.0038			4	0.68	203	0.167
Udalfs	Alfisols	1.853	−0.180				−0.0184			0.0065			0.00040	−0.0020			5	0.44	4505	0.140
Ustalfs	Alfisols	1.673		−0.171	0.0149		−0.0122			0.0105		-8.07×10^{-7}		−0.0017			6	0.38	1343	0.142
Xeralfs	Alfisols	1.859	−0.312				−0.0234			0.0103							3	0.53	887	0.179
Aquands	Andisols	1.184					−0.0156										1	0.65	20	0.161
Cryands	Andisols	1.270	−0.224		0.0027		−0.0141			0.0170			0.00164				5	0.63	290	0.202
Udands	Andisols	1.292	−0.141														1	0.24	204	0.251
Ustands	Andisols	1.517					−0.0129										1	0.34	61	0.165
Vitrands	Andisols	1.588	−0.513							0.0099							2	0.72	79	0.203
Xerands	Andisols	1.148	−0.144									1.05×10^{-5}	0.00181				3	0.44	207	0.216
Argids	Aridisols	1.797	−0.182				−0.0130				1.22×10^{-4}			−0.0021			4	0.32	1763	0.146
Calcids	Aridisols	1.743	−0.166				−0.0134					1.91×10^{-6}		−0.0020			4	0.27	872	0.164
Cambids	Aridisols	1.755		−0.087			−0.0245				1.97×10^{-4}			−0.0024			4	0.53	607	0.147
Durids	Aridisols	1.625	−0.194													-5.15×10^{-7}	2	0.18	390	0.176
Salids	Aridisols	1.348								0.0046							1	0.26	51	0.150
Aquents	Entisols	1.731	−0.288							0.0058					-3.10×10^{-5}		3	0.77	183	0.137
Fluvents	Entisols	1.591	−0.114				−0.0170			0.0102				−0.0014			4	0.31	815	0.136
Orthents	Entisols	1.661	−0.167				−0.0295	0.00042		0.0098							4	0.33	1006	0.168
Psamments	Entisols	1.674	−0.310							0.0150					-2.41×10^{-4}		3	0.52	425	0.157
Saprists	Histosols	1.488					−0.0095										1	0.45	23	0.345
Aquepts	Inceptisols	1.736	−0.142				−0.0438	0.00048		0.0209	-1.25×10^{-4}						5	0.66	724	0.166
Cryepts	Inceptisols	1.722	−0.289							0.0085				−0.0049			3	0.62	209	0.202
Ochrepts	Inceptisols	1.577	−0.390			0.0006				0.0046							3	0.59	126	0.186
Udepts	Inceptisols	1.682	−0.205				−0.0277	0.00029		0.0087			0.00078				5	0.61	1477	0.186
Ustepts	Inceptisols	1.707	−0.271				−0.0185			0.0119						-4.13×10^{-7}	4	0.51	456	0.171
Xerepts	Inceptisols	1.731	−0.199				−0.0427		2.0×10^{-5}	0.0170							4	0.61	293	0.182
Albolls	Mollisols	1.740	−0.302			0.0003	−0.0295			0.0171							4	0.61	186	0.162
Aquolls	Mollisols	1.691		−0.056			−0.0231		3.0×10^{-6}	0.0109							4	0.46	1176	0.163
Borolls	Mollisols	1.577	−0.243							0.0043							2	0.58	122	0.151
Cryolls	Mollisols	1.644	−0.221				−0.0196			0.0136				−0.0022			4	0.57	575	0.176
Udolls	Mollisols	1.590	−0.131					−0.00053		0.0099			0.00032			-4.67×10^{-7}	5	0.45	2192	0.128
Ustolls	Mollisols	1.677	−0.216					−0.00016		0.0076			−0.00028	−0.0024			5	0.31	4130	0.152
Xerolls	Mollisols	1.759	−0.299		0.0043		−0.0242		4.3×10^{-6}	0.0172	-9.49×10^{-5}			−0.0016			7	0.46	2081	0.166
Udox	Oxisols	1.805		−0.031			−0.0112								-8.39×10^{-5}		3	0.58	192	0.098
Ustox	Oxisols	0.702								0.0225	-1.66×10^{-4}						2	0.70	37	0.085
Aquods	Spodosols	1.876	−0.337														1	0.61	158	0.201
Cryods	Spodosols	1.277	−0.185										0.00357				2	0.58	175	0.239
Orthods	Spodosols	1.780	−0.379										0.00123				2	0.75	687	0.174
Aquults	Ultisols	1.867	−0.255													-1.85×10^{-7}	2	0.64	311	0.113
Humults	Ultisols	1.789	−0.197				−0.0176					1.13×10^{-6}					3	0.50	206	0.160
Udults	Ultisols	1.783	−0.191				−0.0266			0.0083			0.00017				4	0.41	3004	0.130
Xerults	Ultisols	1.686	−0.304														1	0.57	71	0.152
Aquerts	Vertisols	1.641		−0.089			−0.0160			0.0101							3	0.47	317	0.144
Uderts	Vertisols	1.891		−0.087												-6.04×10^{-7}	2	0.28	343	0.130
Usterts	Vertisols	1.711			−0.0487	0.0059				0.0020							3	0.23	619	0.115
Xererts	Vertisols	1.720			−0.0181		−0.0218			0.0105							3	0.54	192	0.138
All-soils model		1.685	−0.198				−0.0133			0.0079			0.00014	−0.0007			5	0.44	47015	0.188

† Number of input parameters.
‡ Number of observations.
§ Root mean square error.

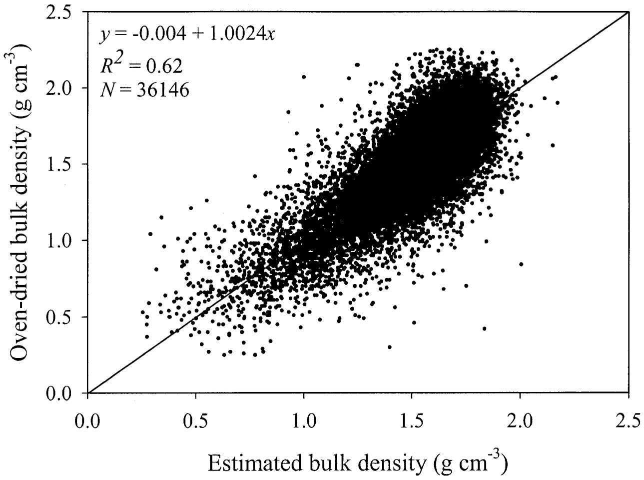

Fig. 1. Observed versus estimated oven-dried bulk density. The estimated bulk density values were obtained from the suborder models.

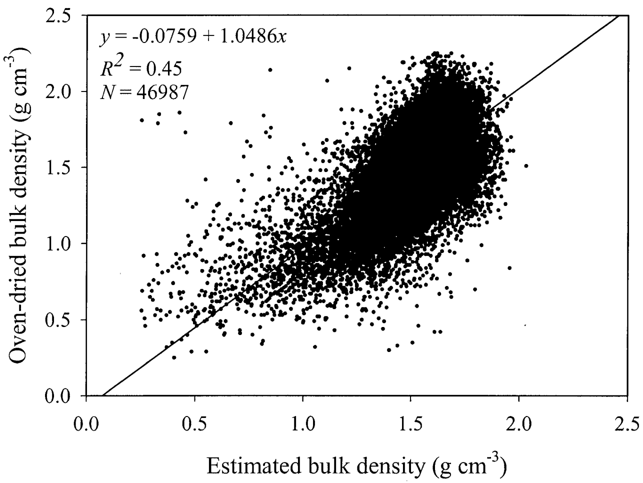

Fig. 2. Observed versus estimated oven-dried bulk density. The estimated bulk density values were obtained from the all-soil model.

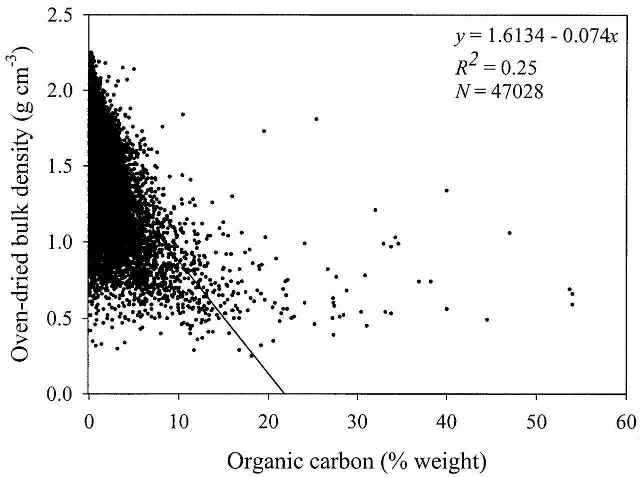

Fig. 3. Observed oven-dried bulk density versus organic C content.

with little or no organic C have lower R^2 values. These include suborders in the Aridisol and Vertisol orders. Xererts have the highest R^2 of the suborders in the Vertisol order since water and clay content explain 49% of the variation in bulk density. This is consistent with the high shrink-swell potential of Xerert soils. Silt and clay content explained most of the variation in bulk density for suborders in the Aridisol order. This also makes physical sense because many Aridisols have high silt and clay contents. With the exception of Cryalfs and Boralfs, Alfisols also have low quantities (<0.75%wt) of organic C. The square root of organic C content described 34 and 40% of the variation in bulk density for Boralfs and Cryalfs, respectfully. Clay and water content explained an additional 25% of the variation in bulk density for Cryalfs; this is why Cryalfs have a much higher R^2 value than Boralfs.

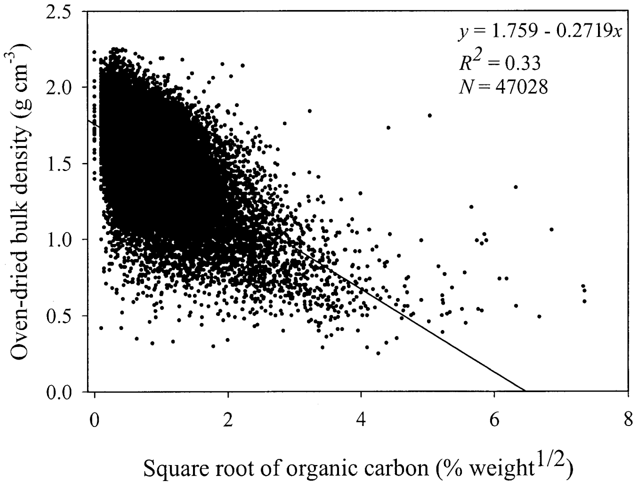

Fig. 4. Observed oven-dried bulk density versus the square root of organic C content.

Suborders of the Entisols show the greatest variation in R^2 values (Table 3). Aquents have the highest R^2 value of all suborders yet Arents were unable to be modeled. This variation can be explained by the fact that Entisols are soils of recent origin that are diverse in environmental setting and land use (USDA, 2004). The high R^2 value for Aquents results from the fact that 54% of the variation in bulk density was explained by the square root of organic C and clay explained an additional 20%. Water content and the square root of organic C content are variables that explained the major portion of the variation in bulk density for suborders in the Andisol order. Water content explained all of the variation in bulk density for both Aquands and Saprists, and both models show an inverse relationship between bulk density and water content. This makes physical sense because Aquands and Saprists are commonly saturated with water.

Organic C content or the square root of organic C content explained most of the variation in bulk density for suborders belonging to the Inceptisol, Spodosol, Ultisol, and Mollisol orders. Organic C, however, explained little or no variation in bulk density for Oxisols. Water and silt content explained most of the variation in bulk density for Udox, and clay content explained 49% of the variation in bulk density for Ustox. Overall, the suborder models developed in this study accounted for between 18 and 77% of the variation in bulk density.

For most soils, depth is inversely related to organic C content. Thus, depth was included in the analysis

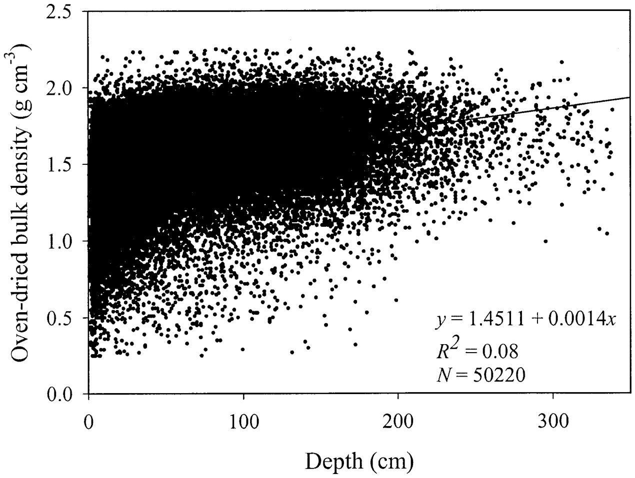

Fig. 5. Observed oven-dried bulk density versus sample depth.

to prevent confounding. Depth is directly related to mechanic stress caused by the weight of overburden soil. It seems logical to expect that this stress would affect soil bulk density. Despite this, results show that depth is not a strong predictor of bulk density. This is due to the distribution of bulk density as a function of depth as seen in Fig. 5. Note the low R^2 value of Fig. 5 and a large variation in bulk density regardless of depth. Depth described 0.08% of the variation in bulk density in the all-soils model. For the suborder models, the depth was not significant enough (*p* value too high) to be included in the finial regression equation for most suborders, and of the suborders that did include depth as a predictor variable, the greatest variation in bulk density that the depth parameter described is 7%.

In comparison with past studies, this study was conducted on a much larger data set. Thus, since regression equations are only valid for the range of data from which they are derived, this range of data improves as more data becomes available. Also, having more samples improves the accuracy of the models since the uncertainties in the regression coefficients are reduced. This study was similar to that conducted by Manrique and Jones (1991) and in some ways may be considered a continuation of their work since they also evaluated data from the Soil Survey Laboratory in Lincoln, NE. This study was conducted on a larger number of samples because more data are now available. Results, however, are not directly comparable with those of Manrique and Jones (1991) since they developed models for predicting one-third bar bulk density instead of oven-dried bulk density. They also grouped their data by suborders, but did not establish a minimum sample size or conduct some of the statistical analyses included in our study.

Establishing a minimum sample size is necessary to obtain a "valid" model (Muller and Fetterman, 2002) and reduces the chances of getting falsely high R^2 values due to bimodal distributions. In this study a minimum sample size was established based on the number of predictor variables, and additional diagnostic analysis were conducted (examined collinearity, plotted studentized residuals and residual versus predicted values). Thus, this study improved on the methods of past studies and has evaluated the impact of including depth in the statistical analysis.

Of the 136 512 samples in the database, 50 904 samples had an oven-dried measurement, and an estimated oven-dried bulk density was determined for 61 138 samples lacking a measurement. The 24 470 samples could not be modeled because they did not meet quality control limits or they were missing data for variables necessary for modeling. Thus, using a combination of the suborder models, the all-soils model, and the measurement method models, oven-dried bulk density can be predicted for 71% of the soil samples in the database lacking an oven-dried bulk density measurement. Results of this study indicate that regression relationships are useful for predicting bulk density from common soil properties. Results also indicate that regression relationships developed between soil bulk density measurement methods are useful for converting bulk density measurements between methods.

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