EFFECT OF ORGANIC CARBON ON AVAILABLE WATER IN SOIL

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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: a 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 clay, silt, and organic C contents. The model used six parameters (two function coefficients, two energy coefficients, and two critical clay content), and required an initial manual fit of the models to the data points (about 150 ± 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 R². 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 2 to 75% increase in soil AWC depending on the soil texture. (Soil Science 2005;170:96-101)

Key words: Soil texture, field capacity, wilting point, General Energy Model for Limited Systems
it is still surprising because organic matter was generally recognized as important to soil physics and moisture relations. For example, Albury and Nilger (1957) studying continuous cropping and rotation systems, concluded that "the difference in organic-matter content ... caused a marked difference in the amounts of water moisture..." They saw considerable 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) (Hines, 1943; Bunte and Garrison, 1941; Russell et al., 1943; Saller and Haworth, 1941; Hamilton and Davies, 1977; Bunt, 1955). Increases as a result of manure additions have tended to be less than those brought about by indigenous decay of plant material. Thus, the range of estimates for benefits of organic carbon for AWC is quite large.

Even so, Janzen (1953) concluded that except for sandy soils, organic matter increases had little effect on the capacity to store available soil moisture. In 1958, Janzen and Kneen developed a number of simple correlations between available water and several 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, Land 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 Mantle of the Minerals
With the development of the computer and statistical methods, a flood of models was produced in an attempt to describe soil water content. Assuming 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
This component approach attempted to characterize the contributions of various separate soil water components and soil WC in much the same manner as Briggs and Shaw (1912). Using this approach, Saller et al. (1943) noted a different pattern of factors depending on the particle size separation scheme used (U.S. vs. International).

Shaw, Parke and Zwierzch (1968), describing the 25 L. a matrix potential water content convention, used only two soil fractions: soil 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, these models contained no other interaction terms and, in regard to soil structure observations, the situation is important.

![Available Water (%) vs. Organic Carbon (%)](image)

**Fig. 1.** The effect of organic carbon on soil available water content (% obtained by I = Stone and Garrison (1943), I = Hamilton (1943) and I = Saller and Haworth (1941); I = Russell et al. (1955); I = Hamilton and Davies (1977); and I = Emerson (1965). Data from Stone and Garrison and Hines were adjusted according to the methodology: field capacity = 7.04 + 0.72 (water content), a = 0.86 (developed from data given by Bunt, 1943 and Hines, 1950).
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 fractions (usually clay, organic carbon, and bulk density, D). Organic carbon was a factor in water held at -1200 kPa matrix potential, and because, organic carbon was predicted to diminish available water. However, their models for AWC were based on clay (in the range of 0 to 65%) or silt and clay organic carbon was used instead. Despite this, their models did not incorporate all variables like soil texture, organic carbon, and bulk density.

Gupta and Larson (1979) produced a multiple regression model of soil water that included texture, organic matter, and pH. This simple linear and segmented model has given a rather good and comprehensive description of the data, but inclusion of pH and of all texture groups also incorporated collinearity of the variables. Rawls et al. (1982) improved this model and developed a multiple regression model using different combinations of sand, silt, clay or organic carbon, and organic matter. This model is mathematically described as:

\[ \text{AWC} = a + bR_C + cR_S + dR_C^2 + eR_S^2 \]

where: 
- \( a \) = mineral mass divided by the bulk volume, \( V_B \)
- \( b \) = the mass of organic matter divided by the bulk volume (0.01 - 0.04)
- \( c \) = the mass of clay by the bulk volume (0.05 - 0.10)
- \( d \) = the mass of sand by the bulk volume (0.15 - 0.20)
- \( e \) = the mass of silt by the bulk volume (0.25 - 0.30)

Thus, the model is sensitive to a slight increase in organic matter to soil water that will affect the effective increase in water held at -1200 kPa and -1500 kPa, and consequently, it has negligible effect on AWC. Two approaches offer serious objection to the constant effect of 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, and these interactions can affect available soil water contents.

Using a limited data set, 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 integrate the complexity of the effect of organic carbon on soil water retention and acknowledgment implicitly interactions between various components without involving them in a model. He estimates that 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 observed increases happened with soils that contained small amounts of organic material and did not interact with coarse or finer textured soils.

Hettiarachchi (1984) observed that water retained against a given matrix potential increased as the soil pH increased. His observations and those of others have led several workers to use pH in their models. However, pH is described mathematically as:

\[ \text{pH} = a + b \text{Clay} + c \text{Silt} + d \text{Sand} + e \text{Organic matter} \]

Where:
- \( a, b, c, d, e \) are parameters.

This model is sensitive to a slight increase in organic matter to soil water that will affect the effective increase in water held at -1200 kPa and -1500 kPa, and consequently, it has negligible effect on AWC. Two approaches offer serious objection to the constant effect of 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, and these interactions can affect available soil water contents.

Using a limited data set, Hudson (1994) showed that the change in water-holding capacity with changes in mineral matter was closely correlated with the maturation of the clay soil. More clay on surfaces (mainly in many models) is less common. This explains the need for high organic carbon content. De Jong (1960) of the Clapp-Hornberger inappropriately described the conductivity by an equation to accommodate, in both the change in soil and soil structure. Shortly thereafter, the sorption term tended to be ignored.

Bloom (1989) noted that the BBC model is reflected by soil organic matter, and it has since been used for the BBC model in texture classes.

More recently, the empirical Gemset model properties, including a multiple regression that organic carbon content of soils (at least 0.05 and 1.5% organic carbon) is required to be effective in estimating today's yield potential and can be used to estimate for many soils.

Our primary focus is an improved soil water model in the AUS-N farm model, 1999. A second contribution to the same model is the change in soil bulk density (0.15-0.20), and the change in soil texture (0.15-0.20), and the change in soil organic carbon (0.15-0.20), and the change in soil water retention (0.15-0.20).

The Clapp-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
soil was closely correlated with clay content may have been

\[ \text{soil-water retention function for use in the ARS-N] facility decision tool} \]

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appears nearly linear over the range of 0 to 45% clay. Use of the GEMSLS 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 (1971) 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.

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 it is error, it seems to begin at <4% 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 GEMSLS function to the first GEMSLS 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 micro pores that is unavailable to plants, and these two effects are not closely correlated (Stone and Garrison, 1970). The effect is equally apparent in water retention data at ~35kPa 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. 3). 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 GEMSLS to water content at ~1500 kPa 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. 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 10% to 15%.

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 organic 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%.
tion (Childs, 1940). Any change in slope of the water content curve is fairly expressed at base, 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. 6).

![Graph](image-url)

**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 90%.

The indicated relationship was:

\[ k = a - b \times silt \]  

(3)

and this can be rearranged to give:

\[ k = k' \times silt \]  

(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 PROCLM 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:

\[ k'' = k' - b \times \text{clay} \]  

(5)

we obtain:

\[ k'' = k' \times \text{clay} \times (1 - b) \]  

(6)

or

\[ k'' = k' \times \text{clay} \times (1 - b') \times \text{co} \]  

(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, \( k \), was a pore size distribution index. Ayns and Pasta (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 range of organic carbon concentrations. Most, unfortunately, the derivative of the function with respect to soil 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 water holding capacity (Fig. 9). The results 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 contents are 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 0.5% organic carbon to 2.5% 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 at the clay content of 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% as 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 well-norred by most modeling efforts. The results obtained using this approach tend to agree with those of Petersen et al. (1958) 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 Gristline, 1940; Gristline, 1943; Russell et al., 1952; Salter and Hsworth, 1961; Munns and Davies, 1977; Fitterman, 1995); an increase in organic carbon of about 2% will increase AWC by about 1.5 to 17% (Fig. 12). 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 range 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 to a plot.

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, , of adsorbing on the mineral surface or on the previously adsorbed organic carbon, , . Further additions of organic carbon encounter diminishing probabilities of interacting with mineral surface (that is, , decreasing) and increasing probabilities of interacting with previously adsorbed organic carbon (that is, , increasing). 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 water distribution of an organic substance having a mineral-like skeleton. The water retention characteristics begin to mimic those of a pristine or organic material (Fitterman and Byerts, 1954). An additional complexity is the relative state and amount of humic and Fe and Mn oxides (reduced or oxidized), which tend to form an amorphous material-organic carbon complex.
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 (top) 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 scarcity 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 provide a complex nature with regard to the effects of soil organic carbon on soil water retention—a plot of the critical clay concentrations, C₀, 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 C₀ values for ~33 kPa matrix potentials may decrease slightly, but the data are insufficient to reach any conclusion.

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 non-trivial and effective for providing an adequate definition of the extracted particle size coefficient.

The energy coefficients may decrease as the organic carbon content increases, but the number of data points examined 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 at the organic carbon concentration increases. Again, a different analytical approach is needed to determine the relative stability of the energy coefficients. Also, the clay coefficient may decrease in the first phase (silt dominated) 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 for each component.
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 GEMSLS function multipliers, but this would 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.

Variation of models have recently been compared in an attempt to identify the models that have the smallest residuals (for example, Tims and Taposchuk, 1993; Cornells et al, 2001). The same attempts have ignored the redundancy features contained in several models and may be misclassified. Consequently, the true c contribution of individual factors may be unexplained. Residuals obtained with the general energy model for limited systems are on the same order of magnitude as those reported by Tims (1997). Residuals reflect errors in measurement plus other, unaccounted for factors omitted from the GEMSLS. These factors likely represent effects of soil structure that go beyond a description of individual soil components and reflect the component assembly. Model residuals from coarse textured soils with poor structure should quantify effects of measurement errors, whereas residuals from soils with greater clay and organic matter functions include errors caused by structural effect. If so, the effect of soil structure on water retention has economic implications for soils in subarkose and semiarid areas.

A general relationship between soil structure and texture has been recognized for quite a long time. For example, Bradfield and Jansson (1930) observed that soils consisting of mineral material had only single grain structure and had no compound particles. Paterson 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 structure and texture is expected. Jansson and Korth (1958) noted that development of soil structure would improve water storage capacity by itself, and, in some cases, improvements of soil structure seemed to result in both a low of available water storage capacity and increased permeability of soil to water. In 1967, Buckingham attributed differences in rates of evaporation of water from soil to the soil structure. Thirty years later Bradfield and Jansson (1930) lamented that "We do not have... yet, however, satisfactory methods for giving quantitative characterization to the physical state of soil in the natural field conditions. . . . They [professionals] have recognized past differences in the productivity of soils having identical amounts and kinds of cultural material. This difference has been attributed to differences in the arrangement of particles or in the structure of the soil." . . . They also noted that soils having the same total pore space could have very different physical properties. Bioenergy (1990) pure geometry is very important in water: cluded that texture of soil structure. Wture in soil water- edged for more of the still have no explicat one of the most critical factors and have a direct effect on the ability to extract water from the soil.
Physical properties with respect to water retention: Bloomer (1950) 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 to soil water retention has been acknowledged for more than a century, at this time we have no rapid means of measuring or assessing this very fundamental soil property.

Conclusions: The development of the model of water retention, we have ignored possible effects of clay mineralogy. The work of Woodroof (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 others, rather than pure mineralogical forms. In addition, reduced sensitivity 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 attempts were made to separate soils by mineralogical or geographical origin, and data were included regardless of particle size distribution.

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