Fractal Analysis of Soil Water Desorption Data Collected on Disturbed Samples with Water Activity Meters

E. Perfect,* A. B. Kenst, M. Díaz-Zorita, and J. H. Grove

ABSTRACT

We combined water activity meters and fractal modeling to facilitate rapid, physically based characterization of the soil water retention curve. Desorption data (6 points per sample) were collected in the tension (*h*) range 2.0×10^2 to 1.5×10^5 kPa using the gravimetric method to measure water content (*w*) and water activity meters to measure *h*. Thirty-two disturbed samples from a long-term nitrogen fertilization and tillage comparison study on a silt loam soil were analyzed. A new form of an established fractal equation was derived: $w = ah^{D-3} - \rho_w/\rho_s$, where *a* is a compound parameter including the bulk density (ρ_b) and air entry tension (h_a), *D* is the mass fractal dimension, ρ_w is the density of water, and ρ_s is the particle density. This model was fitted to the measured water retention curves by nonlinear regression analysis. The *a* and *D* parameters were estimated, while ρ_w and ρ_s were fixed at 1.00 and 2.65 Mg m^{-3}, respectively. Convergence was always achieved and the equation fitted the data extremely well; residual sums of squares ranged from 1.2×10^{-6} to 6.7×10^{-5}, with a median value of 2.2×10^{-5}. Estimates of *a* (0.62–0.74) and *D* (2.948–2.963) were physically reasonable, and sensitive to soil management practices. The *a* parameter increased, $r = 0.80$ ($P < 0.01$), (signifying decreasing ρ_b and/or h_a) whereas *D* decreased, $r = -0.75$ ($P < 0.01$), (signifying more rapid capillary drainage) with increasing soil carbon content. Additional research is needed to test this approach on other soil types, and to assess the influence of soil disturbance and variations in ρ_s on the model's performance.

The variably-saturated subsurface, or vadose zone, is a critical component of the global hydrologic cycle. However, our understanding of this zone is insufficient to make accurate predictions about unsaturated flow and transport. This is partly because soil hydraulic properties are often difficult and time consuming to measure. Moreover, the equations commonly used to parameterize such properties are not physically based.

The water retention curve is one of the most important soil hydraulic properties. It is widely used for estimating the amount of water that can be extracted from soil by plants in an agronomic context, and for modeling flow and transport through the vadose zone in environmental applications. For a review of current knowledge on water retention theory see Bachmann and van der Ploeg (2002). Although this property is hysteretic, normally only the main drying branch or desorption curve is measured. It can take weeks to determine an entire desorption curve using traditional pressure plate methods. However, recent progress in instrumentation and technology have facilitated the rapid measurement of desorption curves using water activity meters (Gee et al., 1992; Scanlon et al., 2002).

Water activity meters are based upon the chilled mirror dew point method. This technique involves equilibrating moist soil with water vapor in air within a sealed chamber. When equilibrium is reached, a photodetector attached to a cooled mirror senses when condensate begins to form on the mirror. Assuming the osmotic potential due to dissolved salts in the soil solution is negligible as compared with matric forces, the tension, *h* (Pa), of the soil water can be calculated from

$$h = (RT/V_w)\ln(p/p_0), \qquad [1]$$

where *R* is the gas constant (8.31 J mol^{-1} K^{-1}), *T* is the sample temperature in K, V_w is the molar volume of water (1.8×10^{-5} m^3 mol^{-1}), *p* is the vapor pressure of air inside the sampling chamber (Pa), and p_0 is the saturation vapor pressure (Pa) (Gee et al., 1992; Scanlon et al., 2002). The water content (*w*) of the sample is measured gravimetrically. A series of paired measurements of *h* and *w* are used to construct the desorption curve, *w*(*h*). This method is limited to disturbed samples and soil water tensions in the range 0.1 to 100 MPa (Gee et al., 1992; Scanlon et al., 2002).

Although water activity meters are commercially available, relatively few studies have published *w*(*h*) data measured using this method. Gee et al. (1992) employed a model CX-1 water activity meter (Decagon Devices, Inc., Pullman, WA) to determine *h* on field samples from DOE's Hanford Site, WA. These authors also presented *w*(*h*) curves for four different soils. Campbell and Shiozawa (1992) used a similar instrument, along with a suite of other techniques, to construct *w*(*h*) curves over the entire tension range from saturation to oven dryness for six soil types. Andraski (1996) used the CX-1 in combination with pressure plate methods to measure water retention curves on 92 samples from a commercial waste burial site near Beatty, NV. Perfect et al. (2002) also combined the pressure plate and water activity methods to measure desorption curves on 24 samples from four KY soils. They used the WP4 Model (Decagon Devices, Inc.). While other studies may have been conducted that we are unaware of, it is clear from the paucity of published data that additional research with this promising technique is warranted.

A variety of equations have been used to parameterize retention data collected with water activity meters. Gee et al. (1992) used the Fink and Jackson (1973) equation for describing water adsorption isotherms of soils, as well as a semilogarithmic model. Andraski (1996)

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Abbreviations: NT, no-till; PD, plowed and disked treatment.

used the Rossi and Nimmo (1994) model for extending water retention curves to oven dryness. Campbell and Shiozawa (1992) and Perfect et al. (2002) used the Campbell (1974) power law function. Campbell and Shiozawa (1992) also used a modified form of the van Genuchten (1980) equation, in which adsorption of water on soil was described with a semi-logarithmic expression. Fayer and Simmons (1995) further extended this model, resulting in an equation with six unknown parameters. Most of these models are empirical and lack any physical basis.

Fractal geometry offers new opportunities for parameterizing $w(h)$ data based on sound physical principles. Fractals are proving to be effective tools for quantitatively describing the physical relationship between soil and water by providing a geometrical basis for modeling soil structure (Perrier et al., 1996; Giménez et al., 1997). While these models are based on shapes and patterns that only approximate much more complex soil structures, research is beginning to show they are reliable analogs for describing and estimating soil pore size distributions (Perrier et al., 1996).

Several fractal equations have been proposed for modeling the water retention curve of soils. Perhaps the most well known are those by Tyler and Wheatcraft (1990), Rieu and Sposito (1991a), and Perfect (1999). Tyler and Wheatcraft (1990) based their model on a two-dimensional Sierpinski carpet that was stretched to form a capillary bundle. While this model can easily be extended to three dimensions, it only applies in the limit of infinite iterations, when the porosity (ϕ) is unity. Rieu and Sposito (1991a) developed a three-dimensional prefractal model for the water retention curve that treats soil as a partially fragmented porous medium with $\phi \leq 1$. This model was successfully tested on six soils of diverse texture and origin by Rieu and Sposito (1991b). Perfect (1999) derived an alternative prefractal model based on the pore-size distribution of a Menger sponge constructed with a finite number of iterations. This model was successfully fitted to the data of Campbell and Shiozawa (1992), yielding physically reasonable parameter estimates.

The objectives of this paper are: (i) to demonstrate the equivalence of the Tyler and Wheatcraft (1990), Rieu and Sposito (1991a), and Perfect (1999) models; (ii) to derive a new form of the Rieu and Sposito (1991a) model based upon w instead of the volumetric water content; (iii) to fit this model to water desorption data collected with water activity meters; and (iv) to investigate the sensitivity of the resulting parameter estimates to different management practices on a single soil type.

THEORY

Equivalence of Tyler and Wheatcraft (1990), Rieu and Sposito (1991a), and Perfect (1999) Equations

The Rieu and Sposito (1991a) prefractal model for the water retention curve is given by

$$\theta = \phi - 1 + (h/h_a)^{D-3}, \quad [2]$$

where θ is the volumetric water content, h_a is the air entry tension, and D is the mass fractal dimension. Noting that $\theta = 0$ at the tension associated with oven dryness, h_d, we can rearrange Eq. [2] to define the porosity:

$$\phi = 1 - (h_d/h_a)^{D-3}. \quad [3]$$

Substituting Eq. [3] into Eq. [2] yields

$$\theta = (h/h_a)^{D-3} - (h_d/h_a)^{D-3}. \quad [4]$$

Finally, dividing Eq. [4] by Eq. [3] gives

$$\theta/\phi = (h^{D-3} - h_d{}^{D-3})/(h_a{}^{D-3} - h_d{}^{D-3}), \quad [5]$$

which is identical to Perfect's (1999) prefractal expression.

Extended to three dimensions, the Tyler and Wheatcraft (1990) fractal water retention model can be written as:

$$\theta = (\mathrm{h}/\mathrm{h}_a)^{D-3} \quad [6]$$

Comparing Eq. [6] with Eq. [2], it is clear that Tyler and Wheatcraft's (1990) expression is a special case of Rieu and Sposito's (1991a) model for the condition $\phi = 1$.

We have shown the Rieu and Sposito (1991a), Tyler and Wheatcraft (1990), and Perfect (1999) equations are essentially the same. Since Eq. [2] is the most general form, and was published before Eq. [5], it has precedence.

Gravimetric Form of Rieu and Sposito (1991a) Equation

Desorption curves determined with water activity meters are normally expressed in terms of gravimetric water content; the volumetric water content is unknown since the soil is disturbed. Thus, it is desirable to derive Eq. [2] in terms of w. The gravimetric and volumetric water contents are related by:

$$\theta = (\rho_b/\rho_w)w, \quad [7]$$

where ρ_b is the bulk density and ρ_w is the density of water. Introducing Eq. [7] into Eq. [2] and rearranging gives

$$w = (\phi\rho_w/\rho_b) - (\rho_w/\rho_b) + (\rho_w/\rho_b \mathrm{h}_a{}^{D-3})h^{D-3}. \quad [8]$$

Recall that ϕ is related to ρ_b by

$$\phi = 1 - (\rho_b/\rho_s), \quad [9]$$

where ρ_s is the particle density. Inserting Eq. [9] into Eq. [8] and rearranging yields,

$$w = ah^{D-3} - (\rho_w/\rho_s) \quad [10]$$

where $a = \rho_w/(\rho_b h_a{}^{D-3})$. If one assumes standard values for ρ_w and ρ_s, Eq. [10] can be fitted to experimental data as a two-parameter model.

MATERIALS AND METHODS

Soil samples were collected from a long-term field experiment at the Kentucky Agricultural Experiment Station, Spindletop Farm near Lexington, KY (Frye and Blevins, 1997; Perfect and Caron, 2002). Continuous tillage (spring moldboard plowed and disked, PD; and no-till with chemical weed control, NT) and nitrogen fertilization (0, 84, 168, and 336 kg N ha^{-1} yr^{-1}) treatments have been maintained at this site since 1970. Corn (*Zea mays* L.) is grown each year followed by a cover crop of winter rye (*Secale cereale* L.). The soil is a Maury silt loam (fine, mixed, semiactive, mesic Typic Paleudalf), well drained on a 1 to 3% slope, and without evident rill erosion.

Soil sampling was conducted in late April 2001 just before tillage of the PD treatment. The soil was in a friable state suitable for tillage. Composite disturbed samples were obtained from a depth of zero to 10 cm in each of the 32 plots

Table 1. Soil water pH, and total carbon and nitrogen contents at the field site.

		Water pH		Total C (%)		Total N (%)	
Tillage†	N Rate	Mean	SD	Mean	SD	Mean	SD
	kg ha^{-1} yr^{-1}						
PD	0	6.93	0.53	1.11	0.13	0.12	0.01
	84	7.08	0.46	1.22	0.07	0.13	0.01
	168	6.53	0.49	1.26	0.08	0.14	0.01
	336	6.33	0.41	1.39	0.18	0.15	0.01
NT	0	7.18	0.31	1.78	0.19	0.20	0.01
	84	7.00	0.26	1.99	0.23	0.22	0.03
	168	5.83	0.40	2.15	0.15	0.23	0.00
	336	6.28	0.36	2.73	0.29	0.28	0.03

† NT = no-tillage, PD = plowed and disked.

(= 2 tillage treatments × 4 N application rates × 4 replicates) with a 2.5-cm-diam. core sampler. The samples were sealed in plastic bags and stored at 4°C until analyzed.

In the laboratory, the field-moist soil was passed through a 4-mm sieve. Approximately 1 g of soil from each field sample was weighed out, placed in a sample cup, and wetted to saturation by capillarity with filter paper in contact with a reservoir of tap water. The soil was then allowed to slowly air dry on a bench top at approximately 20°C. Two different commercial water activity meters were employed to record h over time. A WP4 Dew Point PotentiaMeter (Decagon Devices, Inc.) was used for $h < 40$ MPa, and an AquaLab model CX-2T Water Activity Meter (Decagon Devices, Inc.) was used for $h > 40$ MPa (Scanlon et al., 2002). The mass of the sample was also recorded. At the end of the drying period the soil was oven dried at 105°C for 24 h, and values of w were calculated. Six paired measurements of w and h were made on each sample. Other soil properties measured (Table 1) included water pH, and total carbon and nitrogen contents (expressed as gravimetric percentages of the oven-dry soil mass) determined by the dry combustion technique (Page et al., 1982).

Data were analyzed using correlation (PROC CORR), linear regression (PROC REG), nonlinear regression (PROC NLIN), and ANOVA (PROC GLM) with the SAS/STAT statistical software program (SAS Institute, 1999). Equation [10] was fitted to the $w(h)$ data for each sample by the Newton method in PROC NLIN; ρ_w and ρ_s were fixed at 1.00 and 2.65 Mg m^{-3}, respectively, while a and D were estimated. Convergence was achieved according to the SAS/STAT (SAS Institute, 1999) default criterion in every case.

RESULTS

Measured values of w and h ranged from 0.02 to 0.17, and from 2.0×10^2 to 1.5×10^5 kPa, respectively. Since the data were collected at tensions well in excess of the air entry value, w always decreased with increasing h. Equation [10] fitted the experimental data extremely well. Two representative $w(h)$ curves are shown in Fig. 1, along with their corresponding best-fit relations. Residual sums of squares for all of the fits ranged from 1.2×10^{-6} to 6.7×10^{-5}, with a median value of 2.2×10^{-5}. Adjusted R^2 values computed by linear regression of predicted and observed values were ≥0.99.

Predicted vs. observed water contents for the entire data set (n = 32 samples × 6 tensions = 192) are shown in Fig. 2. Overall the water content values predicted by

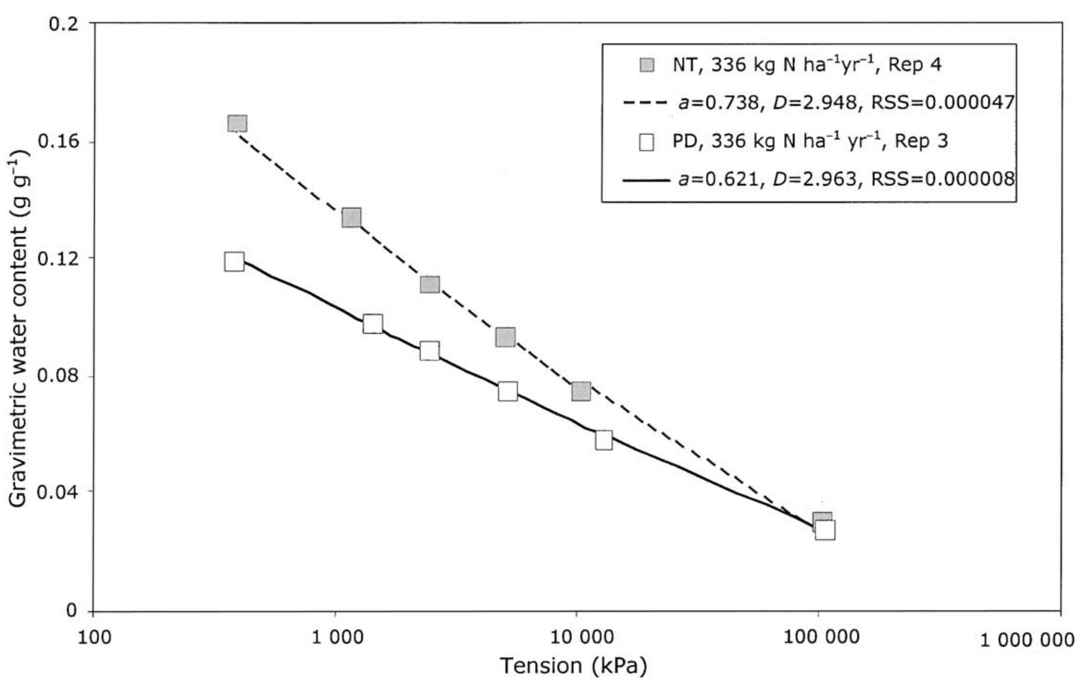

Fig. 1. Measured soil water desorption curves and best fits of Eq. [10] for samples yielding maximum and minimum estimates of mass fractal dimension (D). a = a compound parameter including the bulk density and air-entry tension, PD = spring moldboard plowed and disked, NT = no-till with chemical weed control, RSS = residual sum of squares.

Table 2. Summary of analyses of variance for the *a* and *D* parameters.

	F value†					
Parameter	Model	Tillage	N rate	Tillage × N rate interaction	Replicate	R^2
a	5.60	25.62	ns	4.16	3.43	0.727
D	4.73	20.38	ns	3.39	3.38	0.693

† All values are significant at $P < 0.05$ except for those denoted by ns.

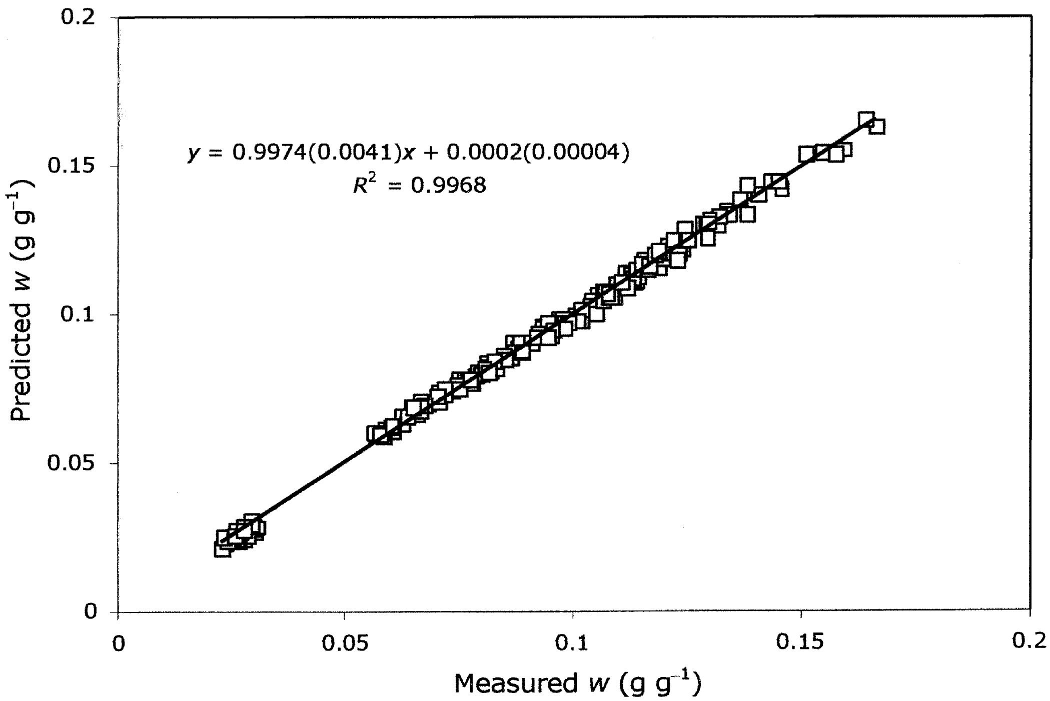

Fig. 2. Predicted gravimetric water contents (*w*) from best fits of Eq. [10] vs. the measured *w* values. Standard errors of regression parameters are given in parentheses.

the model were very close to the observed water contents. Regression analysis (Fig. 2) indicated only minimal deviations from a 1:1 relationship. The gap in the data between $w \approx 0.03$ and 0.06 in Fig. 2 is the result of two different instruments used to measure h. Values of $w > 0.06$ correspond to measurements of h made with the WP4, while those <0.03 correspond to data collected with the CX-2T.

Estimates of the a parameter in Eq. [10] ranged from 0.62 to 0.74 kPa^{3-D}. Analysis of variance (Table 2) indicated significant tillage and tillage by N rate interaction effects on a. These effects are illustrated by the mean values in Fig. 3A. When no nitrogen fertilizer was applied, the mean values of a were similar for both tillage treatments. With increasing nitrogen fertilizer application rate, the a parameter increased under NT but remained constant under PD. From Eq. [10], an increase in a can be the result of a decrease in ρ_b, a decrease in h_a, or decreases in both of these properties. Since both ρ_b and h_a are structure dependent, the a parameter should be sensitive to soil structural conditions (see *Discussion and Conclusions*). Thus, assuming soil disturbance has little impact on the $w(h)$, it is possible to infer from a that increasing N fertilization combined with no-tillage management increases total porosity (by decreasing ρ_b) and/or increases the size of the largest pores present (by decreasing h_a). The replication effect in Table 2 suggests some differences in physical conditions across the site, possibly related to spatial variation in soil texture.

Estimates of the mass fractal dimension were always significantly less than three at $P < 0.05$. Although D only ranged from 2.948 to 2.963, it was still highly sensitive to the imposed tillage and fertilization treatments. Analysis of variance identified the same significant effects as those found for the a parameter (Table 2). The mean D values decreased with increasing nitrogen fertilizer application rate under NT and remained relatively constant under PD (Fig. 3B). The fractal dimension controls the shape of the $w(h)$ curve; curvature is more pronounced (when viewed on a semi-log scale) with lower values of D. This increased curvature signifies more rapid capillary drainage. Thus, if our estimates of D for disturbed samples are applicable to field conditions, then high rates of N fertilization combined with no-till management should increase the proportion of readily drainable meso-pores present. The effect of increased N fertilization on $w(h)$ appears to be eliminated by the annual inversion and fragmentation of soil produced by tillage operations in the PD treatment (Fig. 3B).

There was a very strong inverse correlation between the a and D parameters ($r = -0.993$, $P < 0.0001$), indicating lower bulk density and/or air entry values are associated with more rapid capillary drainage. This relationship suggests that the extrapolated tensions as $w \rightarrow 0$ should be the same for all of the water retention

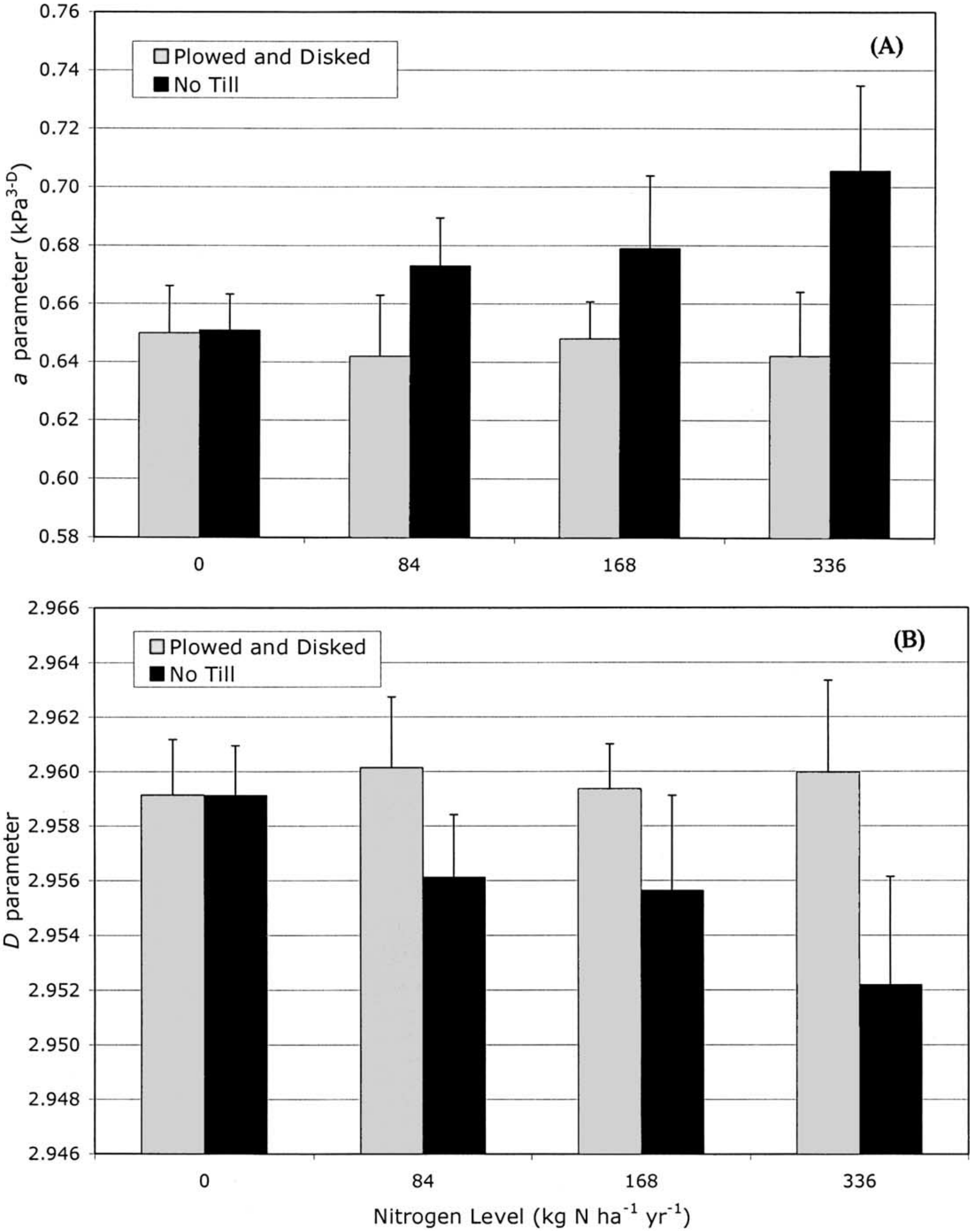

Fig. 3. Comparison of mean values for (A) the *a* parameter and (B) the *D* parameter estimates. Bars denote one standard deviation.

curves. We tested this idea by computing the tension at dryness, h_d, with the following equation derived by setting $w = 0$ in Eq. [10] and solving for h:

$$h_d = (\rho_w/a\rho_s)^{1/D-3} \quad [11]$$

Values of h_d computed by inserting estimates of a and D into Eq. [11] with $\rho_w = 1.00$ Mg m^{-3} and $\rho_s = 2.65$ Mg m^{-3} ranged from 3.8×10^5 to 7.4×10^5 kPa. Analysis of variance (not presented) found no significant tillage, fertilization, or replication effects on h_d at $P < 0.05$. This is to be expected since different management practices on a single soil type should not affect this property. Instead, the tension at dryness can probably be associated with oven drying at 105°C for 24 h. Ross et al. (1991) used Eq. [1] to predict h_d based on typical conditions associated with oven drying. For an oven temperature of 105°C, h_d can theoretically range from 4.7×10^5 to 1.4×10^6 kPa depending on the temperature and relative humidity of the external air (Ross et al., 1991). The fact that >80% of the estimated h_d values fell within this range instills confidence in the veracity of these calculations.

DISCUSSION AND CONCLUSIONS

Most soils contain some dissolved salts which become more concentrated during drying, thereby decreasing the osmotic potential, ψ_o, of the soil solution. Application of the water activity meter method to measure h assumes that $|\psi_o|$ is negligibly small compared with h.

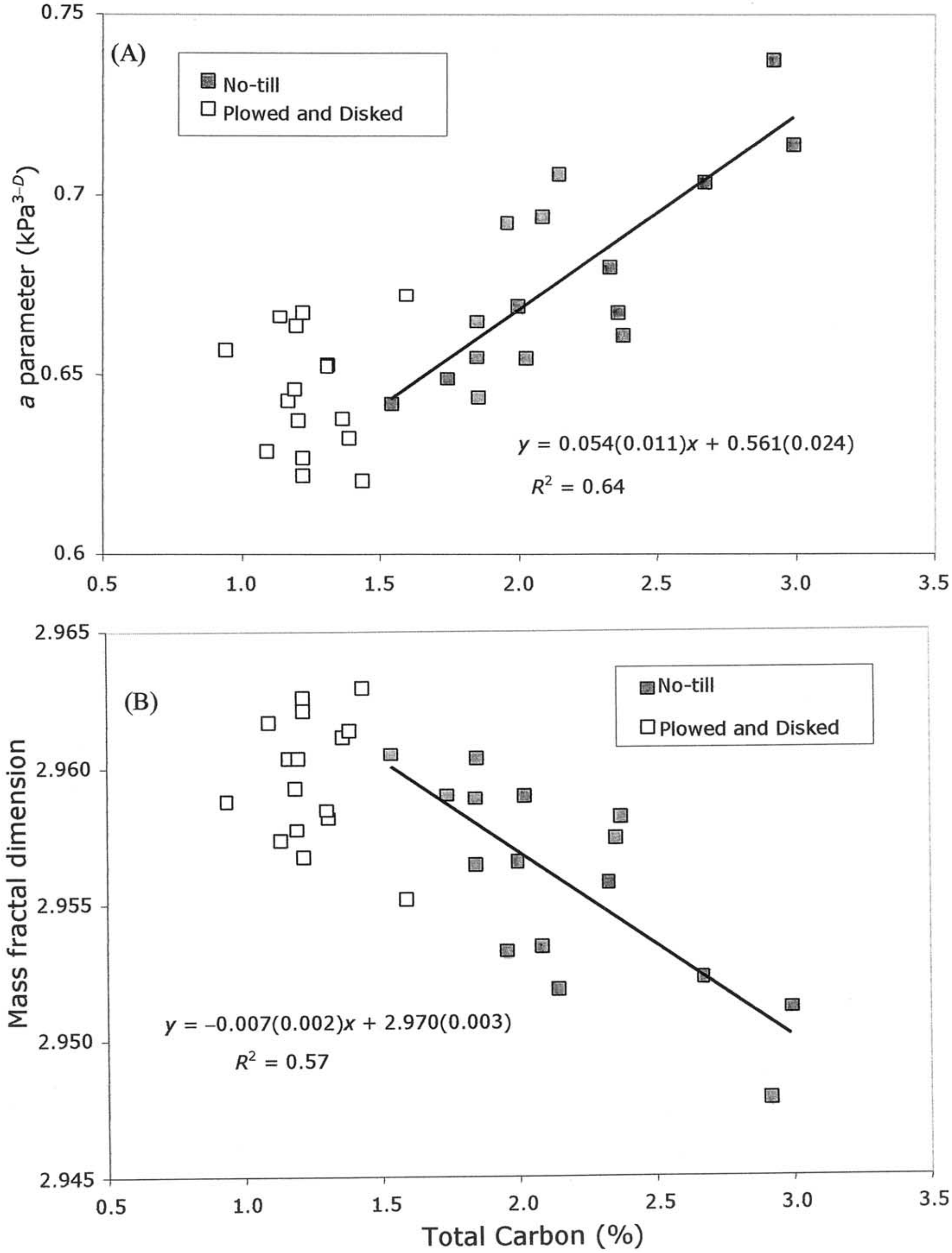

Fig. 4. Relationships between (A) the *a* parameter and (B) the *D* parameter and soil carbon content for the PD (plowed and disked) and NT (no-till) tillage treatments. Standard errors of regression parameters are given in parentheses.

From Eq. [2] it is easy to show that $h \propto (\theta - \phi + 1)^{1/D-3}$, whereas for an ideal solution, $|\psi_o| \propto \phi/\theta$ (Rawlins and Campbell, 1986). Since $\theta < \phi \ll 1$ and $2 \ll D < 3$, it follows that changes in h due to decreasing water content will be much greater than those for $|\psi_o|$. Thus, considering the relatively dry conditions over which water activity meters operate, the assumption that $|\psi_o|$ is negligible compared with h is not unreasonable.

Equation [10] assumes that all pores fill and drain according to the Young-Laplace equation, that is, capillarity dominates over adsorption (Rieu and Sposito, 1991a). It is traditionally assumed that capillary phenomena give way to an adsorption-controlled regime at very low water contents. It is obvious from Fig. 1 and 2, however, that Eq. [10] can be applied across a very wide range of tensions without any obvious break in the fractal scaling indicative of a crossover point. This observation is consistent with recent reports (Ma et al., 1999; Broseta et al., 2001) that indicate capillary-based models provide a more accurate estimate of the fractal dimension at low water contents than those which assume water is primarily located in thin surficial films of uniform thickness. In this context, more research is needed to compare fractal dimensions measured using the approach outlined in this paper with those obtained from adsorption isotherm or small angle x-ray and neutron scattering experiments performed on the same samples.

Another potential limitation of the proposed technique is its reliance on the use of small disturbed soil samples. Water activity meters operate at tensions >100 kPa, where the $w(h)$ curve depends mainly on soil texture and organic carbon content. Thus, there should be very little influence of soil disturbance on the raw data. However, extrapolation of the fitted model into the wet range of the $w(h)$ to predict bulk density and/or the air-entry value may be problematic since these quantities are primarily structure dependent. For structured soils, sample disturbance could undermine the scaling of Eq. [10] as $h \rightarrow h_a$. The small size of the samples used may also be insufficient to fully represent the heterogeneity of some of the structural units that are present. Additional research is needed to address these important issues.

The treatment effects on a and D that are apparent in Fig. 3 can probably be explained in terms of soil carbon and nitrogen contents. The long-term management practices at this site have produced a range of soil nitrogen levels (Table 1). The resulting differences in soil fertility give rise to systematic spatial and temporal variations in crop biomass (Frye and Blevins, 1997), and thus, variable amounts of residues returned to the soil across time. These differences in organic matter input have created a wide range of total C contents under the different treatments (Table 1). This interpretation of the data in Table 1 is supported by a strong positive correlation between total soil carbon and nitrogen contents ($r = 0.975$, $P < 0.0001$).

For the PD treatment, neither a nor D showed any overall trend with increasing total soil C content (Fig. 4). In contrast, both parameters were strongly correlated with total soil carbon levels under NT. In the absence of tillage, the a parameter increased (Fig. 4A), while the fractal dimension decreased (Fig. 4B) with increasing soil C contents. From Eq. [10] it can be seen that as bulk density and/or the air-entry tension become smaller, a becomes larger. Thus, as carbon contents increase under NT, our analysis predicts an increase in total porosity and/or greater macropore size. In addition, lower D values indicate a greater proportion of drainable pores. Presumably, the organic component of the total carbon pool acts as a cementing agent, creating more mesopores by aggregation of soil particles. Thus, as the carbon content increases, the D value decreases. The trends observed in Fig. 4 indicate that variations in soil carbon content have a definite effect on the $w(h)$ curve under NT conditions.

Soil management effects on the $w(h)$ curve are commonly expressed in terms of field capacity, wilting point, and plant available water. It is possible to compute these quantities by inserting the estimates of a and D into Eq. [10], setting $h = 30$ and 1500 kPa, and solving for w to give field capacity and wilting point, respectively. Plant available water is then simply the difference between these two values. This approach, like that used to estimate h_d, involves considerable extrapolation. However, it is theoretically justified by our use of a prefractal model which automatically assumes the form of the $w(h)$ curve is scale-invariant over the entire range of tensions from h_a to h_d. Analysis of variance (not presented) identified significant tillage, tillage by N level interaction, and replication effects at $P < 0.05$ for all three calculated quantities. The mean values resulting from this analysis are summarized in Table 3, and are clearly sensitive to the imposed treatments. Thus, by combining fractal modeling with water activity meter technology it may be possible to rapidly estimate conventional parameters used to characterize the $w(h)$ curve. Such an approach could prove invaluable in the evolving field of precision agriculture.

In conclusion, we have shown that chilled mirror water activity meters can be used to rapidly generate soil water retention curves for disturbed samples across a wide range of tensions. Application of a physically-based fractal model provides a convenient way of parameterizing such data. The model parameters, a and D, were shown to be sensitive to tillage and nitrogen fertilizer management on a single soil. Additional studies are needed to evaluate the utility of this approach on other soil types. The model can be used to predict field capacity, wilting point, available water content, and the tension at dryness. However, further research is needed to compare these predictions with data obtained on undisturbed samples using standard procedures. In this study, the model was fitted to the data assuming both ρ_w and ρ_s are known. Goodness of fit and accuracy of the model predictions might be improved by measuring ρ_s. Because the fractal model is physically based, it may be possible to estimate its parameters from independent measurements. For example, a can be predicted from measurements of bulk density and the air entry value, while D can be obtained from small angle x-ray or neutron scattering. This capability warrants a thorough examination. Finally, it would be very interesting to investigate hysteresis with this approach. The wetting curve could easily be obtained by slowly wetting oven-dried samples with a vaporizer.

Table 3. Mean values of w at field capacity and wilting point and plant available water calculated for the different treatments.

Tillage†	N rate	Field capacity	Wilting point	Plant available water
	kg ha^{-1} yr^{-1}	g g^{-1}		
PD	0	0.19a‡	0.10a	0.08a
	84	0.18a	0.10a	0.08a
	168	0.18ab	0.10a	0.08ab
	336	0.18ab	0.10ab	0.08ab
NT	0	0.19ab	0.11ab	0.08ab
	84	0.20bc	0.11bc	0.09bc
	168	0.20c	0.11cd	0.09c
	336	0.22d	0.12d	0.10d

† NT = no-tillage, PD = plowed and disked.
‡ Means with the same letter within a column are not significantly different at $P < 0.05$ according to a t test.

REFERENCES

Andraski, B.J. 1996. Properties and variability of soil and trench fill at an arid waste-burial site. Soil Sci. Soc. Am. J. 60:54–66.

Bachmann, J., and R.R. van der Ploeg. 2002. A review of recent developments in soil water retention theory: Interfacial tension and temperature effects. J. Plant Nutr. Soil Sci. 165:468–478.

Broseta, D., L. Barré, and O. Vizika. 2001. Capillary condensation in a fractal porous medium. Phys. Rev. Lett. 86:5313–5316.

Campbell, G.S. 1974. A simple method for determining unsaturated hydraulic conductivity from moisture retention data. Soil Sci. 117:311–314.

Campbell, G.S., and S. Shiozawa. 1992. Prediction of hydraulic properties of soils using particle size distribution and bulk density data. p. 317–328 *In* Proc. of an International Workshop on Indirect Methods for Estimating the Hydraulic Properties of Unsaturated Soils. Univ. of California Press, Berkeley.

Fayer, M.J., and C.S. Simmons. 1995. Modified soil water retention functions for all matric suctions. Water Resour. Res. 31:1233–1238.

Fink, D.H., and R.D. Jackson. 1973. An equation for describing water vapor adsorption isotherms of soils. Soil Sci. 116:256–261.

Frye, W.W., and R.L. Blevins. 1997. Soil organic matter under long-term no-tillage and conventional tillage corn production in Kentucky. p. 227–234 *In* E.A. Paul et al. (ed.) Soil organic matter in temperate agroecosystems: Long-term experiments in North America. CRC Press, Boca Raton, FL.

Gee, G.W., M.D. Campbell, G.S. Campbell, and J.H. Campbell. 1992. Rapid measurement of low soil water potentials using a water activity meter. Soil Sci. Soc. Am. J. 56:1068–1070.

Giménez, D., E. Perfect, W.J. Rawls, and Ya. Pachepsky. 1997. Fractal models for predicting soil hydraulic properties: A review. Eng. Geol. 48:161–183.

Ma, J., H. Qi, and P. Wong. 1999. Experimental study of multilayer adsorption on fractal surfaces in porous media. Phys. Rev. E: Stat. Phys., Plasmas, Fluids. Relat. Interdiscip. Top. 59:2049–2059.

Page, A.L., R.H. Miller, and D.R. Keeney. (ed.) 1982. Methods of soil analysis: Part 2—Chemical and microbial properties. 2nd ed. Agron. Monogr. 9. ASA and SSSA, Madison, WI.

Perfect, E. 1999. Estimating soil mass fractal dimensions from water retention curves. Geoderma 88:221–231.

Perfect, E., and J. Caron. 2002. Spectral analysis of tillage-induced differences in soil spatial variability. Soil Sci. Soc. Am. J. 66:1587–1595.

Perfect, E., M.C. Sukop, and G.R. Haszler. 2002. Prediction of dispersivity for undisturbed soil columns from water retention parameters. Soil Sci. Soc. Am. J. 66:696–701.

Perrier, E., M. Rieu, G. Sposito, and G. de Marsily. 1996. Models of the water retention curve for soils with a fractal pore-size distribution. Water Resour. Res. 32:3025–3031.

Rawlins, S.L., and G.S. Campbell. 1986. Water potential: Thermocouple psychrometry. p. 597–618. *In* A. Klute (ed.) Methods of soil analysis. Part 1, 2nd ed. Agron. Monogr. 9. ASA and SSSA, Madison, WI.

Rieu, M., and G. Sposito. 1991a. Fractal fragmentation, soil porosity, and soil water properties: 1. Theory. Soil Sci. Soc. Am. J. 55:1231–1238.

Rieu, M., and G. Sposito. 1991b. Relation pression capillaire-teneur en eau dans les milieux poreux fragmentés et identification du caractère fractal de la structure des sols. C.R. Acad. Sci. Paris 312(II):1483–1489.

Ross, P.J., J. Williams, and K.L. Bristow. 1991. Equation for extending water-retention curves to dryness. Soil Sci. Soc. Am. J. 55:923–927.

Rossi, C., and J.R. Nimmo. 1994. Modeling of soil water retention from saturation to oven dryness. Water Resour. Res. 30:701–708.

SAS Institute. 1999. SAS/STAT User's Guide. v. 8. SAS Inst., Cary, NC.

Scanlon, B.R., B.J. Andraski, and J. Bilskie. 2002. Miscellaneous methods for measuring matric or water potential. p. 643–670. *In* J.H. Dane and G.C. Topp (ed.) Methods of soil analysis: Part 4—Physical methods. Book Ser. No. 5. SSSA, Madison, WI.

Tyler, S., and S.W. Wheatcraft. 1990. Fractal processes in soil water retention. Water Resour. Res. 26:1047–1054.

van Genuchten, M.Th. 1980. A closed form equation for predicting the hydraulic conductivity of unsaturated soils. Soil Sci. Soc. Am. J. 44:892–898.