0038-075X/05/17002-90–101
Soil Science

February 2005
Vol. 170, No. 2
Printed in U.S.A.

EFFECT OF ORGANIC CARBON ON AVAILABLE WATER IN SOIL

Alan Olness and David Archer

A model of the water-holding characteristics of soil is needed to develop a systematic method for determining the value of organic C in soil. In the United States, available water-holding capacity (AWC) in soil is that water retained in soil between field capacity and the permanent wilting point; these limits are approximated by that water retained between two energy limits: −1500 matrix potential (hygroscopic and micropore water) and about −33 kPa matrix potential (capillary rise). The General Energy Model for Limited Systems (GEMLS) was used to describe the effects of clay, silt, and organic matter on the AWC limits. The U.S. national soil inventory database (more than 100,000 entries) was segmented into narrow ranges of organic C content and silt content. The data from each subset were plotted as a function of soil clay content. Because of an apparent matrix transition effect, two complementary GEMLS functions were used to describe the −33 kPa and −1500 kPa water content as a function of soil clay, silt, and organic C contents. The model used six parameters (two function coefficients, two energy coefficients, and two critical clay contents), and required an initial manual fit of the models to the data subsets (about 100 ± 20 observations). Criteria for acceptance were uniform and homogenous distribution of the model residuals, absence of a detectable trend in the residual distribution, zero error sum, and maximal R^2. The primary energy coefficients were correlated with silt content. After the initial manual fit, the data were subjected to analysis using the SAS PROC MODEL procedure and a variable energy coefficient. Subsequent analyses indicated a complex relationship between the energy coefficients and the soil organic C content. A 1% increase in soil organic carbon causes a 2 to >5% increase in soil AWC depending on the soil texture. (Soil Science 2005;170:90–101)

Key words: Soil texture, field capacity, wilting point, General Energy Model for Limited Systems

THE effect of organic carbon on available water-holding capacity (AWC) in soil has been a source of controversy for nearly a century. Working with a muck soil, Buckingham (1907) noted that it retained much greater amounts of water (as much as 65% water) than mineral soils at similar gravitational heads. Still, early observers tended to regard organic matter as an incidental and temporal contaminant of soil. Some of the first soil water retention models ignored the effects of both organic matter and particle interactions (Briggs and Shantz, 1912; Alway and Russell, 1916; Smith, 1917; Middleton, 1920). Because the models included all three particle separates, they also incorporated a flaw of multicollinearity. Nevertheless, all stressed the importance of soil texture on water retention, and clay was viewed as a major factor. Thirty years later, Smith and Browning (1947) showed a very distinct soil-texture effect on the water content at −33 kPa and at −1500 kPa. They too ignored organic matter. However, their data showed that soil that had a much larger organic matter content had the greatest available soil moisture capacity among the soils compared.

While omission of organic matter from consideration in early studies is thus understandable,

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Received June 2004; accepted Oct. 7, 2004.
DOI: 10.1097/01.ss.0000155496.63323.35

February 2005
Vol. 170, No. 2
Printed in U.S.A.

it is still surprising because organic matter was generally recognized as important to soil tilth and moisture relations. For example, Alway and Neller (1919) studying continuous cropping and rotation systems, concluded that . . . *"the difference in organic-matter content . . . caused a marked difference in the amounts of useful moisture"* . . . They saw measurable increases in both available water and crop yield.

Several studies obtained increases in AWC ranging from about 0.8 to 8.4% for each percent increase in organic carbon (Fig. 1) (Havis, 1943; Stone and Garrison, 1940; Russell et al., 1952; Salter and Haworth, 1961; Hamblin and Davies, 1977; Emerson, 1995). Increases as a result of manure additions have tended to be less than those brought about by indigenous decay of plant materials. Thus, the range of estimates for benefits of organic carbon for AWC is quite large.

Even so, Jamison (1953) concluded that except for sandy soils, organic matter increases had little effect on the capacity to store available soil moisture. In 1958, Jamison and Kroth developed a number of simple correlations between available water and textural components and showed that organic matter was correlated with available water when all samples were considered. Clay and coarse silt seemed most consistently correlated and organic matter was weakly correlated with available water. In 1959, Lund also noted the strong relationship of clay and available soil water content, but like previous authors, he ignored effects of soil organic matter on available water content.

The March of the Models

With the development of the computer and statistical methods, a flood of models was produced in an attempt to describe soil water content. Assessing the factors that contribute to water retention in soil has followed two approaches: the component approach and the systems or energy approach.

The Component Approach

The component approach attempted to characterize the contribution of various separates to soil AWC in much the same manner as Briggs and Shantz (1912). Using this approach, Salter et al. (1966) noted a different pattern of factors depending on the particle size separation scheme used (U.S. vs international).

Shaykewich and Zwarich (1968), describing −33 kPa matrix potential water content correctly, used only two soil separates plus organic carbon and an organic carbon by clay interaction. All coefficients are positive and, philosophically speaking, this seems improbable; interactions of particle separates and organic matter should effect reductions in some contributions. However, their model contained no other interaction terms and, in regard to soil structure observations, the omissions are important.

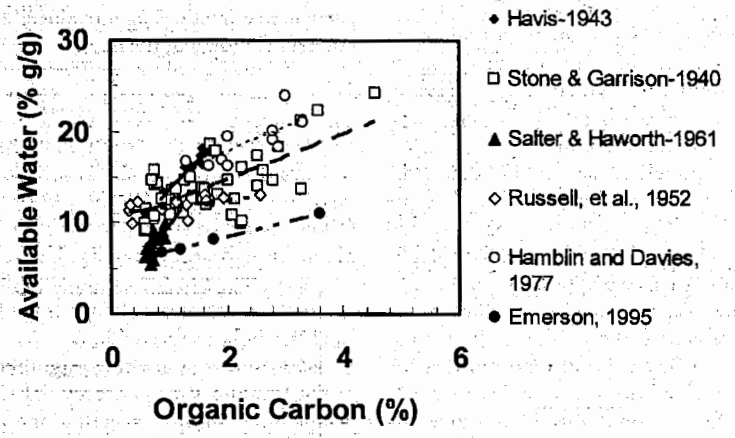

Fig. 1. The effect of organic carbon on soil available water content (%) obtained by □ = Stone and Garrison (1940); ◆ = Havis (1943); and, ▲ = Salter and Haworth (1961); ◇ = Russell, et al. (1952); ○ = Hamblin and Davies (1977); and ● = Emerson (1995). Data from Stone and Garrison and Havis were adjusted according to the relationship: Field capacity = 7.04 + 0.721*Moisture equivalent, R^2 = 0.86 (developed from data given by Veihmeyer and Hendrickson, 1931).

Petersen et al. (1968) produced partial or simple linear segmented models of soil water using regression techniques for each soil textural class in the USDA system. These models used one or two soil separates (usually clay), organic carbon, and bulk density (ρ_B). Organic carbon was a factor in water held at −1500 kPa matrix potential, and increases in organic carbon were predicted to diminish available water. However, their models for AWC often used clay (in the range of 0 to 65%) or silt and ρ_B but organic carbon was used infrequently. Like Lund (1959), Petersen et al. (1968) stressed clay content as a major factor in both −33 kPa and −1500 kPa matrix potential water contents and often in AWC. Their quadratic equations require AWC, as a function of clay content, to decrease once the clay content reaches about 34%.

Gupta and Larson (1979) produced a multiple regression model of soil water that included texture, organic matter, and ρ_B. This simple linear and segmented model has given a rather good and competitive description of the data, but inclusion of ρ_B and of all texture groups also incorporated collinearity of the variables. Rawls et al. (1982) used the Gupta and Larson approach and developed three regression models using different combinations of sand, sand and clay or silt and clay, organic matter, and, for some, ρ_B. Baumer and Brasher (1982) developed a similar model but included cation exchange capacity and pore volume in lieu of ρ_B. However, inclusion of cation exchange capacity creates another parameter identification problem due to collinearity. If cation exchange capacity is an important variable, it suggests that both clay type and organic carbon are important. Much earlier (1950), Woodruff's work also suggested that clay type might influence water retention.

Thus, most models to date predict that addition of organic matter to soil will effect a simple increase in water held at both −33 kPa and −1500 kPa limits and, consequently, have negligible effect on AWC. Two approaches offer serious opposition to acceptance of the constant effect of added organic carbon. In 1992, Bauer and Black (Bauer and Black, 1992) reported that increases in organic carbon had no effect on available water for fine textured soils. Their model indicates that both organic carbon and clay interact in a complex manner but do not affect available soil water content.

Using texturally limited data sets, Hudson (1994) showed that the change in water-holding capacity with changes in organic carbon was dependent on soil texture. This work was really the first to illustrate the complexity of the effect of organic carbon on soil water retention and acknowledged implicitly interactions between various components without involving them in a model. His estimates for increases in available water ranged from about 2.2% to 3.7% per percent organic carbon and are very similar to those of Stone and Garrison (1940). The largest increases observed by Hudson came with silt loam soils and diminished with coarser or finer textured soils.

Heinonen (1954) observed that water retained against a given matrix potential increased as the ρ_B of the soil increased. His observations and those of others have led several workers to use ρ_B in their models. However, ρ_B is described mathematically as:

$$\rho_B = k^*\%\text{clay} + k^*\%\text{ silt} + k^*\%\text{ sand} + m_{om}V_o^{-1} \quad (1)$$

Where k = mineral mass divided by the bulk volume, V_o,

$$\text{and} \quad m_{om}V_o^{-1} = \text{the mass of organic matter divided by the bulk volume.} \quad (2)$$

While k varies slightly between soils, the range of values is often rather small. That ρ_B is describable mathematically as a function of particle separates explains why correlations have been obtained between soil water content and ρ_B (Renger, 1971). However, when used in combination with any particle size fraction, ρ_B introduces an element of collinearity (or redundancy).

Systems Approach

Parallel with the component approach, several investigators used the systems or energy approach of Burdine (1953). Brooks and Corey (1964) used this model to describe fluid movement through porous media. The relative saturation was related to the minimal capillary pressure at which a continuous nonwetting phase (air) existed throughout the medium.

Most subsequent authors ignored a weakness of the Burdine-Brooks-Corey (BBC) model, the power function superstructure, and proceeded to evaluate the exponent. The power function cannot accommodate both upper and lower limits. Clapp and Hornberger (1978) showed that the exponent of the BBC model could be related to clay content, but they ignored effects of organic carbon, and their conclusion that the exponent

was closely correlated with clay content may have been compromised by ignoring changes in organic matter content that also generally correlate with clay content. Most soil organic matter is adsorbed on surfaces (mainly clay), and the clay component in many models is really a clay-organic complex. This explains the relative success of models that ignore organic carbon as an independent component. De Jong (1982) pointed out that application of the Clapp-Hornberger parameters were often inadequate to describe soil water retention.

Mualem (1976) proposed describing relative conductivity by expanding the effective saturation to accommodate the change in water content with the change in matrix potential through modification of the exponent of the BBC model. Shortly thereafter, van Genuchten (1980) incorporated additional parameters in the effective saturation term needed to fit observations.

Bloemen (1980) showed that the exponent of the BBC model is closely correlated to (or affected by) soil organic matter content. McCuen et al. (1981) also found that the parameter values for the BBC model varied collectively across soil texture classes.

More recently, Tomasella et al. (2000) estimated the empirical constants of the van Genuchten model (1980) as functions of soil properties, including ρ_B and organic carbon using a multiple regression technique. They concluded that organic carbon has little effect on the water content of soils (organic carbon ranged from as little as 0.06 to 59.5 g kg^{-1} soil) except in the −1500 kPa range.

The energy models are all closely related and suffer the same weaknesses. They assume, without justification, that a simple power function for the superstructure of the model is adequate if not correct. These models also assume a constant slope in the release of water as a function of the energy imposed between the limits of the air entry matrix potential and field capacity; several authors have noted that this assumption is violated for many soils.

Our primary objective was development of an improved soil water retention function for use in the ARS-N fertilizer decision aid (Olness et al., 1999). A second objective was resolution of the contribution by organic carbon to soil water retention and to available soil water. For this evaluation we adopted the energy concept (Burdine, 1953; Brooks and Corey, 1964; Mualem, 1976; van Genuchten, 1980) of fluid retention, but we used the general energy model for limited systems (GEMLS; see appendix) for its description.

MATERIALS AND METHODS

Available water was calculated as the difference between −33 kPa and −1500 kPa and water contents in the USDA-NRCS national soils inventory database (Lincoln, NE; for methods see USDA-NRCS, 1966). Because the database is very large (>100,000 entries), it was segmented in a stepwise manner. First, the database was segmented into organic carbon intervals of 0.1%. Next, each subset was divided into silt ranges of 5%. Finally, each subsubset was divided into groups of about 100 ± 20 entries to enable graphical visualization of individual data points. Five organic carbon content ranges centered on 0.35, 0.85, 1.35, 2.35, and 4.85% were selected for model fitting and parameter estimation. As the organic carbon content increases, the number of entries for each range lessens. To obtain sets with similar numbers of values, ranges were expanded. The ranges were: 0.30 to 0.40%, 0.80 to 0.90%, 1.0 to 1.7%; 2.1 to 2.6%; and 4.0 to 5.7%.

Data from each subsubset were plotted and initially fitted manually to the GEMLS using clay content as a surrogate for surface area (hygroscopic and pore). A fit was accepted when the sum of the errors equaled 0 and the residual values were uniformly distributed without evidence of pattern when plotted against the clay content. After a manual fit was obtained, the estimated parameters were used with the SAS PROC MODEL routine to obtain refined model estimates. The energy coefficients were then plotted against silt content to determine whether the energy coefficients were stable over all silt ranges or, if not stable, whether they showed a consistent pattern.

Once the clay and silt particle size fractions were evaluated, estimates of water retained at −33 kPa and −1500 kPa matrix potential were obtained and the available water content range determined. Available water content ranges for two organic carbon subsets were assessed, and an estimate of the effect or lack thereof of organic carbon was estimated. In order to obtain an estimate of the relative effect of increasing soil organic carbon on plant available water, we arbitrarily chose the organic carbon ranges of 0.35% and 2.35% for evaluation.

RESULTS AND DISCUSSION

For soils with about 0.35% organic carbon, water retained at both energy levels (−33 kPa and −1500 kPa matrix potentials) were strongly correlated with clay content (Fig. 2). The relationship

appears nearly linear over the range of 0 to 45% clay. Use of the GEMLS resulted in a uniform distribution of residuals (Fig. 3). Most residuals were less than 5%, but a few were greater than 10%. The results were not much different than those observed by Smith (1917) for much simpler models. However, when the clay content range is extended beyond 45%, a change in the slope of the relationship is clearly evident (Fig. 4). This change in slope begins between 40 and 50% clay content.

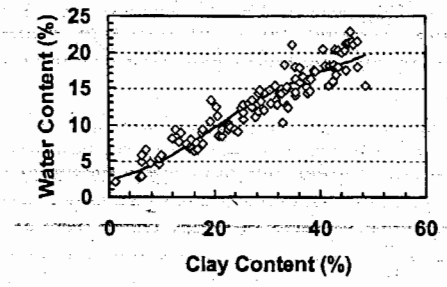

Fig. 2. A typical relationship of water content as a function of soil clay content. The values represent water content at −1500 kPa matrix potential for soils containing 0.35% organic carbon and silt contents of 50% to 55%.

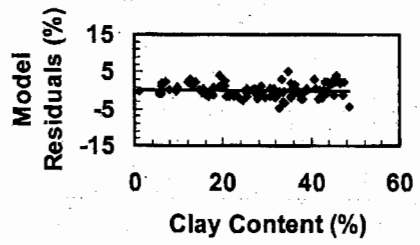

Fig. 3. Distribution of residuals for the general energy model systems applied to the data shown in Fig. 2.

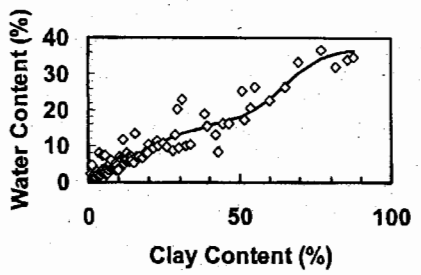

Fig. 4. A typical relationship of water content as a function of soil clay content. The values represent water content at −1500 kPa matrix potential for soils containing 0.35% organic carbon and silt contents of 10% to 15%.

Many previous efforts either ignored soils having very large clay fractions or assumed that any change in slope was an error of measurement. The change in slope could, however, be an artifact of measurement; that is, the relationship is really continuous and a single energy effect is involved. If an error, it seems to begin at clay contents of about 20% or that amount of clay at which the water content increases, at a decreasing rate, as the clay content increases. If this is the case, the error seems to diminish as the clay content exceeds 40%. An alternative hypothesis is that a second energy effect becomes dominant at clay contents greater than 40%; this is accommodated by adding a second GEMLS function to the first GEMLS function (see example in Fig. 4) to create a two-function model. Certainly, water retention at −1500 kPa matrix potential involves both hygroscopic water and water contained in micropores that is unavailable to plants, and these two effects are not closely correlated (Stone and Garrison, 1940). The effect is equally apparent in water retention data at −33 kPa matrix potential (data not shown).

Regardless of the cause of the change in slope, the two-function model gives a close description of the data as is shown by the residual distribution (Fig. 5). The variance in water content increases as the clay content increases (not shown), and this may reflect water retention in micropores (a structural effect), increasing difficulty in obtaining retention data, or both.

Application of the GEMLS to water content at −33kPa matrix potential shows a similar fit with the data (Figs. 6 and 7), but the variance has increased substantially. It seems reasonable that part of the increase in variance is the result of differences in soil structure and pore size distribu-

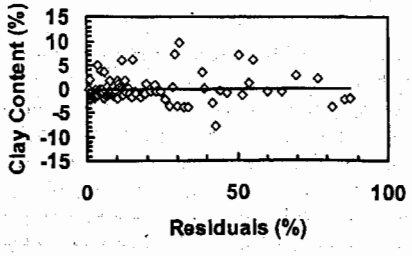

Fig. 5. Distribution of residuals for the two function energy model systems applied to the data shown in Fig. 4. The values represent water content at −1500 kPa matrix potential for soils containing 0.35% organic carbon and silt contents of 25 to 30%.

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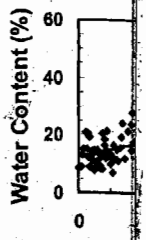

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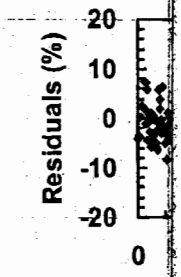

Fig. 7. Distribution
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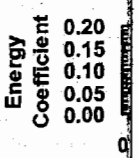

Fig. 8. A plot of th
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tion (Childs, 1940). Any change in slope of the water content curve is faintly expressed at best, but a slightly better fit (lack of pattern in the residuals) is obtained by retaining the two-function model.

A plot of the energy coefficients, k values, as a function of silt content suggested a systematic variation with silt content (Fig. 8).

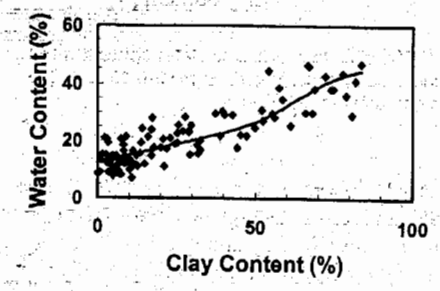

Fig. 6. A typical relationship of water content as a function of soil clay content. The values represent water content at −33 kPa matrix potential for soils containing 0.35% organic carbon and silt contents of 15 to 20%.

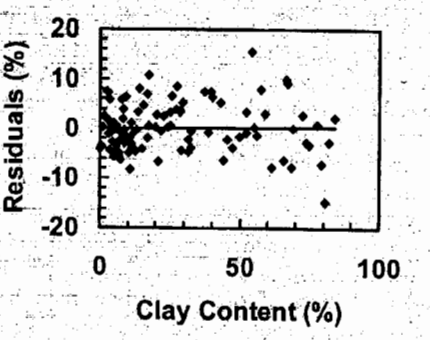

Fig. 7. Distribution of residuals for the two function energy model systems applied to the data shown in Fig. 6. The values represent water content at −33 kPa matrix potential for soils containing 0.35% organic carbon and silt contents of 15 to 20%.

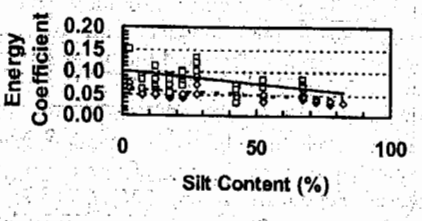

Fig. 8. A plot of the derived energy coefficients (◇) = first function and □ = second function) as a function of soil silt content for −1500 kPa matrix potential water content and organic carbon content of 0.35 ± 0.05%.

The indicated relationship was:

$$k = a - q\ (\%\ \text{silt}) \tag{3}$$

and this can be rearranged to give:

$$k = k'(p - \%\ \text{silt}) \tag{4}$$

This relationship is quite logical because as the number of coarser silt particles increase, the total surface area decreases and the amount of water retained also tends to decrease. Substituting the silt relationship into the model and evaluating the data with SAS PROC Model, we obtain refined estimates of the remaining parameters.

When the energy coefficient, k, in the equation is substituted into the model, k′ becomes the new energy coefficient, and we obtain a logical silt-by-clay interaction in addition to independent silt and clay contributions. For example, substituting into the original equations:

$$e^{k(\%\ \text{clay} - Co)} \tag{5}$$

we obtain:

$$e^{k'(p\ -\ \%\ \text{silt})*(\%\ \text{clay} - Co)} \tag{6}$$

or

$$e^{k'(p\%\text{clay} - pCo - \%\text{silt}*\%\ \text{clay} + \%\ \text{silt}*Co)} \tag{7}$$

where p = a coefficient modifying the relative contribution of clay.

Thus, the model indicates that total surface area available for interaction or pore surface formation is more important than particle size distribution. It is important to remember that the choice of particle size limits in soil is arbitrary. For example, if the finer silt size limit were adjusted to something greater or lesser than two microns, the general relationship would be retained but the value of p would change. It quickly becomes apparent that the appropriate parameter for use in the exponent is total mineral surface area or the geometric mean particle radius. In this respect, the surface area conclusion is consistent with the suggestion of Brooks and Corey (1964) that the exponent in the BBC model, λ, was a pore size distribution index. Arya and Paris (1981) made a similar suggestion using a very different approach on soils without organic matter. Certainly, total pore space depends on the total mineral surface area, and this can be apportioned between many small pores or a few large pores.

A comparison of the water contents at −33 kPa matrix potential with that at −1500 kPa matrix potential provides an estimate of the available water at a given subrange of organic carbon concentrations. More importantly, the derivative of the function with respect to silt or clay shows the marginal contribution of either component (or total surface area) within the matrix to water content at a fixed carbon content. Because the residuals of the models are distributed uniformly, the final difference between models for −1500 kPa and −33 kPa matrix potentials is equal to that obtained by modeling available water directly.

The next step is application of the same model fitting procedure to soil having different organic carbon content ranges. Once each carbon content range is modeled, the difference between any two ranges for a given textural class provides an estimate of the contribution of organic carbon to available soil water-holding capacity (Fig. 9). The result shown in Fig. 9 is also obtained manually by subtracting available water at one organic carbon range from that at another organic carbon range. The results illustrate that available water content is strongly influenced by soil organic carbon and that the effect of organic carbon varies with soil texture or total mineral surface area. For example, without clay content, an increase from 0.35% organic carbon to 2.35% organic carbon increases available water content by about 5% (gravimetric) or about 2.5% for each percentage increase in organic carbon. At clay content of 40%, the same change in organic carbon increases the available water content by more than 10%. The effect of increasing available water content with increasing organic carbon content ceases at about 40% clay content, decreases as the clay content increases from 40 to 60%, and then increases rapidly with clay content greater than 60%. Over the textural range used, the results are consistent, in a general manner, with those of Hudson (1994). The pronounced increase in available water at clay contents greater than 60% at first seems to be an anomaly, but it is actually a consequence of the apparent change in slope of the water retention curve. This region has been virtually ignored by most modeling efforts. The results obtained using this approach tend to agree with those of Petersen et al. (1968) in that their quadratic model suggests a decrease in the effect of increasing the clay content beyond 40%. The magnitude of the effect of organic carbon on AWC also seems consistent with many other observations (Stone and Garrison, 1940; Havis, 1943; Russell et al., 1952; Salter and Haworth,

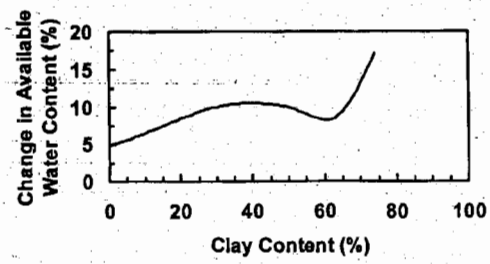

Fig. 9. The change in available water content caused by an increase of organic carbon from 0.35 to 2.35% for soils containing ≤75% clay.

1961; Hamblin and Davies, 1977; Emerson, 1995): an increase in organic carbon of about 2% will increase AWC by about 1.5 to 17% (Fig. 1). Part of the range of values is undoubtedly the result of the different methods used and the errors involved in reconciling them. In all cases, however, the increase in available water content with an increase in organic carbon seems to be nearly constant over the ranges examined.

Why do our results contrast so strongly with those obtained by many others? First many of the modeling efforts have used segmented models of the soil components with no interactions, and several have assumed, at least implicitly, a constant contribution of each component *a priori*.

In the absence of organic matter, all water is retained as a function of soil porosity and total exposed mineral surface area. As an increment of organic matter is added, it is adsorbed on and occludes a portion of the mineral surface. A subsequent addition of organic carbon then has a probability, p_i, of adsorbing on the mineral surface or on the previously adsorbed organic carbon, p_c'. Further additions of organic carbon encounter diminishing probabilities of interacting with mineral surfaces (that is, $p_{ix} < p_{io}$) and increasing probabilities of interacting with previously adsorbed organic carbon (that is, $p_{cx} > p_{co}$). A situation is finally reached when most increases of organic carbon must interact with previously adsorbed organic carbon and the water retention characteristics are largely determined by pore size distribution of an organic substrate having a mineralogical skeleton. The water retention characteristics begin to mimic those of a peat or organic material (Feustal and Byers, 1936). An additional complexity is the relative state and amount of amorphous Fe and Mn oxides (reduced or oxidized), which tend to form an amorphous mineral-organic carbon complex.

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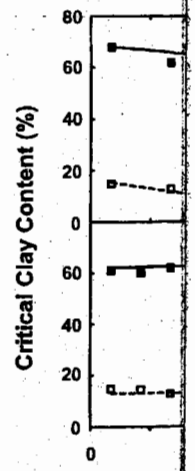

Fig. 10. Estimates of
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and B = −1500 kPa
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Thus, as the carbon content increases, the system changes gradually from a mineral-dominated matrix to a carbon-dominated matrix; the organic carbon content at which this change in domination occurs depends on the amounts and types of clay (total surface) present. This changing nature of the matrix explains some (but certainly not all) divergent conclusions reached by others with regard to the importance of organic carbon in soil.

The fundamental nature of water retention by both soil mineral and organic matter also explains why large losses of organic carbon caused by cultivation have resulted in less than catastrophic losses in soil water retention. It also explains the source of much of the confusion that was apparent in earlier modeling efforts on water retention by soil.

We expect, then, that the model presented will show a complex nature with regard to the effects of soil organic carbon on soil water retention. A plot of the critical clay concentrations, C_o, for both −1500 kPa and −33 kPa matrix potentials for four carbon ranges suggests that the critical clay concentrations vary only slightly and could be treated as constants (Fig. 10). The C_o values for −33 kPa matrix potentials may decrease slightly, but the data are insufficient to reach any conclusion.

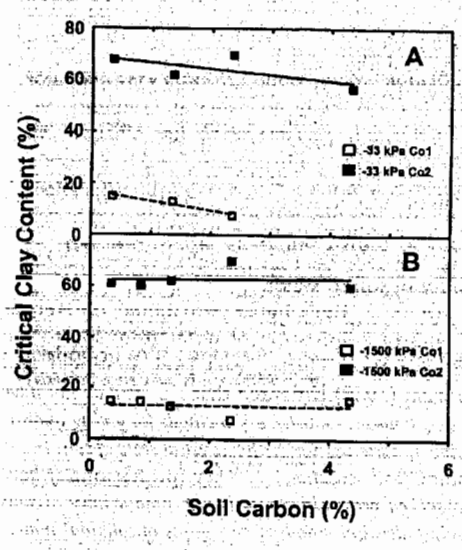

Fig. 10. Estimates of the critical clay concentrations (E_o in the basic equations) for A = −33 kPa matrix potential and B = −1500 kPa matrix potential moisture contents as a function of percent soil organic carbon.

The particle size coefficient, p, may be decreasing as the organic carbon content increases (Fig. 11). Such a result is logical because the effect of clay and mineral surfaces on water retention diminishes continually as the organic carbon content increases. The approach used here is tedious and ineffective for providing an adequate definition of the extracted particle size coefficient.

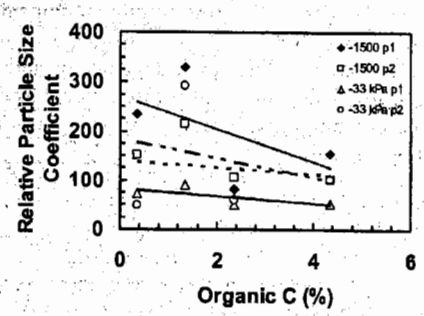

Fig. 11. A plot of particle size coefficients, p, in the water retention model as a function of percent soil organic carbon.

The energy coefficients may decrease as the organic carbon content increases, but the number of data points extracted are too few and the variance too great to conclude that this is the case (Fig. 12). A decrease in the energy coefficient, k', would suggest that the organic carbon effect is complex. Such a result is consistent with greater organic carbon to organic carbon interactions as the organic carbon concentration increases. Again, a different analytical approach is needed to determine the relative stability of the energy coefficient. Also, the clay coefficient may decrease in the first phase (silt dominant) but remain rather stable in the second portion of the model (clay dominant). If this is the case, then these coefficients can be partitioned further to provide organic carbon interactions with each component.

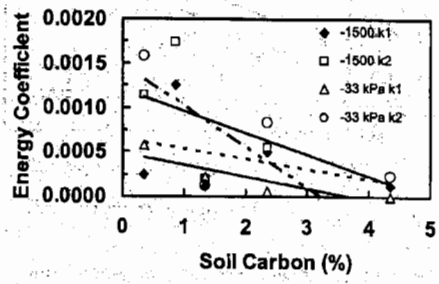

Fig. 12. Water retention energy coefficients, k, plotted as a function soil carbon.

In addition to its possible effects in the model exponents, organic carbon also seems to affect the model function multipliers directly (Figs. 13 and 14). These seem to increase as organic carbon content increases when the matrix potential is −33 kPa. The effect of changes in organic carbon on function multipliers seems much smaller at −1500 kPa matrix potential, except, perhaps, for the second GEMLS function multiplier, but this should affect only those soils with greater than 40% clay content. The result suggests an additional, nearly independent of texture, effect of soil organic carbon on water retention at −33 kPa matrix potential.

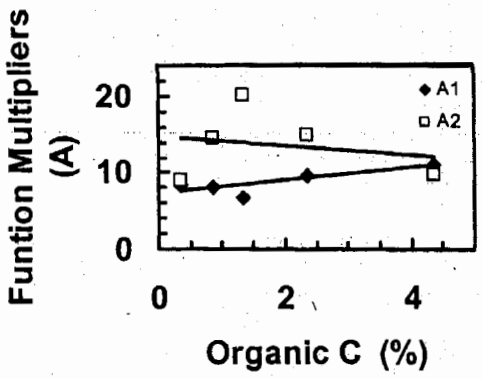

Fig. 13. Function multipliers for the general energy model for water retained by soil at −1500 kPa matrix potential plotted as a function of soil organic carbon content.

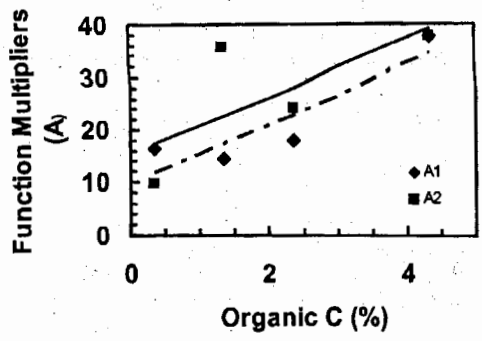

Fig. 14. Function multipliers for the general energy model for water retained by soil at −33 kPa matrix potential plotted as a function of soil organic carbon content.

Various models have recently been compared in an attempt to identify the model that has the smallest residuals (for example, Tietje and Tapkenhinrichs, 1993; Cornelis et al., 2001). These attempts have ignored the redundancy features contained in several models and may be misspecified. As a consequence, the true contribution of individual factors may be unresolved. Residuals obtained with the general energy model for limited systems are on the same order of magnitude as those reported by Smith (1917). Residuals reflect errors in measurement plus other, unaccounted for factors omitted from the GEMLS. These factors likely represent effects of soil structure that go beyond a description of individual soil components and reflect the component assemblage. Model residuals from coarse textured soils with poor structure should quantify effects of nonstructural errors, whereas residuals from soils with greater clay and organic matter functions include errors caused by structural effects. If so, the effect of soil structure on water retention has economic implications for soils in subhumid and semiarid areas.

A general relationship between soil structure and texture has been recognized for quite a long time. For example, Bradfield and Jamison (1938) observed that soils devoid of colloidal material had only single grain structure and had no compound particles. Petersen et al. (1968) concluded that interaction terms between textural classes in water retention models were necessary to describe the effect of structure on soil available water-holding capacity. Cosby et al. (1984) acknowledged that a close relationship between texture and structure is expected. Jamison and Kroth (1958) noted that development of soil structure did not improve water storage capacity by itself, and, in some cases, improvement of soil structure seemed to result in both a loss of available water storage capacity and increased permeability of soil to water.

In 1907, Buckingham attributed differences in rates of evaporation of water from soil to the soil structure. Thirty years later Bradfield and Jamison (1938) lamented that . . . "*We do not have as yet, however, satisfactory methods for giving quantitative characterization to the physical state of soils in the natural field condition . . . They* (professionals) *have recognized great differences in the productivity of soils having identical amounts and kinds of colloidal material. This difference has been attributed to differences in the arrangement of particles or to the structure of the soil*" . . . They also noted that soils having the same total pore space could have very different

physical properties with respect to water retention. Bloemen (1980) agreed and noted that both pore geometry (structure) and particle shape are important in water retention; they further concluded that hysteretic effects were a consequence of soil structure. While the importance of structure in soil water retention has been acknowledged for more than a century, at this time we still have no rapid means of measuring or assessing this very fundamental soil property.

Throughout development of the model of water retention, we have ignored possible effects of clay mineralogy. The work of Woodruff (1950) suggests that clay type influences water retention. Certainly, differences in clay mineralogy contribute to model residuals, but the clay fraction of soils is generally a mixture of materials, including silica, rather than pure mineralogical forms. In addition, redox sensitive oxides tend to obscure some properties of individual minerals. As a consequence, the impact of clay mineralogy is much less than that which one would predict for pure minerals. Could clay mineralogy contribute to the change in slope of the water retention curves at about 45% clay content? Here, no attempt was made to separate soils by mineralogical or geographical origin, and data were included regardless of particle size distribution.

CONCLUSIONS

Application of the general energy model to water retention data shows that organic carbon in soil has a very complex effect on available soil water content. The effect of added organic carbon on available soil water capacity depends on soil texture and the initial organic carbon content. For many agricultural soils, water content is mainly affected by soil organic matter and soil structure.

Because of the changing nature of the soil matrix (mineral-dominated to organic carbon-dominated surfaces), the change in AWC ranges from about 2.5 to 5% per 1.0% change in organic carbon in soils containing less than 2.5% organic carbon and less than 40% clay.

APPENDIX

A Brief Review of the Theory of the General Energy Model for Limited Systems

Because retention of water in soil has natural upper and lower limits, a power function model such as that of Burdine (1953), Mualem (1976) or van Genuchten (1980) is fundamentally inadequate. A more appropriate model is the general energy model for limited systems (Olness et al., 1998), which has natural upper and lower limits. The general energy model is a composite of the rate models of Arrhenius (1889) and Mitscherlich (1930) integrated over unit time. The basic function is:

$$Q = A[(e^{k(E-Eo)} - e^{-k(E-Eo)})/(e^{k(E-Eo)} + e^{-k(E-Eo)})]\int dt$$

where:

- Q = a quantity; in this case, Q is the gravimetric moisture content of soil,
- k = an energy coefficient in $\%^{-1}$,
- A = the maximal value of any quantity; here water that can be retained by the soil at a given pressure or matrix potential,
- E = the intensity of the energy form; here it is the % clay which is a surrogate for mineral surface area.
- E_o = a critical energy intensity given in terms of the main factor as a specific value; here it is given in % clay. Briefly, it is that point at which Q increases at decreasing rates as the energy intensity (surface area) increases, and
- t = time.

When $e^{-k(E-Eo)} << e^{k(E-Eo)}$ in the denominator, the expression reduces to the well known Mitscherlich function. When $e^{k(E-Eo)} << e^{-k(E-Eo)}$ in the denominator, the expression reduces to:

$$A(e^{2k(E-Eo)} - 1),$$

and, essentially, we have the Arrhenius function in slightly modified form.

By adding a constant ≥ 1, the GEMLS becomes a relative descriptor and negative values are avoided. When a constant is added, the coefficient, A, must be appropriately reduced.

ACKNOWLEDGMENTS

The authors thank Drs. W.W. Emerson (CSIRO-Australia, retired) and Tyson Ochsner (USDA-ARS, St. Paul) for valuable comments during the preparation of this paper. We are very appreciative of the data supplied by the USDA-NRCS, Lincoln, Nebraska. Thanks are also offered to Ms. Jana Rinke for assistance with figures and to the secretarial and support staff of the North Central Soil Conservation Research Laboratory, Ms. S. Groneberg, B. Burmeister, and P. Groth.

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