Int. Agrophysics, 1995, 9, 1-9

STATISTICAL MODELS FOR PREDICTING AGGREGATE STABILITY FROM INTRINSIC SOIL COMPONENTS

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Accepted May 9, 1994

Abstract. The objective of this study was to evaluate the nature of the relationship between the water-stability of soil aggregates and some physical, chemical and mineralogical properties of surface (0-20 cm) soils from central Italy. The index of stability used is the mean-weight diameter of water-stable aggregates (MWD). The ratio of total sand to clay which correlated negatively with MWD (r=-0.638) is the physical property which explained most of the variability in aggregate stability. The chemical properties which correlated best with aggregate stability are FeO (r=0.671), CaO (r=0.635), $CaCO_3$ (r=0.651) and SiO_2 (r=-0.649). Feldspar, chlorite and calcite are the minerals with the most controlling influence on MWD with respective r values of -0.627, 0.588 and 0.550. The best-fit model developed from soil physical properties explained 59 % of the variation in MWD with a standard error of 0.432. The best-fit model developed from chemical properties explained 97 % of the variation in MWD with a standard error of 0.136 and that developed from mineralogical properties explained 78 % of the variation in MWD with a standard error of 0.222. Also the closest relationship between measured and model-predicted MWD was obtained with the chemical properties-based model (r=0.985), followed by the mineralogical properties-based model (r=0.884) and then the physical properties-based model (r=0.656). This indicates that the most reliable inference on the stability of these soils in water can be made from a knowledge of the amount and composition of their chemical constituents.

Keywords: aggregate stability, soil properties, statistical models

INTRODUCTION

One of the measures of the structural status of agricultural soils is the stability of their aggregates when in contact with water. This property is used to assess soil characteristics, such as the tendency to slake and disperse in water [6,15], to compress under static or dynamic load [12], and to erode by water or wind forces [18,22]. Bryan [4] reviewed the relationship between several aggregate stability indices and soil erodibility and found the mean-weight diameter of water-stable aggregates proposed by Van Bavel [21] as one of the best that correlated with simulated soil loss. Egashira *et al.* [7] found this index reliable for predicting the erodibility of allophanic soils in Japan. Elwell [8] also obtained a significant positive correlation between the mean-weight diameter index and rainfall-simulated soil loss from a red tropical clay soil. Furthermore Chisci *et al.* [5] proposed this index as a reliable one for characterizing the structural status of some Mediterranean soils subjected to different intensities of land use.

In spite of the wide use of this index for routine characterization of soil structure, the main soil properties influencing it are not known. This aspect is important for modelling spatial and temporal variations in soil structure from invariant and dynamic properties.

The objectives of this study are threefold:

(i) to identify the main soil physical, chemical and mineralogical properties that correlate best with the mean-weight diameter index (MWD);

(ii) to develop empirical models for predicting MWD from these soil properties, and

(iii) to compare the predictive ability of the models as to ascertain which set of soil properties is most reliable for estimating the stability of the soils in water.

MATERIALS AND METHODS

The fifteen topsoil samples (0-20 cm) used for this study were collected from different parts of the sub-Appenine region of north central Italy. They were chosen to represent the different parent materials, geology, vegetation, climate and dominant land use in the region and to provide a wide variation in aggregate stability to water. Some of the characteristics of the soils are given in Tables 1-3.

Determination of the mean-weight diameter

The samples were air-dried at room temperature (about 20 °C) and presieved through a 4 mm mesh before determining the MWD according to the procedure suggested by Kemper and Chepil [11]. In this method 20 g of the < 4 mm air-dry aggregates were placed on the top of a nest of four sieves of diameters 2, 1, 0.5, and 0.25 mm and soaked in distilled water for 10 min. The sieves and their contents were then oscillated vertically for 20 times along a 4 cm stroke at the rate of 1 oscillation per second.

The aggregates retained on the sieves were oven-dried at 105 °C and their masses recorded. The mass of the 0.25 mm fraction was obtained by difference. The respective dry masses were used to compute the MWD as:

$$\mathrm{MWD} = \sum_{i=1}^{n} W(i)\, \bar{X}_i \qquad (1)$$

where $\bar{X}_i$ is the arithmetic mean diameter of the i-1 and i sieve openings (mm), $W(i)$ is proportion of the total sample weight (uncorrected for sand and gravel) occurring in the fraction (dimensionless), and n is total number of size fractions (in this case 5). Three replicate determinations were made on each soil sample.

Determination of physical, chemical and mineralogical properties

The < 2 mm fraction of the soil samples

Table 1. Some physico-chemical characteristics of the 0-20 cm horizon soil samples

Soil No.	Sand (%)	Silt (%)	Clay (%)	Texture*	Org. C (%)	Mean -weight (mm)	CEC (me/100 g soil)	Classification (soil taxonomy)
01	12.2	41.4	46.4	SiC	1.31	0.78	31.5	Vertic Xerochrept
02	13.1	40.1	46.8	SiC	1.55	0.76	29.9	Vertic Xerochrept
03	56.8	25.1	18.1	L	1.14	0.63	21.7	Fluventic Xerochrept
04	54.2	21.7	24.1	L	1.53	0.73	23.9	Fluventic Xerochrept
05	51.6	28.7	19.7	SCL	1.71	0.75	22.8	Typic Xerochrept
06	54.1	28.1	17.8	SCL	1.51	0.67	22.8	Typic Xerochrept
07	26.0	36.6	37.4	CL	1.35	1.52	22.3	Vertic Xerochrept
08	28.9	34.1	37.0	CL	0.92	1.18	28.3	Vertic Xerochrept
09	22.2	34.0	43.8	C	0.88	0.61	22.8	Vertic Xerochrept
10	52.0	28.3	19.7	L	0.54	0.18	21.2	Typic Psammaquent
11	59.1	24.9	16.0	SL	1.14	0.25	22.3	Typic Psammaquent
12	66.1	19.3	14.6	SL	0.53	0.17	16.9	Typic Psammaquent
13	64.6	22.1	13.3	SCL	1.62	0.50	20.7	Typic Psammaquent
14	49.2	29.9	20.9	SCL	1.49	0.39	21.7	Aquic Xerofluvent
15	46.4	36.0	17.6	SCL	1.71	0.45	25.0	Aquic Xerofluvent
CV %	41.7	22.7	46.9	-	31.1	56.6	15.9	-

*SiC - Silty Clay; L - Loam; SCL - Sandy Clay Loam; CL - Clay Loam; C - Clay; SL - Sandy Loam.

Table 2. Mineralogical properties of the clay fraction of 0-20 cm horizon soil samples

Soil No.	Quartz	Calcite	Muscovite	Chlorite	Feldspar	Kaolinite
			(%)			
01	14.04	12.90	17.0	14.0	10.0	33.0
02	13.91	12.81	16.0	15.0	10.0	34.0
03	26.70	9.60	13.0	12.0	14.0	27.0
04	25.90	10.00	14.0	11.0	13.0	28.0
05	42.70	0.00	10.0	6.0	14.0	25.0
06	40.50	0.00	11.0	6.0	14.0	24.0
07	21.48	7.50	17.0	16.0	11.0	26.0
08	20.52	7.20	16.0	15.0	12.0	25.0
09	20.00	7.60	18.0	17.0	12.0	27.0
10	27.70	0.00	22.0	6.0	25.0	21.0
11	26.80	0.00	23.0	7.0	25.0	21.0
12	29.80	0.00	23.0	6.0	18.0	25.0
13	30.20	0.00	22.0	6.0	17.0	24.0
14	35.40	0.00	33.0	13.0	11.0	10.0
15	36.00	0.00	34.0	13.0	12.0	10.0
CV %	31.7	116.2	36.8	39.0	33.2	28.0

Table 3. Metallic oxides and carbonate contents of the 0-20 cm horizon soil samples

Soil No.	$CaCO_3$	MgO	FeO	CaO	K_2O	Al_2O_3	SiO_2	$\frac{SiO_2}{Al_2O_3}$	TiO_2	MnO
					(%)					
01	13.70	2.5	5.1	8.8	2.8	15.6	51.7	3.31	0.55	0.13
02	13.60	2.6	5.1	8.7	2.6	15.6	52.0	3.33	0.55	0.14
03	11.90	1.6	3.8	7.6	2.3	12.4	61.2	4.94	0.39	0.13
04	12.10	1.8	3.9	7.9	2.4	12.8	61.3	4.79	0.41	0.12
05	0.02	2.8	4.0	0.9	2.0	11.3	71.6	6.33	0.28	0.29
06	0.00	2.6	3.7	0.6	2.1	12.3	70.9	5.76	0.27	0.30
07	12.20	3.6	5.3	7.4	2.5	14.2	55.1	3.88	0.51	0.12
08	11.90	3.4	5.0	7.1	2.5	13.9	55.2	3.97	0.52	0.10
09	12.10	3.0	4.8	6.8	2.6	13.7	55.6	4.06	0.52	0.11
10	0.00	1.9	3.7	0.7	2.5	14.2	67.3	4.68	0.43	0.08
11	0.00	2.3	3.9	1.3	2.6	14.8	69.8	4.72	0.44	0.09
12	0.01	2.6	3.7	1.0	2.4	13.9	69.6	5.01	0.49	0.09
13	0.05	3.7	4.1	1.5	2.4	15.1	68.9	4.56	0.48	0.08
14	0.00	1.5	4.5	1.4	2.4	14.1	68.6	4.86	0.65	0.11
15	0.01	1.7	4.6	1.5	2.5	14.7	67.9	4.62	0.67	0.10
CV%	110.8	26.7	13.6	82.5	8.2	9.0	11.9	17.7	23.80	51.60

was used for these determinations. Particle size analysis was done by the pipette method after dispersing with sodium hexametaphosphate (calgon). The liquid limit was determined by the cone penetrometer technique [17,20] using a standard laboratory penetrometer (Seta Model, 1970). This cone penetration test is a form of shear test which defines the liquid limit by means of a 30° cone, weighing 0.75 kg, that penetrates the wet soil over a distance of 10 mm. The plastic limit was obtained by the classical and conventional Cassagrande method [19], whereas the plasticity index was calculated as the difference between the liquid limit and the plastic limit.

The metallic oxides were determined by X-ray fluorescence, whereas the clay minerals were identified and quantified by a combination of peak intensity and use of internal standards. The cation exchange capacity (CEC) was determined by the sodium acetate displacement method and exchangeable sodium using 1 N ammonium acetate extraction solution. The exchangeable sodium percentage (ESP) is the ratio of exchangeable sodium to the CEC.

Data analysis and model development

First, a correlation matrix of each of the physical, chemical and mineralogical properties data sets and the MWD was produced so as to identify properties that are strongly autocorrelated. The correlation coefficients (r) between MWD and each property were then extracted and evaluated in terms of their statistical significance.

The MWD was thereafter fitted into a generalized multivariate model of the form:

$$\mathrm{MWD} = B_o + B_1X_1 + B_2X_2 + \ldots + B_kX_k + e \quad (2)$$

where e is random error, X_1 to X_k the independent variables in each data set, and B_o to B_k, empirical constants whose values are being estimated, and analysed sequentially using the step-wise multiple regression technique. The model with the highest coefficient of determination (R^2) and the smallest standard error (S.E.) of prediction was chosen as the best. Finally for each of the soils the measured and model predicted MWD were plotted for a graphical evaluation of how close the two values are.

RESULTS AND DISCUSSION

The stability of aggregates in water depends on the energy input from the applied forces and the method of application vis-a-vis the concentration of aggregate stabilizing and destabilizing materials present [10].

When an aggregate is suddenly emersed in water (as was done here) the outside of the aggregate is wetted as water moves into it. Air within the intra aggregate pores is compressed and the wetted zone becomes weak by swelling. As the entrapped air is further compressed its pressure builds up until the aggregate shatters into tiny fragments of different sizes and strength and the entrapped air escapes. Further breakdown occurs during sieving in water when the energy input exceeds the strength of the immersed aggregates. In this study the characteristics of the energy input were kept constant by using the same quantity of water of the same ionic strength and temperature and by using the same number of oscillations along the same stroke during each determination. In this way any difference in the stability of the soil aggregates is due to differences in the intrinsic properties of aggregates which control stability.

Some of the soil properties which influence aggregate stability are the moisture and O.M. contents at the time of sieving, and the concentration and nature of the constituent aggregate-stabilizing agents (such as amount of clay, silica polyvalent cations, free $CaCO_3$, oxides of iron and aluminium, and type of minerals). The moisture content was kept constant by using air-dry aggregates so that the influence of the other more intrinsic factors can be evaluated.

Physical properties and aggregate stability

The correlation coefficients between MWD and the measured soil physical properties are shown in Table 4.

Although the absolute values of the correlation coefficients are generally small and may not mean much in physical terms some significant relationships are worth pointing out. The negative correlation of total sand (TS) and positive correlation of clay (CL) with MWD agree with literature. Clay particles have large surface areas and act as the building blocks of aggregates (at the fundamental level of aggregation) by forming linkages with humic substances which are mediated by polyvalent

Table 4. Correlation between mean-weight diameter of water-stable aggregates (MWD) and selected soil physical properties

Variables	Correlation coefficient (r)	Probability level of significance
Total Sand (TS)	-0.578	*
Silt (Si)	0.512	*
Clay (CL)	0.589	*
Fine Sand (FS)	-0.520	*
Course Sand (CS)	-0.437	NS
Liquid Limit (LL)	0.514	*
Plastic Limit (PL)	0.106	NS
Plasticity Index (PI)	0.609	**
TS/CL	-0.638	**
(FS+Si)/CL	-0.610	**
FS/CL	-0.623	**
CS/CL	-0.056	NS

* Significant at P=0.05; ** Significant at P=0.01; NS - not significant.

metals. The sand fractions on the other hand have small surface areas and are difficult to adhere together, hence they are easily disaggregated in water. The ratio of TS/CL gave the highest r value with MWD (-0.638) which further confirms that the relative proportions of these two particle fractions are important in assessing the structural status of these soils. When the r values for fine sand (FS) and coarse sand (CS) fractions are compared (-0.520 vs -0.437) it is obvious that the fine sand component of total sand is contributing more of the negative influence of TS on MWD. This assertion is also confirmed by the r values for FS/CL and CS/CL (-0.623 vs -0.056).

The positive correlation between the silt (Si) fraction and MWD is difficult to explain, more especially since it is known that the higher the FS+Si fractions in soils the greater their tendency to erode [22]. The negative correlation (-0.610) between (FS+Si)/CL ratio and MWD confirms this. It is possible that some aggregate stabilizing substances (e.g., humic substances and metallic oxides) which are concentrated in the silt fraction gave this indication that the silt fraction contributes to stabilizing aggregates.

The best-fit multiple regression model relating MWD to the physical properties is given in Table 5 and it accounted for just 59 % of the variability in aggregate stability. Considering that most of the variables in this model are autocorrelated (data not shown), and the ratios are derived properties, it is reasonable to accept the TS/CL ratio as the physical variable which explains most of the variation in MWD. This is consistent with literature as it is closely related to the clay ratio of Bouyoucos [2] and agrees with the findings of Bruce-Okine and Lal [3] and Mbagwu [13] who related particle size fractions to a raindrop energy-based index of aggregate stability. This model is:

$$\mathrm{MWD} = 0.99 - 0.64\,(\mathrm{TS/CL}) \qquad (3)$$

and explained 41 % of the variation in MWD.

Table 5. Stepwise multiple regression model relating mean-weight diameter of water-stable aggregates (MWD) to selected soil physical properties

Variables[x]	B	Standard error (SE) of B	Coefficient of determination (R^2)
TS/CL	-0.567	4.36	0.406
CS/CL	-0.024	0.11	0.437
(FS+Si)/CL	-0.901	4.35	0.464
PI	0.059	0.09	0.492
TS	0.437	0.156	0.564
Si	0.127	0.374	0.574
FS	0.066	0.213	0.585
FS/CL	-0.183	0.972	0.588
CL	0.020	0.146	0.590
PL	-0.014	0.129	0.591
Constant	0.94		

S.E. of predicted MWD: 0.432

[x] Variables are explained in Table 4.

Chemical properties and aggregate stability

Of the twelve chemical variables considered in this study only four are significantly related to MWD (Table 6). These are $CaCO_3$, FeO and CaO which influenced MWD positively and SiO_2 which had a negative effect on MWD. These results confirm those of Baver *et al.* [1] and Harris *et al.* [9] who noted that the stability of aggregates requires the cementation of the flocculated finer soil particles by

Table 6. Correlation between mean-weight diameter of water-stable aggregates (MWD) and selected soil chemical properties

Variables	Correlation coefficient (r)	Probability level of significance
CEC[x]	-0.241	NS
ESP[xx]	-0.262	NS
$CaCO_3$	0.651	**
MgO	-0.132	NS
FeO	0.671	**
CaO	0.635	**
K_2O	0.022	NS
Al_2O_3	-0.090	NS
SiO_2	-0.649	**
SiO_2/Al_2O_3	-0.339	NS
TiO_2	-0.024	NS
MnO	-0.181	NS
O.C.%	0.282	NS

[x]CEC - Cation Exchange Capacity; [xx]ESP - Exchangeable Sodium Percentage; **Significant at P=0.01; NS - not significant.

Table 7. Stepwise multiple regression model relating mean-weight diameter of water-stable aggregates to soil chemical properties

Variables	B	Standard error (SE) of B	Coefficient of determination (R2)
FeO	1.33	0.28	0.450
TiO_2	-3.01	1.04	0.763
Al_2O_3	0.47	0.19	0.810
CaO	0.19	0.06	0.819
SiO_2	-0.22	0.07	0.855
SiO_2/Al_2O_3	-1.56	0.52	0.912
CEC	0.53	0.03	0.948
K_2O	-0.81	0.78	0.968
MnO	0.13	0.04	0.969
ESP	-0.87	0.06	0.970
MgO	0.54	0.01	0.971
Constant	-2.74		

S.E. of predicted MWD: 0.136

iron and aluminium oxides, calcium oxide and calcium carbonate. Working on some of these soils, Mbagwu and Bazzoffi [14] also observed that increasing stability of the aggregate was associated with increasing clay, iron oxide and decreasing SiO_2. The best-fit complete model relating the MWD to chemical properties is given in Table 7 and it accounted for 97 % of the variability in aggregate stability. Of this 97 %, three minerals (FeO, TiO_2 and Al_2O_3) accounted for 81 % whereas the other eight variables accounted for just 16 % of the total variance in aggregate stability. In fact, for all practical purposes, it is the oxides of iron and titanium that explained most of the variability (76 %) in MWD. The model is:

$$MWD = 1.33\,(FeO) - 3.01\,(TiO_2) - 1.97 \quad (4)$$

Iron and aluminium oxides contribute positively to aggregate stability by bridging the negatively charged organic matter and also negatively charged clay particles. This is the well-known clay-polyvalent metal-organic matter model of aggregation proposed by Harris *et al.* [9].

The negative influence of TiO_2 on aggregate stability has not been elucidated. What this study has shown, however, is that the presence of large amounts of TiO_2 in soils will diminish the positive contribution of Fe and Ca oxides on aggregate stability.

Mineralogical properties and aggregate stability

The correlation between aggregate stability and the six measured mineralogical properties is given in Table 8. Of these variables only three are significantly related to MWD. These are calcite and chlorite with positive correlation and feldspar with negative correlation. This indicates that the clay minerals chlorite and calcite increase aggregate stability, an observation made also by Nwadialo and Mbagwu [16] at the micro-aggregation level. This study also indicates that soils in which the minerals: feldspar, quartz and muscovite dominate the clay fraction should be expected to have lower stability in water than those dominated by kaolinite, chlorite and calcite irrespective of the absolute amount of clay particles present.

The best-fit complete model relating the MWD to these mineralogical properties is given in Table 9 and it accounted for 78 % of the variability in aggregate stability. Three of

Table 8. Correlation between mean-weight diameter of water-stable aggregates (MWD) and selected soil mineralogical properties

Variables	Correlation coefficient (r)	Probability level of significance
Quartz	-0.348	NS
Calcite	0.550	*
Muscovite	-0.480	NS
Chlorite	0.588	*
Feldspar	-0.627	**
Kaolinite	0.393	NS

* Significant at P=0.05; ** Significant at P=0.01; NS - not significant.

the minerals, feldspar, muscovite and chlorite accounted for 64 % whereas the rest (calcite, quartz and kaolinite) accounted for just 23 % of the variability in MWD. This indicates that the amount of the expanding mineral (chlorite), the flat-shaped mineral (muscovite) and feldspar in these soils has a controlling influence on the stability of the aggregates in water.

Table 9. Stepwise multiple regression model relating mean-weight diameter of water-stable aggregates to soil mineralogical properties

Variables	B	Standard error (SE) of B	Coefficient of determination (R2)
Feldspar	-0.076	0.04	0.394
Muscovite	-0.085	0.03	0.551
Chlorite	0.026	0.06	0.639
Calcite	0.059	0.04	0.692
Quartz	-0.073	0.04	0.712
Kaolinite	0.084	0.05	0.784
Constant	7.93		

S.E. of predicted MWD: 0.222

Comparison of the predictive ability of the models

The goodness of fit of these models was assessed by the magnitude of the coefficient of variation (R^2) and the standard error (S.E.) of the predicted values as well as by comparing the measured and predicted MWD values. The physical-properties based model has R^2 of 59 % and S.E. of 0.432; the mineralogical properties-based model has R^2 of 78 % and S.E. of 0.222 whereas the chemical properties-based model has R^2 of 97 % and S.E.of 0.136. A comparison of the measured and predicted MWD values is shown in Fig. 1. Again the closest agreement between measured and predicted values was obtained with the chemical properties-based model (r = 0.985), followed by the mineralogical properties-based model (r = 0.884) and least with the physical properties-based model (r = 0.656). Considering the magnitude of the R^2 (the higher the better), that of standard error (the lower the better) and the closeness of the measured and predicted MWD values, it is concluded that the model developed from the chemical properties of these soils is the most reliable for estimating the aggregate stability of these soils, followed by the mineralogical properties-based model. In terms of the ease of determining the variables, the physical properties-based model is the simplest but it is the least reliable in terms of its predictive ability.

Determination of the chemical and mineralogical properties of soils for the sole purpose of using them to predict aggregate stability is very time-consuming. The usefulness of this study is that it has identified which set of properties has the most controlling influence on aggregate stability. Also on similar soils where these properties have been determined already, an assessment of their comparative structural status can be made by utilizing these models.

ACKNOWLEDGEMENTS

This study was partially financed through a research grant (TWAS RG MP 92-043) awarded to the second author by the Third World Academy of Sciences, Trieste, Italy, to carry out 'A Multivariate Analysis of Intrinsic Factors Controlling Water-Stability of Soil Aggregates'.

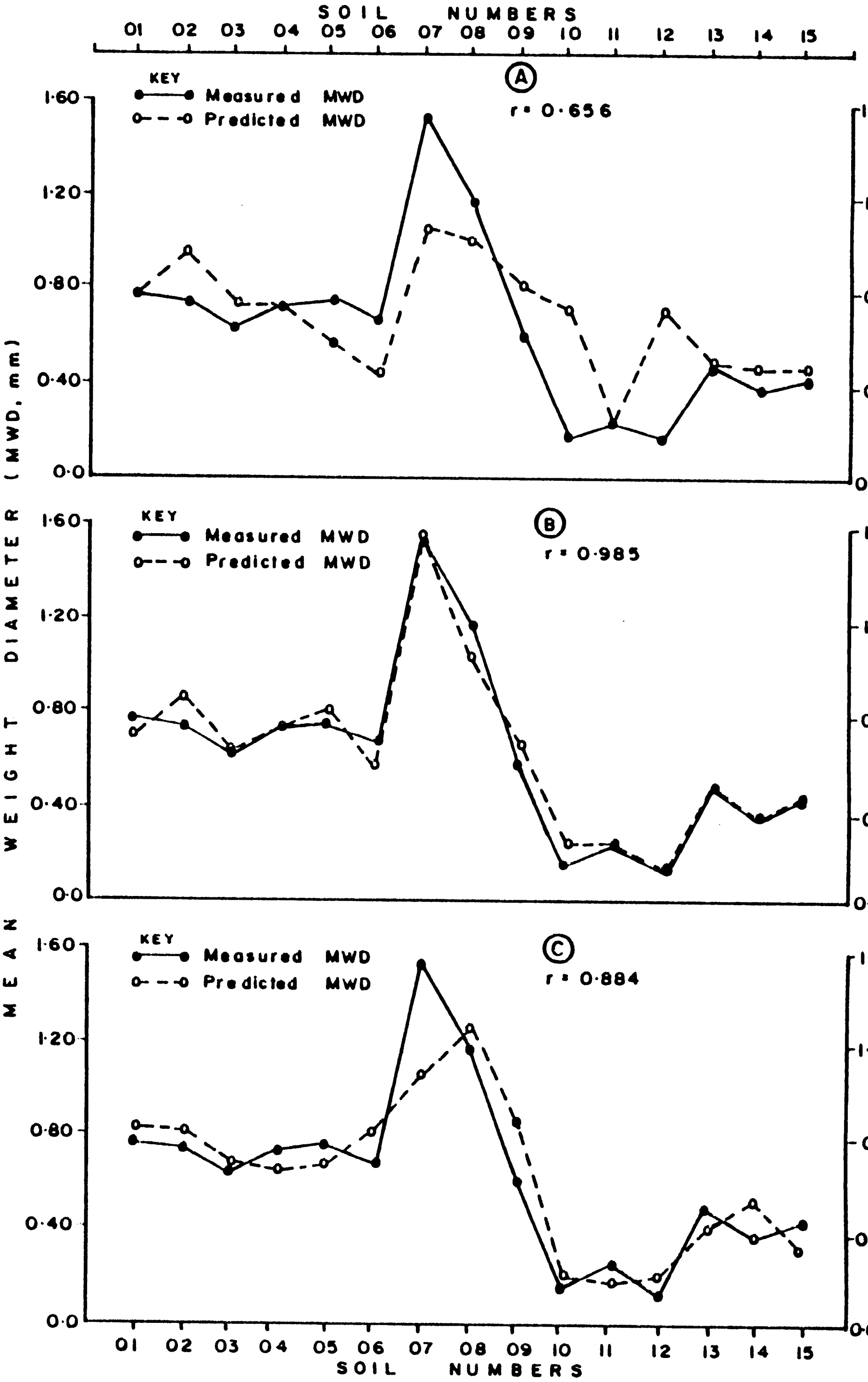

Fig. 1. Comparison of measured and predicted mean-weight diameter of water-stable aggregates. A, B and C - models developed with physical, chemical and mineralogical properties, respectively.

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