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RELATIONSHIPS AMONG PHYSICAL AND CHEMICAL PROPERTIES OF REPRESENTATIVE SOILS OF THE TROPICS FROM PUERTO RICO

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Relationships Among Physical and Chemical Properties of Representative Soils of the Tropics from Puerto Rico[1]

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ABSTRACT

In an investigation of the extent to which predictive soil property relationships can be relied upon in characterizing soils of the tropics classified at the reconnaissance level, 9 to 15 soil properties, of 370 horizons, from 84 Puerto Rican profiles, were studied by correlation and multiple linear regression. The soils represented six orders of the new US Soil Taxonomy (7th Approximation): Vertisols, Mollisols, Alfisols, Inceptisols, Ultisols, and Oxisols. Multiple regression equations were formed from the data of each order, with 15-bar moisture content, CEC, organic carbon, extractable iron, and base saturation as dependent variables. The results indicate that, although it is possible to eliminate certain properties from tropical soil data acquisition and still adequately characterize the soil, the specific properties that can be successfully eliminated depend on the soil order.

Additional Index Words: multiple linear regression, Oxisols Ultisols, Vertisols, Inceptisols, Alfisols, Mollisols, tropical soils.

EXTENSIVE AREAS of the tropics contain soils which are unmapped or have been mapped only at a reconnaissance[3] level. Although this lack of basic information points to the need for rapid soil data acquisition, consideration must be given to the limited resources available. The works

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[2] Graduate Research Assistant and Professor of Soils, respectively.

[3] The term reconnaissance in this paper refers to soil surveys with map scales at about 1:100,000 to 1:1,000,000 and with map units defined at high categorical levels, e.g., the order level of the new US Soil Taxonomy (7th Approximation).

Table 1—Soil properties and codings

A. Properties Derived from Field Data (discontinuous code numbers are associated with intermediate property values)

Depth (DEP): code mean horizon depth to nearest centimeter.
Color value (CV): code value reported

Structural grade (GD):
1-single grain or massive; 2-very weak; 3-weak; 5-moderate; 7-strong; 8-very strong

Size of structural unit (SZ):
1-very fine; 3-fine; 5-medium; 7-coarse; 9-very coarse

Shape of structural unit (SH):
1-platy; 2-prismatic or columnar; 4-angular blocky; 6-subangular blocky; 8-granular; 9-crumb

Moist consistence (MC):
1-loose; 2-very friable; 3-friable; 5-firm; 7-very firm; 8-extremely firm

Sticky consistence (SC):
1-non-sticky; 3-slightly sticky; 5-sticky; 7-very sticky

Plastic consistence (PC):
1-non-plastic; 3-slightly plastic; 5-plastic; 7-very plastic

B. Properties Derived from Laboratory Data (Soil Conservation Service, 1967a)

Clay (CL): code percentage reported
Soil reaction (pH): code value determined by "Soil suspension, water dilution 1:1"
15-bar moisture content (15W): code percentage determined by "Pressure-membrane extraction, (15 bars)"
Cation exchange capacity (CEC): code meq/100 g determined by "NH_4OAc, pH 7.0, direct distillation"
Organic carbon (OC): code percentage determined by "Acid-dichromate digestion, $FeSO_4$ titration"
Extractable iron (Fe): code percentage determined by "Dithionite-citrate extraction, orthophenanthroline colorimetry"
Base saturation (BS): code percentage determined by "NH_4OAc, pH 7.0"

of researchers such as Sarkar, Bidwell, and Marcus (1966); Swindale (1967); and Banin and Amiel (1970) suggest that statistical relationships among various soil properties could be employed to expedite soil characterization. This study was undertaken to investigate the extent to which predictive soil-property relationships could be relied upon in characterizing reconnaissance soil units of the tropics.

The objective was approached through correlation and multiple linear regression (Draper and Smith, 1966). Applied to soil data, correlation and multiple regression indicate whether the measured values of one or more soil properties can be used to reliably predict the value of other soil properties. If, for example, an equation containing two measured soil properties could reliably predict the value of a third soil property, there would be little reason to measure this third property for soil characterization. Moreover, if measurement of a few selected soil properties could provide nearly the same interpretive description of reconnaissance soil units as measurements of a more complete list of soil properties, then the time, energy, and cost required for characterizing soils in the tropics could be substantially reduced. This is especially true if the selected properties could reliably predict soil properties that would otherwise require costly laboratory analyses.

PROCEDURES

Samples of reconnaissance soil units were obtained by grouping 84 soil series from Puerto Rico into six orders of the new US Soil Taxonomy (7th Approximation): Vertisols, Mollisols, Alfisols, Inceptisols, Ultisols, and Oxisols (Soil Survey Staff, 1960 and 1967). Published morphological and laboratory data on repesentative profiles of the 84 series were used (Soil Conservation Service, 1967b).

The values of 9 to 15 laboratory- and field-determined soil properties from each horizon, in each profile, were coded in accordance with Table 1. A total of 370 horizons were thereby included, with each horizon's soil property values being punched onto a single IBM card.

Table 2—Soil property means and standard deviations

	Orders					
	Vertisol	Mollisol	Alfisol	Inceptisol	Ultisol	Oxisol
Cases:	49	45	42	47	108	79
prop	Mean (sd)	Mean (sd)	Mean (sd)	Mean (sd)	Mean (sd)	Mean (sd)
DEP	26.4(18.1)	16.4(14.4)	19.5(14.9)	17.7(15.1)	25.3(19.3)	27.6(20.1)
GD		2.8(1.4)	3.2(1.3)	2.4(1.4)	3.6(1.6)	3.7(1.0)
SZ						3.5(1.4)
SH						5.3(1.3)
MC				3.9(1.8)	4.1(1.3)	4.1(1.0)
SC	4.2(1.6)			2.4(1.1)	2.3(1.0)	2.6(0.9)
PC	4.9(0.4)			3.3(1.6)	3.5(1.4)	4.1(1.4)
CV	3.3(0.8)	3.5(1.1)	4.5(1.0)	4.4(1.1)	4.5(1.0)	3.7(0.7)
CL	58.3(5.1)	33.7(13.5)	40.8(16.1)	29.0(16.4)	51.7(15.5)	69.2(13.2)
pH		6.7(0.7)	5.5(1.0)	5.6(0.8)	4.7(0.3)	5.1(0.5)
15W	24.8(2.3)	16.4(5.7)	18.0(7.7)	16.1(7.4)	25.0(6.1)	29.4(4.8)
CEC	41.9(9.1)	27.0(10.4)	19.5(8.9)	20.8(12.8)	12.9(4.7)	8.7(3.5)
OC	0.8(0.7)	1.1(0.9)	0.7(0.8)	0.9(0.8)	1.0(1.1)	1.1(1.3)
Fe	2.3(1.0)	2.8(1.2)	3.8(2.1)	2.8(2.2)	6.4(3.0)	12.8(3.7)
BS			77.1(29.5)	81.6(31.2)	22.1(17.0)	30.1(27.3)

The soil property data associated with each of the six orders were put separately into a multiple regression program (BIOMEDICAL, BMDO2R. STEPWISE REGRESSION) on the Cornell University IBM 360/65 computer. Each of the six program outputs provided: (i) correlations between each pair of input soil properties, and (ii) multiple linear regression equations, with 15-bar moisture content, cation exchange capacity, organic carbon, extractable iron, and base saturation as dependent variables.

In formulating the equations, laboratory- and field-determined soil properties were treated so that two types of equations would result: (i) the dependent property vs. field properties, and (ii) the dependent property vs. both laboratory and field properties. Although clay content and soil reaction were obtained by laboratory analyses, they were treated as field-determined properties. Their importance for prediction has been demonstrated with generalized soil data (Philipson and Drosdoff, 1970), and both are commonly estimated or measured in the field.

RESULTS

The means and standard deviations of each soil property and the number of cases (i.e., soil horizons) included in each of the six order programs are recorded in Table 2.

Pairs of soil properties, that occurred in any of the six programs and exhibited coefficients of determination, r^2, greater than 0.500 in at least one of the programs, are listed in Table 3.

Multiple linear regression equations were computed with 15-bar moisture content (15W), cation exchange capacity (CEC), organic carbon (OC), extractable iron (Fe), and base saturation (BS) each, in turn, serving as the dependent variable. The independent variables consisted of either field-determined properties or laboratory- and field-determined properties. The coefficients of multiple determination, R^2, and the standard errors of estimates (se) of both "field property" and "laboratory and field property" equations are listed in Table 4. In addition to the R^2 and standard error computed with all independent variables in the equation, the table records: (i) the stepwise order in which the primary variables entered the equation; (ii) the input variable which first provided a cumulative R^2 of at least 50%; (iii) the last variable to enter, contributing at least 5% to the cumulative R^2; and (iv) the standard error of estimate based on those variables listed.

For example. in predicting 15-bar moisture content

Table 3—Coefficients of determination, r^2

Variable pairs	Orders					
	Vertisol	Mollisol	Alfisol	Inceptisol	Ultisol	Oxisol
DEP vs. OC	0.557†	0.436	0.412	0.504	0.348	0.466
15W vs. CEC	0.398	0.731	0.308	0.557	0.487	0.000
15W vs. CL	0.428	0.812	0.767	0.812	0.790	0.283
CEC vs. CL	0.033	0.734	0.187	0.324	0.379	0.015
SC vs. PC	0.026			0.619	0.086	0.221
15W vs. MC	*			0.557	0.075	0.103
15W vs. SC	0.033			0.552	0.089	0.088
15W vs. PC	0.000			0.591	0.045	0.412
CL vs. MC				0.646	0.177	0.001
CL vs. SC	0.094			0.530	0.158	0.278
CL vs. PC	0.002			0.677	0.096	0.096
BS vs. pH			0.729	0.694	0.218	0.517
Fe vs. 15W	0.015	0.415	0.789	0.375	0.504	0.008
CL vs. Fe	0.054	0.296	0.513	0.167	0.284	0.225
OC vs. CEC	0.110	0.305	0.036	0.130	0.297	0.702

* A blank indicates that one or both of the variables were absent from the particular program.
† An underlined value indicates that r^2 is based on a negative r.

(15W) of Vertisols from field properties, clay content (CL) was the most important variable, depth (DEP) was the next most important variable, and color value (CV) was the third most important variable. All three variables were required to produce an R^2 of at least 50%, (63%), and based on these three variables, the standard error of estimate was 1.4. With two additional field properties, the total equation exhibited an R^2 of 68% and a standard error of estimate of 1.3.

As a second example, consider the Oxisol laboratory and field property equation for 15-bar moisture content (15W). With 14 properties, the equation exhibited an R^2 of 76% and a standard error of estimate of 1.5. The most important predictive property was plastic consistence (PC), and the next most important property was clay content (CL). Although these two properties produced an R^2 that exceeded 50%, (54%), a third property—extractable iron (Fe)—is listed since its inclusion increased R^2 by more than 5%, (17%). With these three variables, the equation exhibited an R^2 of 71% and a standard error of estimate of 2.6.

DISCUSSION

Since the 84 soil profiles considered in this study do not represent the complete range of variation of any order of the new US Soil Taxonomy, relationships presented in this report can only be indicative of relationships that may hold at the order level. Moreover, since these relationships are derived from complete profiles, their use for prediction should be limited to profile characterization.

The most useful multiple regression equation represents a balance between the lowest number of independent variables and the highest R^2, that portion of the total variation of the dependent variable accounted for by the regression equation. Although R^2 values of 50% are used as a criterion in this report, the fact that a statistically significant regression equation can account for 50%, or even 90%, of a property's variation does not determine whether the property can be successfully omitted from tropical soil data acquisition. The regression R^2 must be related to the property's actual variation. If the residual error (i.e., standard error of estimate) is still intolerable to the user, he would not forego the property's measurement.

Referring to the R^2 values (Table 4), it is clear that most equations which contained all independent variables exhibited relatively high predictive power. Field property equations did not explain as large a proportion of the variation of the dependent variable as laboratory and field property equations, yet in most cases, their R^2 values did exceed 50%.

Table 4—Order data regression equations

Ord	Field property equations: Total EQN N*	Total EQN R^2† (se)	Primary portion Form-R^2 (se)	Lab and field property equations: Total EQN N	Total EQN R^2 (se)	Primary portion Form-R^2 (se)
			Dep Var: 15-bar moisture content (15W)			
Ver	5	68(1.3)	CL/DEP/CV-63(1.4)‡	8	86(4.5)	CL/CEC-70/DEP/Fe-83 (0.9)
Mol	5	85(2.2)	CL-81(2.5)	8	89(4.3)	CL-81(2.5)
Alf	5	81(3.4)	CL-77(3.7)	9	94(5.0)	Fe-79/CL-91(2.3)
Inc	8	87(2.7)	CL-81(3.2)	12	97(5.4)	CL-81/CEC-89(2.5)
Ult	8	83(2.5)	CL-79(2.8)	12	90(2.5)	CL-79/Fe-87(2.2)
Oxl	10	64(2.9)	PC/CL-54/SH-60(3.0)	14	76(1.5)	PC/CL-54/Fe-71(2.6)
			Dep Var: Cation exchange capacity (CEC)			
Ver	5	55(6.1)	CV/DEP-50(6.4)	8	76(4.5)	15W/CV-67(5.2)
Mol	5	78(4.9)	CL-74(5.3)	8	83(4.3)	CL-74(5.3)
Alf	5	47(6.5)	(5 variables)	9	69(5.0)	Fe/pH-60(5.6)
Inc	8	66(7.5)	SC/pH/DEP-57/CL-62 (7.9)	12	82(5.4)	15W-56/pH/DEP-73 (6.7)
Ult	8	48(3.4)	(8 variables)	12	71(2.5)	15W/OC-61(2.9)
Oxl	10	48(2.5)	(10 variables)	14	82(1.5)	OC-70(1.9)
			Dep Var: Organic carbon (OC)			
Ver	5	67(0.4)	DEP-56/CV/SC-66 (0.4)	8	76(0.3)	DEP-56/CEC/SC-72 (0.4)
Mol	5	64(0.5)	DEP/CV-60(0.6)	8	65(0.5)	DEP/CV-60(0.6)
Alf	5	52(0.6)	DEP/CL/CV-52(0.6)	9	65(0.5)	DEP/Fe-60(0.5)
Inc	8	76(0.4)	DEP-50/GD/pH/PC-74 (0.4)	12	78(0.4)	DEP-50/GD/pH/PC-74 (0.4)
Ult	8	52(0.8)	DEP/CV/GD/CL-51(0.8)	12	67(0.6)	DEP/CEC-59(0.7)
Oxl	10	59(0.8)	DEP/SZ-53(0.9)	14	85(0.5)	CEC-70/DEP-82(0.6)
			Dep Var: Extractable iron (Fe)			
Ver	5	10(0.9)	(5 variables	8	49(0.7)	(8 variables)
Mol	5	67(0.7)	CV/DEP-52/CL/pH-67 (0.7)	8	73(0.6)	15W/pH-59/DEP-66 (0.7)
Alf	5	67(1.2)	CL-51/CV-57(1.4)	9	88(0.7)	15W-79/CV-84(0.8)
Inc	8	45(1.6)	(8 variables)	12	82(0.9)	15W/SC-60/MC/BS-75 (1.1)
Ult	8	62(1.8)	CL/CV/DEP-57(2.0)	12	76(1.5)	15W-50/DEP/CV-69 (1.7)
Oxl	10	57(2.4)	SH/CL/MC-55(2.5)	14	74(1.7)	SH/CL/MC-55/15W-64 (2.2)
			Dep Var: Base Saturation (BS)			
Alf	5	81(13)	pH-73/DEP-79(14)	9	82(12)	pH-73/DEP-79(14)
Inc	8	78(15)	pH-69(17)	12	79(14)	pH-69(17)
Ult	8	50(12)	(8 variables)	12	60(11)	pH/DEP/Fe-51(12)
Oxl	10	81(12)	pH-52/SH-72(14)	14	85(11)	pH-52/SH/PC/Fe-82 (12)

* N equals the number of independent variables.
† R^2 values have been multiplied by 100 and rounded to two significant places.
‡ All regression equations, except Fe vs. field properties in vertisols, are significant at the 0.01 level.

15-Bar Moisture Content (15W)—As reported by many authors (Petersen et al., 1968), clay content (CL) is generally a reliable predictor of 15W. Clay content, alone, accounted for 77 to 81% of the variation of 15W in Mollisols, Alfisols, Inceptisols, and Ultisols. Although CL could account for only 43% of the variation of 15W in Vertisols (Table 3), the total variation to be accounted for was relatively low (Table 2). In contrast, Oxisols exhibited a low correlation (r^2 = 0.283) between CL and 15W. If soil characterizations were to omit 15W, with the presumption that 15W could be reliably predicted by CL, they would likely be in error whenever their source data was heavily weighted with Oxisols or comparable 1:1 clay soils.

Cation Exchange Capacity (CEC)—With laboratory and field properties, one or two variables were sufficient to account for over 50% of the variation of CEC in every order; without laboratory properties, only the Vertisol, Mollisol, and Inceptisol equations could explain 50% of the variation. It is interesting to note that only Mollisols exhibited a high correlation (r^2 = 0.734) between CEC and clay content (CL), and that only Oxisols exhibited a high correlation (r^2 = 0.702) between CEC and organic carbon (OC)

(Hallsworth and Wilkinson, 1958). It is obvious that clay mineralogy has a direct bearing on the capacity of CL to predict CEC (Helling et al., 1964), and with the exception of Oxisols, OC appears to be an unreliable predictor of CEC.

Organic Carbon (OC)—The inclusion of one or two variables in the laboratory and field property equation of each order was sufficient to account for at least 50% of the variation of OC; moreover, the primary variables in the Vertisol, Mollisol, and Inceptisol equations were field-, rather than laboratory-determined, properties. In contrast, with only field-determined properties, the Oxisol, Alfisol, and Ultisol equations required two, three, and four variables, respectively. In that depth (DEP) was the most important predictive property in 11 of the 12 equations, it is thought that a nonlinear model, e.g., log (OC) = a + b (DEP), would provide substantial improvement in the prediction of OC.

Extractable Iron (Fe)—Although neither Vertisol equation could explain 50% of the variation of Fe, only one variable was required with both Alfisol equations, two variables with both Mollisol equations, and three variables with both Oxisol equations. In Ultisols, 15-bar moisture content (15W), alone, accounted for 50% of the variation of Fe; without laboratory properties, three variables were required. The importance of laboratory-determined properties was best evidenced in Inceptisols: with laboratory properties, two variables explained 60% of the variation of Fe, but without laboratory properties, eight variables could explain only 45%. The fact that 15W was often a primary variable in predicting Fe is partly attributed to the association between Fe and soil structure or aggregation (McIntyre, 1956). In this context, shape of structural unit (SH) was the most important predictor of Fe in Oxisols, the only order which contained SH as an input variable.

Base Saturation (BS)—Soil reaction (pH), alone, accounted for over 50% of the variation of BS in Alfisols, Inceptisols, and Oxisols. In contrast, to explain 50% of the variation in Ultisols, the equations required three variables when laboratory properties were included and eight variables when they were not. Although reasonable estimates of BS can generally be obtained from measurements of pH, the low correlation ($r^2 = 0.218$) between BS and pH in Ultisols indicates that this relationship cannot always be employed successfully. (Neither Vertisol nor Mollisol data contained BS.)

CONCLUSIONS

Although the results of this study have inherent limitations (e.g., only 9 to 15 soil properties were considered, sample sizes were small and non-linear models were not investigated), they point to the potential of regression analysis for expediting soil characterization, they emphasize the potential for error, and they suggest one means of alleviating this error.

The potential of regression analysis is demonstrated by the fact that equations comprised of only clay content, soil reaction, and field-determined properties could provide reasonable estimates of: organic carbon in Inceptisols; cation exchange capacity in Mollisols; base saturation in Alfisols and Oxisols; and 15-bar moisture content in Mollisols, Alfisols, Inceptisols, and Ultisols. Further, the inclusion of only one laboratory-determined property in the regression equations of most orders was sufficient to provide reasonable to good estimates of these properties, as well as of extractable iron.

The results of this study also emphasize one obvious, yet easily overlooked, source of error: a soil property that can be reliably predicted in most soils provides no guarantee that it can be reliably predicted in all soils. Although reasonable estimates of 15-bar moisture content or base saturation could generally be obtained from equations which contained only clay content or soil reaction, clay content provided a poor estimate of 15-bar moisture content in Oxisols, and soil reaction provided a poor estimate of base saturation in Ultisols. These findings indicate that soil property values cannot be reliably estimated by regression equations which have been derived in an indiscriminate manner.

Contending that the reliability of predictive soil property relationships, derived from any group of soils, will increase as the degree of homogeneity of the soils in the group increases, it is proposed that soils be classified, if only at a reconnaissance level, before they are subjected to regression analyses. Predictive soil property relationships can thereby be derived from, and assigned to, the respective soil classes.

In this study, soils were grouped into orders of the new US Soil Taxonomy (7th Approximation)—a comprehensive classification system for which relatively few property measurements are required to classify a soil at this categorical level. If many errors associated with regression can be alleviated by some degree of prior soil classification, and if a profile description and a few property measurements are all that is required to place a soil into a meaningful as well as repeatable soil class, there is ample justification for establishing soil classes before regression analyses are initiated. This is not to suggest that regression must be treated in the context of a conventional soil classification system. Conceivably, aerial photographic analysis would provide a suitable means by which to separate sufficiently homogeneous soil units at high categorical levels.

Whether soil property relationships derived from Puerto Rican soils are valid elsewhere in the tropics remains to be tested. It is expected, however, that if a particular soil in Puerto Rico can be classified in accordance with an acceptable classification system, its property relationships should be comparable to a similar soil in any area of the tropics. If predictive soil property relationships can be established in one region of the tropics and applied in a second, the time, energy and cost of soil characterization in the tropics could be substantially reduced.

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