NC STATE UNIVERSITY
DEPARTMENT of SOIL SCIENCE

Influence of Tillage on Pore Size Distribution Inferred from Soil Water Retention Curves

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Rationale

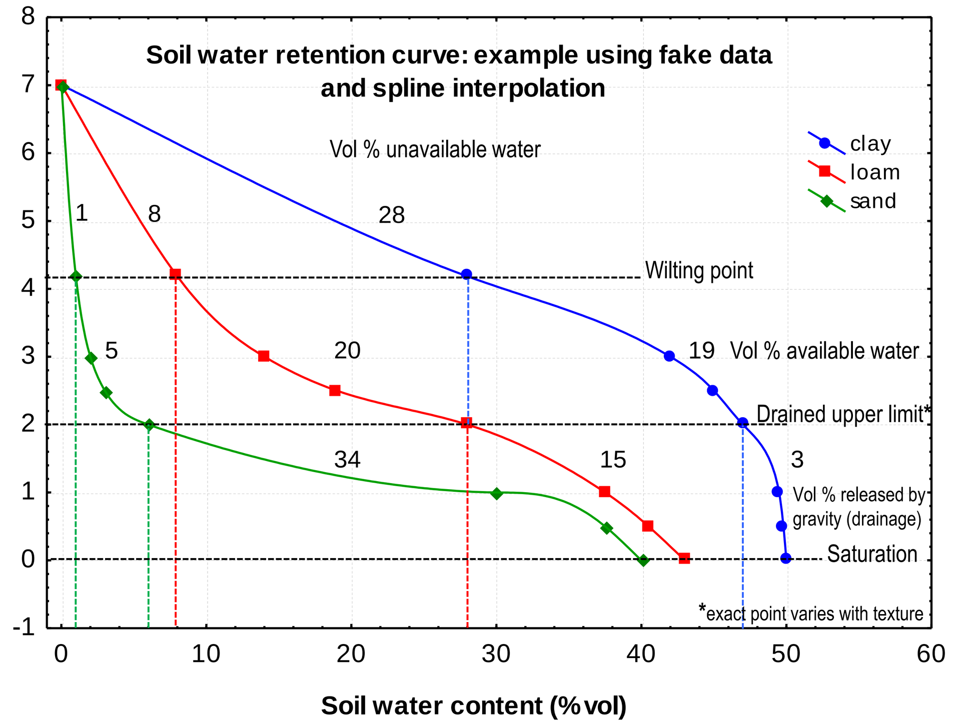
In agronomics, the soil water retention curve (SWRC) may be used to infer information about the soil's pore size distribution governing infiltration, transfer, drainage, and profile water storage. Knowledge of soil water content is important for land preparation via tillage; seed bed preparation and seeding; scheduling irrigation, estimating crop water use or ET, and yield potential; quantification of soil water balance components and water budgeting. Information about soil water content is also needed by engineers in road and building construction and in watershed studies.

The main factor controlling SWRC model shape is soil mineral particle size, which is an invariant physical property. Human activities that influence compaction, erosion, organic matter, and structure may also affect mineral arrangement and packing, so altering pore size distribution in soil. Productivity gains for corn and soybean in southeastern U.S. piedmont Ultisols under conservation tillage have been associated with more efficient capture, utilization, and profile storage of available moisture. However a physical hypothesis for improved soil hydrologic efficacy under conservation tillage remains speculative.

Anatomy of a Soil Water Retention Curve

A soil water retention curve shows the relationship between soil water content and matric suction forces (**Figure 1**). In soil, matric forces arise from the interaction of water and mineral-organic particles through *adhesion* and *surface tension*. Because these forces express binding energy they are also called the soil matric *potential*.

Figure 1.



The matric potential of soil under field conditions may span 3 to 4 orders of magnitude thus soil water potential is usually expressed as the logarithm of the matric suction, h which in **Figure 1** is in units of centimeters of water on the y axis. Examining **Figure 1**, we observe the following:

- Particle size distribution (aka 'texture') strongly influences the shape of the SWRC.
- At saturation, clay holds more water than loam or sand.
- The volume of soil water released through drainage is least for clay and increases as the amount of sand particles in soil increases.
- Clay has the most water held in soil between field capacity and the wilting point ('plant available water'), which decreases with increasing amounts of sand particles in soil.
- Clay has a larger fraction of unavailable water compared to sand and loam.

Modeling the Soil Water Retention Curve

A common equation for modeling the SWRC is the van Genuchten function (van Genuchten, 1980).

$$\theta_{\psi} = (\theta_{sat} - \theta_{res})[1+(\alpha\psi)^{n}]^{-(1-1/n)} + \theta_{res}$$

where:

- θ_{ψ} is the soil volumetric water content (%) at a specific soil water matric potential.
- θ_{sat} is the soil volumetric water content at saturation (%).
- θ_{res} is the residual water content (%) as the soil water matric potential approaches infinity.
- ψ is the soil water matric potential (hPa).
- α is proportional to the inverse of the air-entry suction (hPa^{-1}).
- n is a measure of the pore size distribution (dimensionless) and is related to the slope of the water release curve.
- n is subject to the Mualem constraint $m = (1 - 1/n)$ (Mualem, 1976).

The adjustable parameters θ_{sat}, θ_{res}, α, and n may be estimated by non-linear optimization algorithms such as Levenberg-Marquardt (van Genuchten, 1991).

The matric suction at the ***inflection point*** I(h), and the ***slope*** (S) of the soil water retention curve, is estimated in terms of parameters α and n in the van Genuchten (1980) function, to which the Mualem constraint may be applied (Dexter, 2009):

$$I(h) = \left(\frac{1}{\alpha}\right)\left(\frac{n}{(n-1)}\right)^{\left(\frac{1}{n}\right)}$$

$$S = -n(\theta_{sat} - \theta_{res})\left[\frac{2n-1}{n-1}\right]^{[(1/n)-2]}$$

Our interpretation of I(h) and S for SWRCs follows :

- At the ***inflection point*** curvature is zero or, where it changes from convex to concave (**Figure 2A**).
- In soils with bi-modal pore size distribution, the ***inflection point*** coordinates where the matrix (intra-aggregate) porosity is saturated and the structural (inter-aggregate) porosity is drained (Dexter, 2009).
- The equivalent pore diameter (EPD) may be calculated from the value of h at the ***inflection point*** *via the capillary rise equation; the EPD at the* ***inflection point*** *represents the most* ***frequently*** *occurring (modal) pore size diameter in the bulk soil, which is a useful physical quality parameter.*
- The slope S is the specific water capacity $c_{\theta}=-d\Theta/dh$ and its modulus may be taken as an objective measure of soil physical quality, i.e. compaction effects on structure can be compared (**Figure 2B**, after Dexter, 2004) .

Soil physical quality categories based on S-theory (Dexter, 2009)

$S \geq 0.050$	very good
$0.050 > S \geq 0.035$	good
$0.035 > S \geq 0.020$	poor
$0.020 > S$	very poor

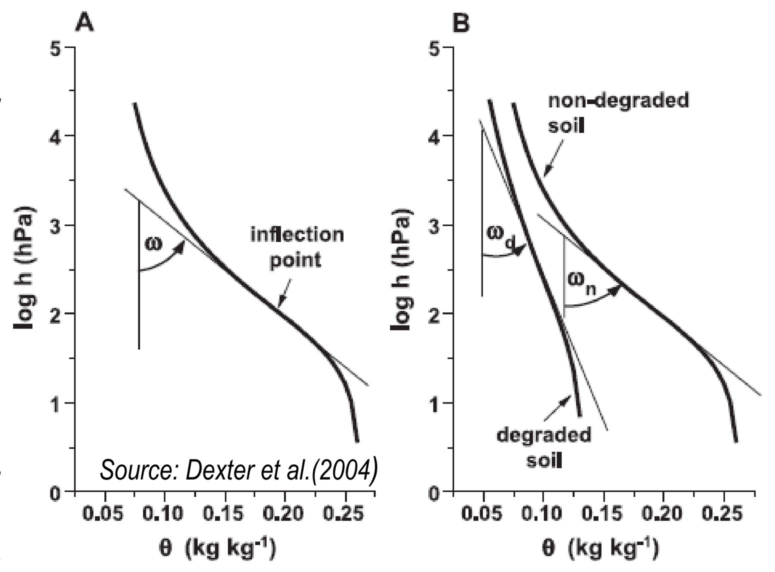


Figure 2A: An example of the inflection point and slope on the SWRC; the slope is given as tanω, the tangent to the curve at the inflection point. **2B:** SWRCs for the same sandy clay loam soil at two different bulk densities. Note that the slope S ***decreases*** when soil is compacted, indicating soil physical degradation. S is also sensitive to physical degradation from sodicity (high sodium content), poor aggregate stability in low-C soils, and tillage operations.

Objectives

- Fit soil drainage characteristic data from two tillage trials to the van Genuchten (1980) equation.
- Evaluate SWRC parameters and physical properties with respect to soil, tillage, and land use history.
- Evaluate differences in SWRC inflection point I(h), and the slope, S.

Our Approach

- We sampled the crop interrow 7.6 cm deep from two, long-term tillage trials, both on fine, kaolinitic, thermic Typic Kanhapludults, at the Upper Piedmont Research Station, Reidsville, NC. Both experiments are randomized complete blocks with four replications and have maintained controlled traffic patterns.
- On a Wedowee sandy clay loam, tillage treatments were no-tillage, shallow under-row (UR) subsoiling, spring chisel plowing with or without disking, spring disking, and spring moldboard plowing. On a Pacolet sandy clay loam, treatments were no-tillage, spring disking, spring-disking with in-season cultivation and, alternating, on an annual basis, no-tillage and disking.
- We sampled one local, old-growth (100+ yr) hardwood forest Pacolet sandy clay loam soil to represent a "virgin" never-tilled reference state Ultisol. Ten, independent 7.6 cm and 7.6-15.2 cm deep locations representing the A_1 and A_2 horizon subdivisions, respectively were collected.
- In the tillage plots, nearly undisturbed soil samples were collected by driving 7.6-cm dia. x 7.6-cm high steel cylinders with a Uhland drive head assembly in late fall after grain harvest.
- Soil water retention was measured by desorption over 48 hr at 0, -10, -50, -100, -200, -300, -400, -500 hPa in a pressure outflow system (**Figure 3**). Bulk density was measured after drying desorbed cylinders at 105˚C; soil was ground to pass a 2-mm aperture sieve and desorbed over 120 hr @ -1,000, -5,000, and -15,000 hPa in a pressure plate apparatus (**Figure 4**). Soil physical properties and indicators were estimated from the modeled SWRCs. We also computed available water between -50 and -1,000 hPa, a range that may better reflect management-sensitive, inter-aggregate (structural) pore water content affecting plant growth in sandy soils.

Matric suction is applied to a soil column via positive pressure (**Figure 3**). High matric suction (≥1,000 hPa) is measured with a pressure plate apparatus (**Figure 4**) .The outflow is measured at different matric potentials and plotted as in **Figure 1**.

- Water retention data was fit plot-wise to three- and four-parameter van Genuchten (1980) functions with the Levenberg-Marquardt algorithm implemented in the NLIN procedure in SAS 9.2 (SAS Institute, Cary, NC). To test the goodness-of-fit, we compared Akaike's Information Criteria corrected for small samples (AIC_C). Parameter estimates for the van Genuchten (1980) function and, coordinates for I(h) and values for S underwent analysis of variance in the MIXED procedure with block and soil as random covariance parameters. Water retention data from the Pacolet reference Ultisol underwent separate analysis in the NLIN procedure. We adopted a 0.05 level of probability to test main effects, and interaction hypotheses with the SLICE statement in SAS 9.2.

Results

Model fitting

- All data converged successfully on three- and four-parameter van Genuchten (1980) model solutions.
- A three-parameter van Genuchten (1980) model was adopted for all 72 SWRC curves based on AIC_C-criteria wherein the model with the lowest AIC_C was preferred.
- θ_{res} did not improve model fit and is not considered here.

Model parameters, inflection point and slope (see Tables 1, 2)

- In a Pacolet soil Θ_{sat} was lowest under no-tillage; highest in the Pacolet reference A_1 horizon and, ~ equal among clean and alternating no-tillage treatments and Pacolet reference A_1 horizon; in a Wedowee soil Θ_{sat} was lower under moldboard plow but tillage effects on Θ_{sat} overall were not as sharp.
- Tillage effects on α and n were not detected in the tilled or reference Pacolet soil; in the Wedowee soil, shape parameter n varied with tillage but α was indifferent.
- Tillage affected the SWRC slope (S) in a Pacolet soil; and inflection point I(h) coordinates in Pacolet and Wedowee soils; soil physical quality, inferred from slope S, was deemed better in the reference A_1 horizon; ~ equal among clean and alternating no-tillage treatments and reference A_1 horizon, and poor under Pacolet no-tillage and Wedowee moldboard plow tillage.
- Proximate I(h) coordinates under Pacolet no-tillage (174 hPa) and in the reference A_2 horizon (249 hPa) infer close correspondence of modal pore size frequencies in the fine 12-17 µm EPD range; and Wedowee spring chisel plow (28.3 hPa) and reference A_1 horizon (21.2 hPa) in the coarser 104-139 µm range; I(h) coordinates in other tillage treatments cluster in 40-70 µm modal range approximating the drained upper limit for sandy soil, an important finding we continue to study (see Pacolet **Figure 5a,b** treatments).
- Van Genuchten (1980) model parameters, slope and inflection point coordinates were unaffected by soil type (data not shown).

Table 1. Tillage effects on model parameters, derived quantities, and soil properties in a tilled and never-tilled Pacolet soil. Mean comparison by Tukey's HSD test; means with the same letter are not different (α=0.05). Reference A_0 and A_1 tested separately by Welch's 2-sample t-test (α=0.05).

Treatment	Parameter			SWRC-Derived Quantity		Soil Property					
	Θ_{sat}[1]	α	n	I(h)	EPD[2]	|S|	Θ_I[3]	Θ_{MACRO}[4]	PAW_T[5]	PAW_S[6]	Θ_{MATRIX}[7]	ρ_b[8]
	m³ m⁻³	hPa⁻¹	---	hPa	µm	---	----------	----------	m³ m⁻³	----------	----------	g cm⁻³
No-tillage	0.305ᵃ	0.032	1.15ᵃ	174ᵃ	16.9	0.030ᵃ	0.231ᵃ	0.035ᵃ	0.138ᵃ	0.078ᵃ	0.193	1.55ᵃ
No-tillage/disk	0.401ᵃᵇ	0.064	1.19ᵃᵇ	72.6ᵃᵇ	40.5	0.048ᵇ	0.292ᵇ	0.089ᵃᵇ	0.202ᵇ	0.128ᵇ	0.184	1.35ᵇ
Disk	0.384ᵃᵇ	0.079	1.20ᵃ	55.4ᵃᵇ	53.1	0.048ᵇ	0.277ᵃᵇ	0.094ᵃᵇ	0.193ᵇ	0.122ᵇ	0.168	1.40ᵃᵇ
Disk+cultivation	0.409ᶜ	0.074	1.22ᵇ	53.8ᵇ	54.7	0.055ᵇ	0.291ᵇ	0.114ᵇ	0.208ᵇ	0.138ᵇ	0.158	1.36ᵇ
Prob > F	<0.0001	NS	0.018	0.002	--	<0.0001	<0.0001	0.0003	<0.0001	0.0003	NS	0.04
Reference A_1	0.520	0.183	1.23	21.2	139	0.069	0.372	0.125	0.267	0.161	0.235	1.11
Reference A_2	0.398	0.022	1.18	249	11.8	0.045	0.294	0.035	0.206	0.116	0.247	1.45
Prob > F	<0.0001	NS	NS	0.034	--	0.0001	0.001	0.011	NS	NS	NS	<0.0001

Table 2. Tillage effects on model parameters, derived quantities, and soil properties in a tilled Wedowee soil. Mean comparison by Tukey's HSD test; means with the same letter are not different (α=0.05).

Treatment	Parameter			SWRC-Derived Quantity		Soil Property					
	Θ_{sat}[1]	α	n	I(h)	EPD[2]	|S|	Θ_I[3]	Θ_{MACRO}[4]	PAW_T[5]	PAW_S[6]	Θ_{MATRIX}[7]	ρ_b[8]
	m³ m⁻³	hPa⁻¹	---	hPa	µm	---	----------	----------	m³ m⁻³	----------	----------	g cm⁻³
No-tillage	0.342ᵇᶜ	0.059	1.197ᵃᵇ	72.3ᵃ	40.7	0.042	0.248ᶜ	0.072ᵈ	0.174ᵃᵇ	0.110ᵃᵇᶜ	0.161	1.49ᵃ
UR subsoiling	0.346ᵇᶜ	0.103	1.160ᵇ	56.7ᵃᵇ	51.9	0.036	0.259ᵃᵇᶜ	0.073ᶜᵈ	0.158ᵃᵇ	0.098ᵇᶜ	0.175	1.37ᵃᵇᶜ
Spr. chisel	0.399ᵃ	0.160	1.194ᵃᵇ	28.3ᵇ	104	0.048	0.291ᵃᵇ	0.124ᵃ	0.179ᵃᵇ	0.116ᵃᵇᶜ	0.158	1.25ᶜ
Disk	0.396ᵃ	0.077	1.230ᵃ	50.6ᵃᵇ	58.1	0.054	0.281ᵃ	0.109ᵃᵇ	0.201ᵃ	0.134ᵃ	0.152	1.30ᵇᶜ
Spr. chisel+disk	0.379ᵃᵇ	0.170	1.206ᵃᵇ	50.3ᵃᵇ	58.5	0.048	0.273ᵃᵇᶜ	0.106ᵃᵇᶜ	0.187ᵃ	0.122ᵃᵇ	0.152	1.32ᵇᶜ
Spr. moldboard	0.334ᶜ	0.154	1.151ᵇ	40.2ᵃᵇ	73.2	0.033	0.253ᵇᶜ	0.086ᵇᶜᵈ	0.139ᵇ	0.087ᶜ	0.161	1.42ᵃᵇ
Prob > F	0.001	NS	0.037	0.028	----	NS	0.010	0.002	0.015	0.014	NS	0.001

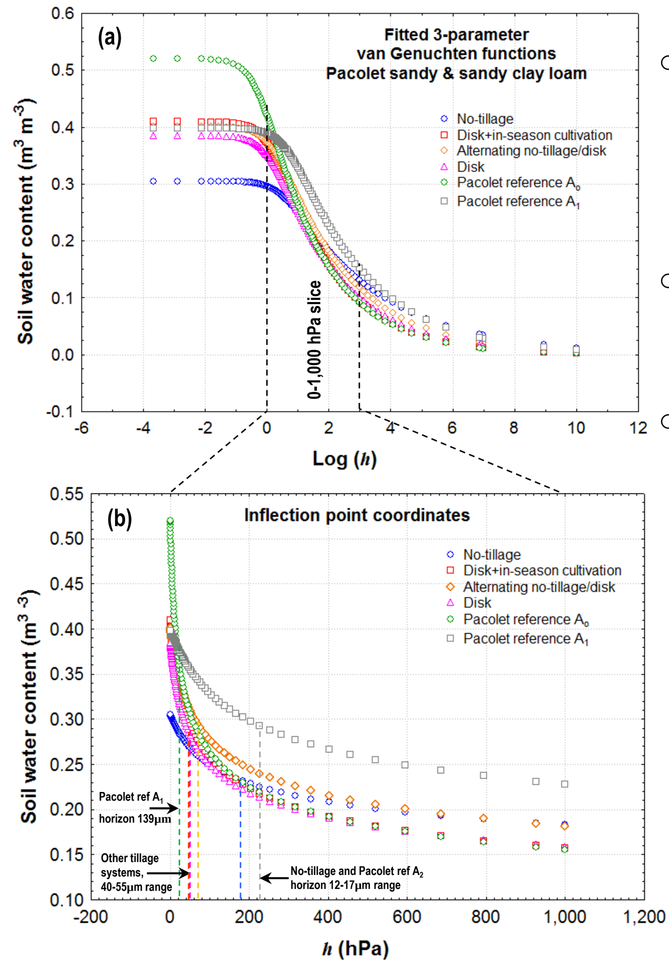
[1] θ_{sat}, model estimate of total porosity
[2] Equivalent pore diameter
[3] Soil water content @ the inflection point
[4] Macropores, > 58 µm e.p.d. aka "drainage pores"
[5] Plant available water, -50 to -15,000 hPa
[6] Available water between -50 and -1,000 hPa (=structural pore water)
[7] Matrix porosity, <3 µm (> -1,000 hPa tension)
[6] Bulk density

Results, con't.

Soil properties (see Tables 1,2)

- In a Pacolet soil, tillage affected Θ_{MACRO}, Θ_I, PAW_T, PAW_S, and ρ_b; no-tillage had *less* total, macro-, and structural porosity, *lower* % saturation at the inflection point, *less* PAW and *higher* ρ_b compared to clean and alternating no-tillage.
- Pacolet ref A_1 horizon Θ_{MACRO} was greater than the A_2 horizon; for Θ_{MACRO} Pacolet ref A_1 = Pacolet no-tillage; Pacolet ref A_1 ρ_b was lower, and % saturation at the inflection point, and PAW_S were higher compared with Pacolet no-tillage.
- In a Wedowee soil, tillage affected Θ_{MACRO}, Θ_I, PAW_T, PAW_S, and ρ_b; moldboard plow tillage decreased PAW_T and PAW_S compared with other tillage systems; % saturation at the inflection point was higher under disk tillage compared with no-tillage and moldboard plow tillage.
- Tillage did not affect Θ_{MATRIX} in the tilled Pacolet or Wedowee soil, or in the Pacolet reference A_1 or A_2 horizons.
- Main effects for soil properties (tilled Pacolet vs Wedowee) were not detected (data not shown).

Figure 5. Fitted SWRCs (**a**) and 0-1,000 hPa slice (**b**).



Interpretive Summary

- Tillage affected total, macro- and structural porosity, % saturation at the inflection point, bulk density, and water retention in Pacolet and Wedowee sandy loam soils.
- SWRC inflection point and slope varied with tillage system, but not soil.
- ***In spite of altering some important physical properties under long-term no-tillage and non-inversion tillage, average corn and soybean grain yield has been <u>equal to or better</u> than clean tillage over a quarter-century. We infer that <u>residue cover</u> on southern Piedmont Ultisols is the prime factor influencing corn and soybean productivity, not tillage-induced changes in pore size distribution and attendant soil quality parameters.***

Further Reading

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