Chapter 8

SOIL AGGREGATES AND WATER RETENTION

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1. INTRODUCTION

Soil aggregate composition is an important characteristic of soil structure and as such has been expected to affect soil water retention. Wittmuss and Mazurak (1958) studied water retention of samples made of individual aggregate fractions of silty clay soil. Water retention of samples from aggregates 0.07–0.15, 0.15–0.3, 0.30–0.60, 0.60–1.20, 1.20–2.4, and 2.4–4.8 was similar whereas aggregates less than 0.07 mm had distinctly different retention for matric potential from 0 to − 1.5 MPa. Those authors noted that the texture of soil in aggregates became finer as the size of aggregates decreased. Tamboli et al. (1964) worked with aggregates from silt loam soil and observed similarity in water retention of aggregates 2–3, 3–5, 5–9.5 and 9.5–12 mm. Water retention of aggregates 1–2 and 1–0.5 mm was lower than for the larger fractions and decreased with the aggregate size. No variation in textural composition with aggregate size was found. Amemiya (1965) studied model samples composed of individual fractions of soil aggregates from silt loam, silty clay loam and clay loam soils in the range of matric potentials from − 0.02 to − 1.2 Mpa. He found water retention to be similar for samples from aggregate fractions 1–2, 2–3, and 3–5 mm, and substantial difference between water retention of samples from aggregates 0.5–1 mm and from larger fractions. Combination of various aggregate fractions in one sample led to both increase and decrease in soil water retention as compared to the water retention of samples made of individual fractions. Abrol and Palta (1970) observed monotonous decrease in water retention of aggregate fractions with aggregate size in the range of matric potential from − 0.045 to − 1 MPa. Chang (1968) compared water retention of <0.25 cm and 1–4.8 cm fractions from clay soil. Water retention of the smaller fraction was smaller at matric potentials from 0 to − 1 kPa. As the matric potential decreased further, smaller fraction had larger water retention. Those differences were viewed as a result of differences in intra-aggregate and inter-aggregate water retention.

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Data on model systems composed of aggregates indicated a potential effect of aggregate size distributions of soils on their water retention. Wu et al. (1990); Wu and Vomocil (1998) had found similarity of cumulative pore, aggregate, and particle size distributions, and used this similarity to transform one of those distributions to another. Our objective is to show how aggregate size distributions affect soil water retention from saturation to the wilting point. We use the van Genuchten approximation of gravimetric water retention data and report effects of both aggregate size and particle size distributions on parameters of the van Genuchten equation. A similar study has been reported for water contents at specific soil water potentials (Guber et al., 2003)

2. SOIL DATABASE

Soil properties were studied on samples of Podzoluvisols, Planosols, Chernozems, Fluvisols, Calcisols, and Gleysols (FAO-UNESCO, 1974; Stolbovoi and Sheremet, 2000) represented with 9, 7, 102, 3, 11, and 10 samples, respectively. Samples were taken in Moscow and Voronezh provinces of Russia, Krasnohvardiis'ka province of Ukraine, and Tashkent and Fergana provinces of Uzbekistan. Soils were sampled at arable lands in A, E, B and transitional horizons. Texture of the samples was measured with the pipette method (Gee and Bauder, 1986) after dispersion with sodium pyrophosphate $Na_4P_2O_7$. Particles diameter groups were <0.001 mm, 0.001–0.005, 0.005– 0.01, 0.01–0.05, 0.05–0.25, >0.25 mm. Those fractions are referred to as clay, fine silt, medium silt, coarse silt, fine sand, and coarse sand, respectively, in this work. The dataset included samples of loam, silt loam, silty clay loam and silty clay soils, represented with 11, 28, 47, and 56 samples respectively. Dry aggregate size distribution was determined by sieving into following aggregate diameter groups: <0.25, 0.25–0.5, 0.5–1, 1–2, 2–3, 3–5, 5–7, 7–10, and >10 mm.

Cumulative distributions were used in data analysis. Particle size variables were $d_{<0.001}$ = the percentage of particles smaller than 0.001 mm, $d_{<0.005}$ = the percentage of particles smaller than 0.005 mm, etc. Aggregate size variables were $a_{<0.25}$ = the percentage of aggregates smaller than 0.25 mm, $a_{<0.5}$ = the percentage of particles smaller than <0.5 mm, etc.

Water retention was measured in sand–kaolin boxes (Stakman et al., 1969; Varallyay and Mironenko, 1979) for matric potentials within range from 0 to -50 kPa and by vapor equilibration above K_2SO_4, KCl and $Ca(NO_3)_2$ solutes at -2.76, -20.5 and -81.6 MPa. Gravimetric water contents W were used in the analysis in this work. Parameters of water retention were found by fitting van Genuchten equation (van Genuchten, 1980) to measured data:

$$W = Wr + (Ws - Wr)/[1 + (\alpha\psi)^n]^m; \qquad m = 1 - 1/n \qquad (1)$$

Here Ws and Wr are saturated and residual water contents, respectively, α, n and m are shape-defining parameters. Equation (1) gave a satisfactory approximation of the gravimetric water retention data in our dataset. Root-mean square errors were between 1.5 and 3.5% in 50% of cases. The Kolmogorov-Smirnov test showed that statistical distributions of RMSE did not differ between textural classes.

Results of grouping samples by textural classes are shown in Table 1. Distributions of all parameters of water retention are similar for silty clays and silty clay loams that have

Table 1
Values of van Genuchten parameters at different probability levels grouped by textural classes

Probability	Loam			Silt loam			Silty clay			Silty clay loam		
	$\alpha * 100$ (cm^{-1})	n	*Ws*	$\alpha * 100$ (cm^{-1})	n	*Ws*	$\alpha * 100$ (cm^{-1})	n	*Ws*	$\alpha * 100$ (cm^{-1})	n	*Ws*
0.1	nd	nd	nd	1.30	1.14	0.344	0.27	1.17	0.343	0.27	1.17	0.344
0.25	0.63	1.15	0.343	1.90	1.19	0.417	0.44	1.18	0.376	0.40	1.18	0.370
0.5	1.30	1.24	0.401	2.90	1.26	0.514	0.91	1.21	0.400	0.90	1.21	0.396
0.75	2.20	1.30	0.420	5.70	1.26	0.587	1.70	1.23	0.440	1.40	1.23	0.419
0.9	nd	nd	nd	10.10	1.31	0.633	2.70	1.25	0.478	2.40	1.26	0.457

relatively low mean values of saturated water content Ws and parameter α. Those soils have also the largest average exponent n as compare with loam and silt loam. The largest mean values of the parameters *Ws*, α and n were found in silt loam soils.

The aggregate size distributions in the database are characterized in Table 2. Aggregate fractions can be divided into three groups by the average content of the fraction. Aggregates smaller than 1 mm form the first group with average content of 3.4–3.8%, and aggregates in the range 1–10 mm form the second group with average contents of 9.9–13.0%. Large soil aggregates (> 10 mm) represent a separate group, which has great variation in contents and average content of 32.8%.

Table 2
Percentage of aggregate fractions at different probability levels

Probability	Aggregate size (mm)								
	<0.25	0.25–0.5	0.5–1.0	1.0–2.0	2.0–3.0	3.0–5.0	5.0–7.0	7.0–10.0	>10
0.1	1	1	1	5	5	8	6	6	6
0.25	1	1	1	7	7	9	7	8	21
0.5	2	2	2	11	10	12	9	9	33
0.75	6	4	4	14	13	16	10	11	45
0.9	8	9	7	17	18	19	15	19	53

3. REGRESSION TREE MODELING

Relationships between soil water retention and distributions of aggregate sizes and particle sizes were established using regression trees (see Section 2 of Chapter 2). The algorithm first finds a partition of the database into two of the most homogeneous subsets. For that, all possible splits of ranges of all input variables are compared in terms of the non-homogeneity of resulting subsets. The input variable that provides the maximum improvement of the non-homogeneity, is thought to have the greatest effect on the output variable and is used for partitioning. The procedure of partitioning is repeated for each of the two subsets, and the next two splitting variables are defined. The result of the algorithm work is a tree-like structure in which two new branches appear after each split. Regression trees were built with the software package SPLUS (MathSoft, 1999). This software uses the sum of squared differences between average in a subset and individual values in this subset as a measure of non-homogeneity within the group. The minimum size of five samples in a subset was set to prevent forming groups that are too small. We terminated the tree-building when the non-homogeneity decreased two times from the value of the whole dataset.

Regression tree for $\lg(\alpha)$ is presented in Figure 1. The total database has first been partitioned by the content of clay. The first group of samples contains the loam and silt loam samples that have the largest values $\lg(\alpha)$ and the lowest clay content. The second group of samples has a finer texture. The splitting variable here is the content of aggregates larger than 10 mm. Samples with high contents of aggregates > 10 mm are then grouped according contents of fine textural fractions. Soils with the negligible sand content form a separate group (node [5]). Soils with high "clay + fine silt" content are grouped at node [4]. Low "clay + fine silt" contents allow further separation into groups with low and high clay content (nodes [2] and [3], respectively). The aggregate size distribution remains the governing parameter for values α when the percentage of aggregates > 10 mm is relatively low (see right branch of the tree in Figure 1). Contents of the largest aggregates continue to be grouping variables as splitting progresses in this part of the database. The largest values of α are found in samples where fraction 7–10 mm is represented well, i.e., constitutes more than 9% (node [7]).

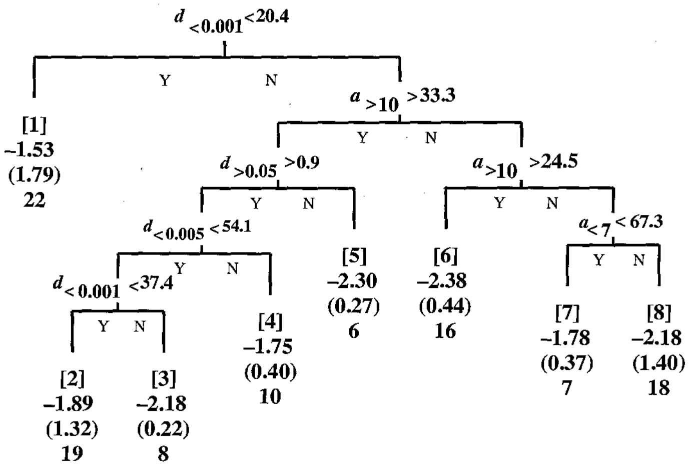

Figure 1. Regression tree to group samples according their $\lg(\alpha)$; "y" and "n" mean "yes" and "no" answers to the condition above the branching point; columns below the terminal nodes contain the node number in brackets, the average $\lg(\alpha)$ for the group, the standard deviation of $\lg(\alpha)$ within groups in parentheses, and the number of samples in the group.

The best partitioning of samples by their van Genuchten's parameter n could be done using the content of aggregates smaller than 1 mm (Figure 2). Contents of small aggregates continue to be the most important partitioning parameter for the samples where the percentage of smallest aggregates relatively is small ($< 10\%$) and fine silt and particles sand fraction constitute a small part of soil textural particles (nodes [1]–[4]). Particle size distribution becomes a source of partitioning parameters for the samples in the right

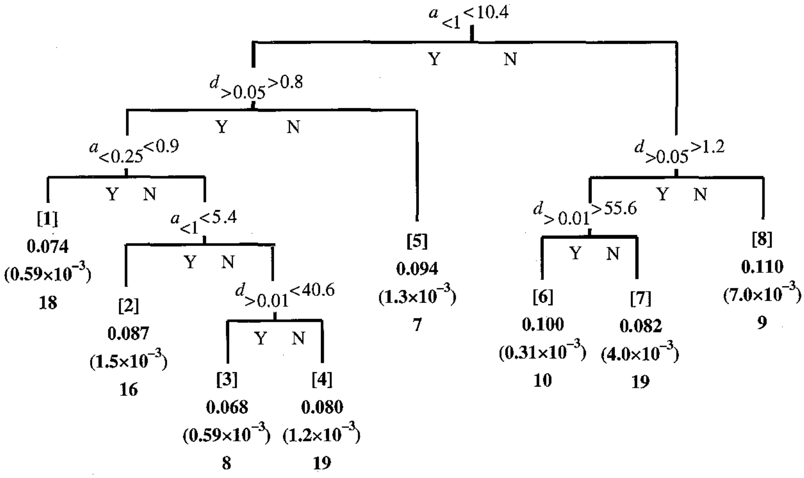

Figure 2. The same as in Figure 1 but for the logarithm of the van Genuchten parameter *n*.

branch of the tree where the content of aggregates < 1 mm is relatively high, i.e., larger than 10.4%. A singular node [8] denotes the group of samples with a negligible sand percentage. The content of coarse textural fractions $d_{>0.01}$ is important for the final partitioning in this group.

The first grouping of samples by their saturated water contents *Ws* has been made according to their clay fraction content $d_{<0.001}$ (Figure 3). The left big branch of the tree

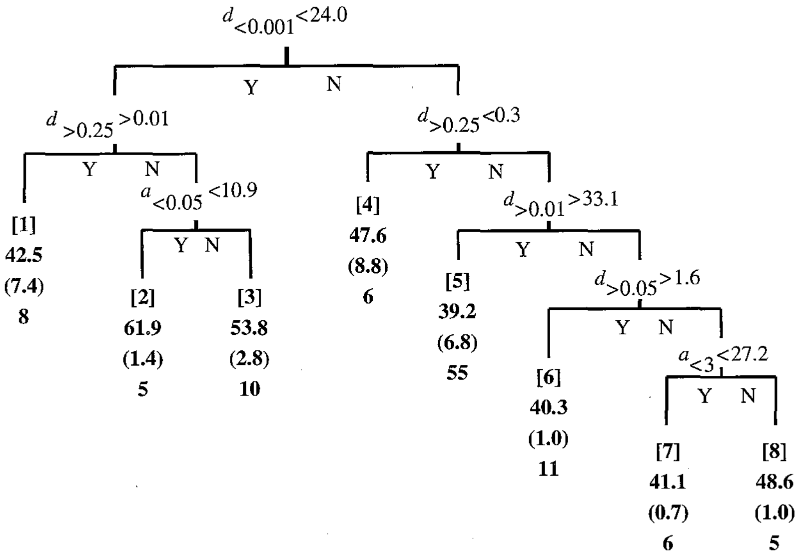

Figure 3. The same as in Figure 1 but for the saturated water contents *Ws* in the van Genuchten equation.

encompasses loam and silt loam samples whereas the right big branch includes "silty clay and silty clay loam" samples. The second partition in both groups occurs according the content of the coarse sand $d_{>0.25}$. Low coarse sand contents are associated with low *Ws* in the "loam + silt loam" group (node [1]) and with relatively high values *Ws* in the "silty clay + silty clay loam" group (node [4]). Low percentage of small aggregates ($a_{<0.05}$) is related the highest *Ws* in loam and silt loam samples (node [2]). An increase in the small aggregate content leads to smaller *Ws* values (node [3]). Partitioning by texture dominates further grouping in the "silty clay + silty clay loam" group (nodes [5]–[7]). A small group of silt clay samples with large content of aggregates <3 cm is separated into node [8] with the highest *Ws*.

The overall accuracy of estimating van Genuchten parameters with the developed regression trees is shown in Table 3 and Figure 4. In spite of giving the same, averaged over a group value to all measured values in the group, regression trees correctly reflect trends.

Table 3
Statistics of water retention parameters obtained with regression trees

Statistics	α (cm^{-1})	n	*Ws*
Mean	0.0157	1.217	43.7
Standard deviation	0.0154	0.045	8.3
Minimum	0.0015	1.148	28.4
Maximum	0.0940	1.462	68.1
RMSE	0.0102	0.030	4.6

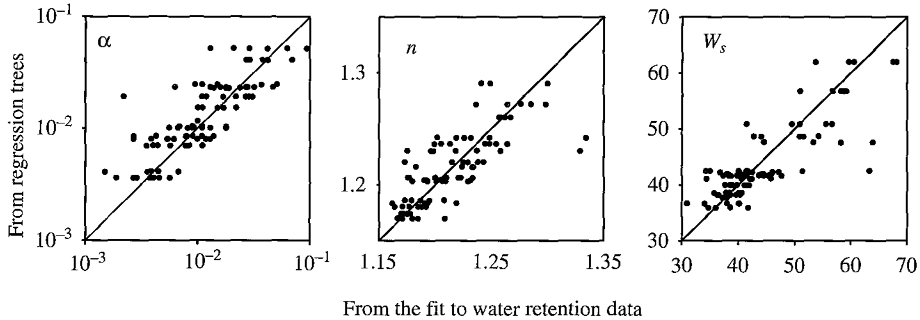

Figure 4. Comparison between van Genuchten parameter values from measured water retention and from regression trees.

4. DISCUSSION AND CONCLUSION

Soil aggregate composition provided important grouping parameters for water retention parameters. Contents of either small aggregates (<0.25 mm, <0.5 mm, <1 mm) or large aggregates (>7 mm, >10 mm) were the splitting variables in most cases for parameters of the van Genuchten equation. Results demonstrate that water retention reflects a complex interaction of texture and structure jointly affecting soil water retention. In silty clay and silty clay loam samples, texture was defining values of α where the amount of large aggregates was relatively low, less than 33%. No effect of texture on the values of α could be seen in samples with high contents of coarse aggregates (Figure 1). Parameter n was affected only by texture if the content of aggregates < 1 was sufficiently large. However, small aggregate contents continued to be splitting variables where the amount of small aggregates was low. One may conclude that if van Genuchten parameter is affected by a parameter from the end of the aggregate size distribution, then further partitioning involves other parameters from the same end of the aggregate size distribution and adds more details about this end of the distribution in the regression tree.

Ranges of aggregate sizes affecting the van Genuchten parameters α and n may be related to the role of those parameters in defining shapes of water retention curves.

The effect of van Genuchten parameters on the shape of water retention curves computed from Equation (1) is shown in Figure 5. Parameter n influences the steepness of the curves in coordinates "water content vs. lg(suction)." Value of n is affected mostly by the small aggregate contents (Figure 2), and larger values on correspond to the larger percentages of small aggregates. A probable reason for that is that large number of small aggregates creates an hierarchical structure that empties gradually as the suction increases; such aggregates would fill space between large aggregates and large particles. Another possible reason for that is a similarity between external water retention of small aggregates and large sand particles. Such similarity was shown by Wittmuss and Mazurak (1958) in studies of columns made from aggregate fractions and from textural particles. They indicated that small aggregates less than 0.3 mm behave in terms of water retention in the same way as soil particles whereas larger aggregates have water retention different from water retention of particles of the same size.

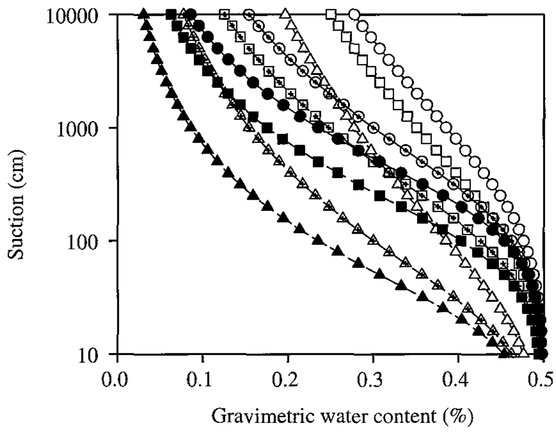

Figure 5. Examples of the effect of van Genuchten parameters α and n on the shape of water retention curves. Values of Ws and Wr were set to 0.5 and 0.0, respectively. Circles squares and triangles denote $\alpha = 0.005$, $\alpha = 0.01$, and $\alpha = 0.015\ \mathrm{cm}^{-1}$, respectively; hollow, dotted, and filled symbols denote $n = 1.1$, $n = 1.3$, and $n = 1.5$, respectively.

Increase in parameter α causes the faster loss of water with an increase in suction values. We have observed an increase in values of α with the increase of the percentage of large aggregates (Figure 1). The larger the amount of large aggregates the more likely is the presence of large intra-aggregate pores that empty at low suctions. Regression tree analysis gave results similar to the results of Gupta and Ewing (1998) who reported a modeling study on effect of aggregate-size distribution of water retention. They found that soils with dominant aggregate sizes in the range 12–50 mm had an inflection point distinctly different from that in soils with dominant aggregate sizes 2–3.3 mm, whereas much less difference was found between soils with dominant aggregate sizes 0.053–0.25 mm and 2–3.3 mm. The decrease in saturated water content *Ws* value in silt loam and loam samples with the increase of small aggregate contents also concurs with modeling results of the Gupta and Ewing (1998) who predicted flatter water retention curves in the low matric potential range for smaller dominant aggregate fractions.

We realize that some results of the regression tree analysis may be specific to our dataset. Effect of the database content on estimation of water retention from other soil properties has been documented (De Jong, 1983; Schaap and Leij, 1998). Comparison of retention parameter distributions shown in Figure 2 with distributions in other databases is problematic because of the definition of clay particles as particles <0.001 mm; the majority of texture classifications use the threshold of 0.002 mm. It remains to be seen whether and how the grouping results and the effect of aggregate distribution parameter on water retention will hold for other databases. This question presents an interesting avenue to explore because of the relatively strong effect of aggregate distribution on water retention parameters observed in this work.

All textural fractions, but not all aggregate fractions were used to partition samples by their water retention with regression trees. Separation of aggregates 1–3 mm into groups 1–2 and 2–3 mm, as well as separation of aggregates 3–7 mm into groups 3–5 and 5–7 mm, was made in measurements of aggregate size distributions but was not reflected in regression trees. One reason for that could be a similarity in water retention of the fractions 1–2 and 2–3 mm or 3–5 and 5–7 mm. Earlier similarity in retention of fractions 1–2 and 2–3 mm was observed by Amemiya (1965) and similarity in water retention of fractions 3–5 and 5–9.5 was observed by Tamboli et al. (1964). The intermediate fractions 1–2, 2–3, 2–5, 5–7 mm probably could be used if the dataset was larger.

Parameters of the aggregate size composition appeared to be important to split the dataset into homogeneous subsets using regression trees. This indicates that aggregate size distributions, if available in soil databases or feasible to measure, can be useful in estimating parameters of soil water retention from other soil properties.

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