

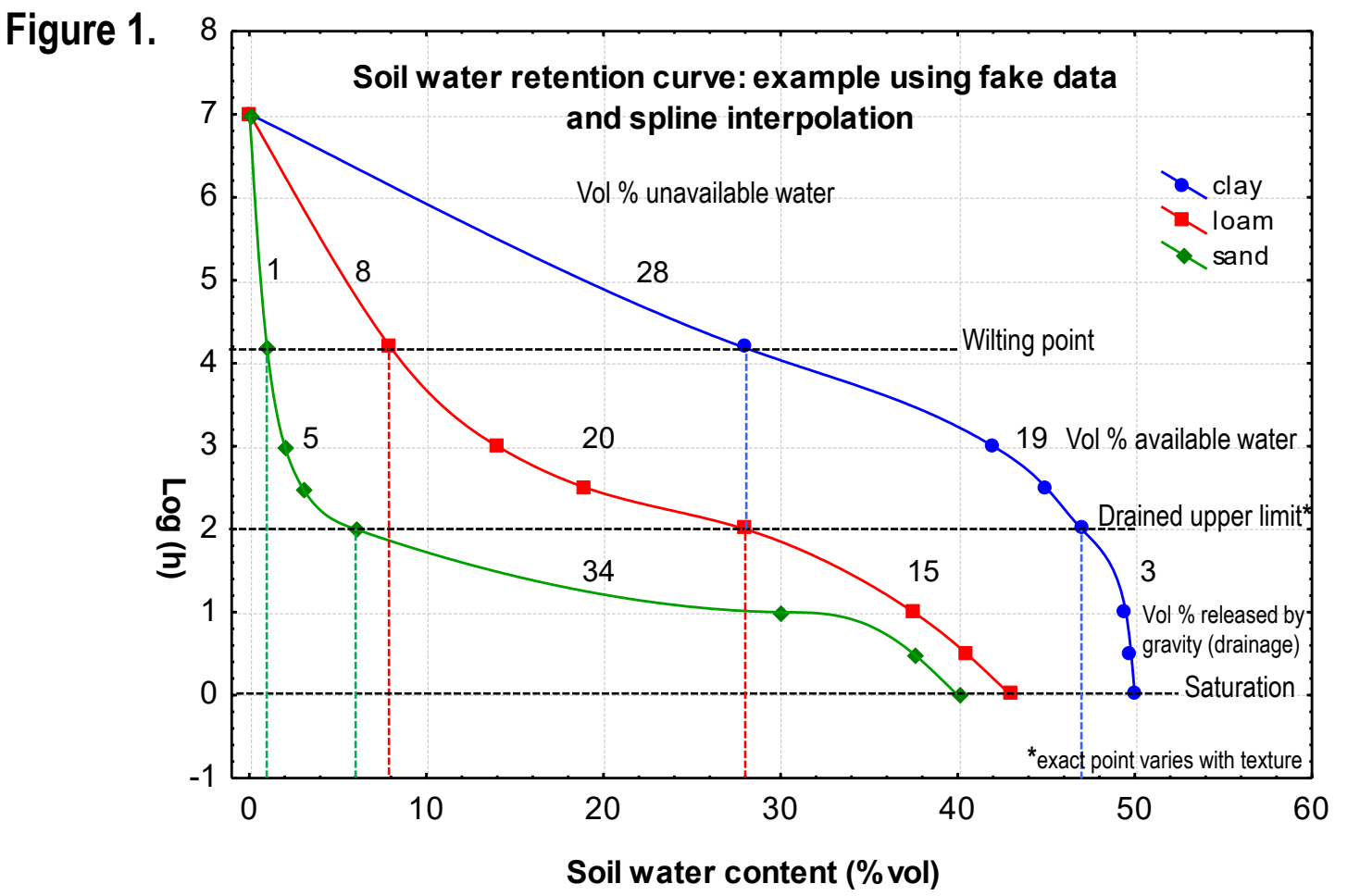
Rationale

The soil water retention curve (SWRC) reflects a soil's pore-size distribution, which governs infiltration, drainage, and profile water storage in cropping systems. Characterizing the SWRC is essential for irrigation scheduling, estimating crop evapotranspiration and yield potential, and constructing soil water balances. Particle-size distribution establishes the textural pore framework, but management-sensitive properties, including organic matter, bulk density, and aggregate stability, modulate pore-size distribution and may substantially alter hydraulic behavior without changing soil texture.

Southern Ultisols, characterized by kaolinitic clay mineralogy and susceptibility to surface sealing, present a challenging case in which hydrologic consequences of management are not well understood. Productivity gains for rainfed corn and soybeans in North Carolina under conservation tillage have been attributed to more efficient capture and profile storage of available moisture, yet the pore-scale mechanisms responsible have not been rigorously characterized. This study addresses that mechanistic gap.

Anatomy of a Soil Water Retention Curve

A soil water retention curve portrays 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 potential binding energy, they are also called the soil *matric potential*.



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 head *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 to drainage is less for sand 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 non-linear function for modeling the SWRC is given by van Genuchten (1980):

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

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):

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

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

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

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 $c_0 = -d\theta/dh$ 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) .

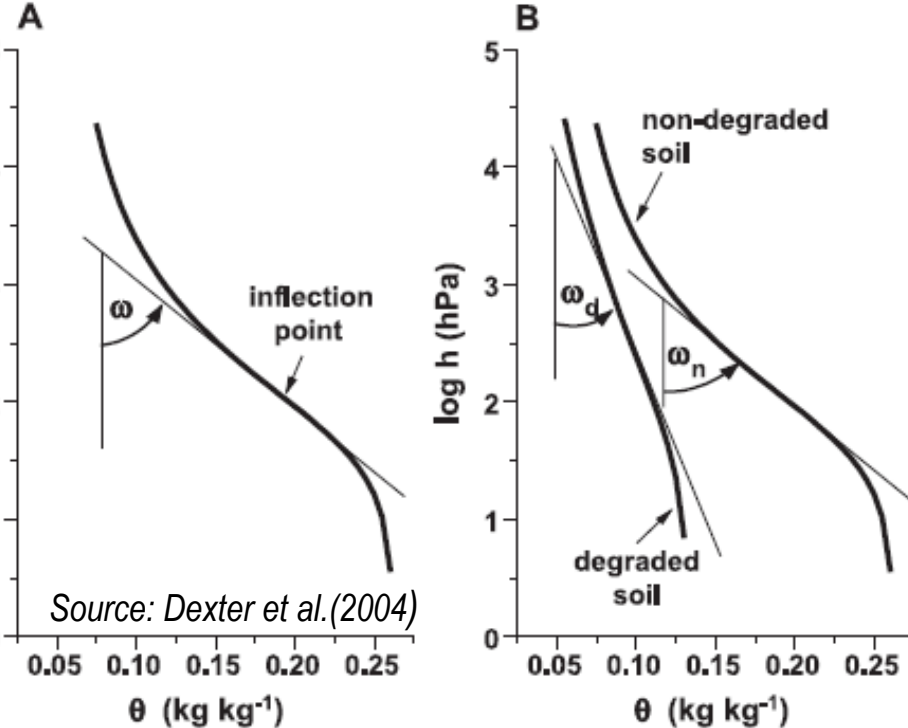


Figure 2A: An example of the inflection point and slope on the SWRC; the slope is given as tanw, the tangent to the curve at the inflection point. **2B:** SWRCs for the same sandy clay loam soil at two different bulk densities. Note that the slope *S decreases* when soil is compacted, indicating soil 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 (28 yr) 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 controlled traffic patterns.
- On a Wedowee sandy loam soil, 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 loam, treatments were no-tillage, spring disking, spring-disking with in-season cultivation and, alternating, on an annual basis, no-tillage and disking.
- We also sampled one local, old-growth (100+ yr) hardwood forest Pacolet sandy loam to represent a "virgin" never-tilled reference soil. Ten, independent 7.6 cm and 7.6-15.2 cm deep samples representing the A₀ mineral-organic and A₁ mineral horizons, respectively were collected.
- Soil samples were collected in the tillage plots by driving 7.6-cm dia. x 7.6-cm high steel cylinders with an Uhland drive head assembly in the fallow season 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, agronomically important inter-aggregate (structural) pore water content.



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**.

- For each sample, water retention data were fitted 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. 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 fit and was omitted from the final model.

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 A₀ horizon and about equal among clean and alternating no-tillage treatments and Pacolet reference A₁ horizon; in a Wedowee soil θ_{sat} was lower under moldboard plow but overall tillage affected θ_{sat} less relative to the Pacolet soil.
- Parameters α and n were not different for the tilled or reference Pacolet soils; in the Wedowee soil, shape parameter n varied with tillage but α was indifferent.
- Tillage influenced the SWRC slope (S) in the Pacolet soil; and inflection point $I(h)$ coordinates in the tilled Pacolet and Wedowee soils; apparent soil physical quality, inferred from slope S , scored "very good" in the reference A₀ horizon; about equally "good" among clean and alternating no-tillage treatments and reference A₁ 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 A₁ 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 A₀ 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).

Treatment	Parameter				SWRC-Derived Quantity				Soil Property						
	θ_{sat}^1 m ³ m ⁻³	α hPa ⁻¹	n	---	$I(h)$ hPa	EPD ² μm	S	---	Θ_3^3	Θ_{MACRO}^4	PAW _V ⁵ m ³ m ⁻³	PAW _S ⁶ m ³ m ⁻³	Θ_{MATRIX}^7	ρ_b^8 g cm ⁻³	---
No-tillage	0.305 ^a	0.032	1.15 ^a	174 ^a	16.9	0.030 ^a	0.231 ^a	0.035 ^a	0.138 ^a	0.078 ^a	0.193	1.55 ^a			
No-tillage/disk	0.401 ^{ab}	0.064	1.19 ^{ab}	72 ^{ab}	40.5	0.048 ^{ab}	0.292 ^{ab}	0.069 ^{ab}	0.202 ^{ab}	0.128 ^{ab}	0.184	1.35 ^{ab}			
Disk	0.384 ^{ab}	0.079	1.20 ^{ab}	55.4 ^{ab}	53.1	0.048 ^{ab}	0.277 ^{ab}	0.094 ^{ab}	0.193 ^{ab}	0.122 ^{ab}	0.168	1.40 ^{ab}			
Disk+cultivation	0.409 ^{ab}	0.074	1.22 ^{ab}	53.8 ^{ab}	54.7	0.055 ^{ab}	0.291 ^{ab}	0.114 ^{ab}	0.208 ^{ab}	0.138 ^{ab}	0.158	1.36 ^{ab}			
Prob > F	<0.0001	NS	0.018	0.002	—	<0.0001	<0.0001	0.0003	<0.0001	0.0003	NS	0.04			
Reference A ₀	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 ₁	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			

Treatment	Parameter				SWRC-Derived Quantity				Soil Property						
	θ_{sat}^1 m ³ m ⁻³	α hPa ⁻¹	n	---	$I(h)$ hPa	EPD ² μm	S	---	Θ_3^3	Θ_{MACRO}^4	PAW _V ⁵ m ³ m ⁻³	PAW _S ⁶ m ³ m ⁻³	Θ_{MATRIX}^7	ρ_b^8 g cm ⁻³	---
No-tillage	0.342 ^{ac}	0.059	1.197 ^{ab}	72.3 ^a	40.7	0.042	0.248 ^a	0.072 ^a	0.174 ^{ab}	0.110 ^{ac}	0.161	1.49 ^a			
UR subsoiling	0.346 ^{ac}	0.103	1.160 ^a	56.7 ^{ab}	51.9	0.036	0.250 ^{abc}	0.073 ^{ad}	0.158 ^{ab}	0.098 ^{bc}	0.175	1.37 ^{abc}			
Spr. chisel	0.399 ^a	0.160	1.194 ^{ab}	28.3 ^a	104	0.048	0.291 ^{ab}	0.124 ^a	0.179 ^{ab}	0.116 ^{ac}	0.158	1.25 ^c			
Disk	0.396 ^a	0.077	1.230 ^a	50.6 ^{ab}	58.1	0.054	0.281 ^a	0.109 ^{ab}	0.201 ^a	0.134 ^a	0.152	1.30 ^{bc}			
Spr. chisel+disk	0.379 ^{ab}	0.170	1.206 ^{ab}	50.3 ^{ab}	58.5	0.048	0.273 ^{abc}	0.106 ^{ab}	0.187 ^a	0.122 ^{ab}	0.152	1.32 ^{bc}			
Spr. moldboard	0.334 ^c	0.154	1.151 ^a	40.2 ^{ab}	73.2	0.033	0.253 ^{bc}	0.086 ^{cd}	0.139 ^a	0.087 ^c	0.161	1.42 ^{ab}			
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)
⁸ 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 reference A₀ Θ_{MACRO} fraction was greater than in the A₁ horizon; Pacolet reference A₁ = Pacolet no-tillage; Pacolet reference A₁ 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 A₀ or A₁ horizons.
- Soil differences (tilled Pacolet vs Wedowee) were not detected (data not shown).

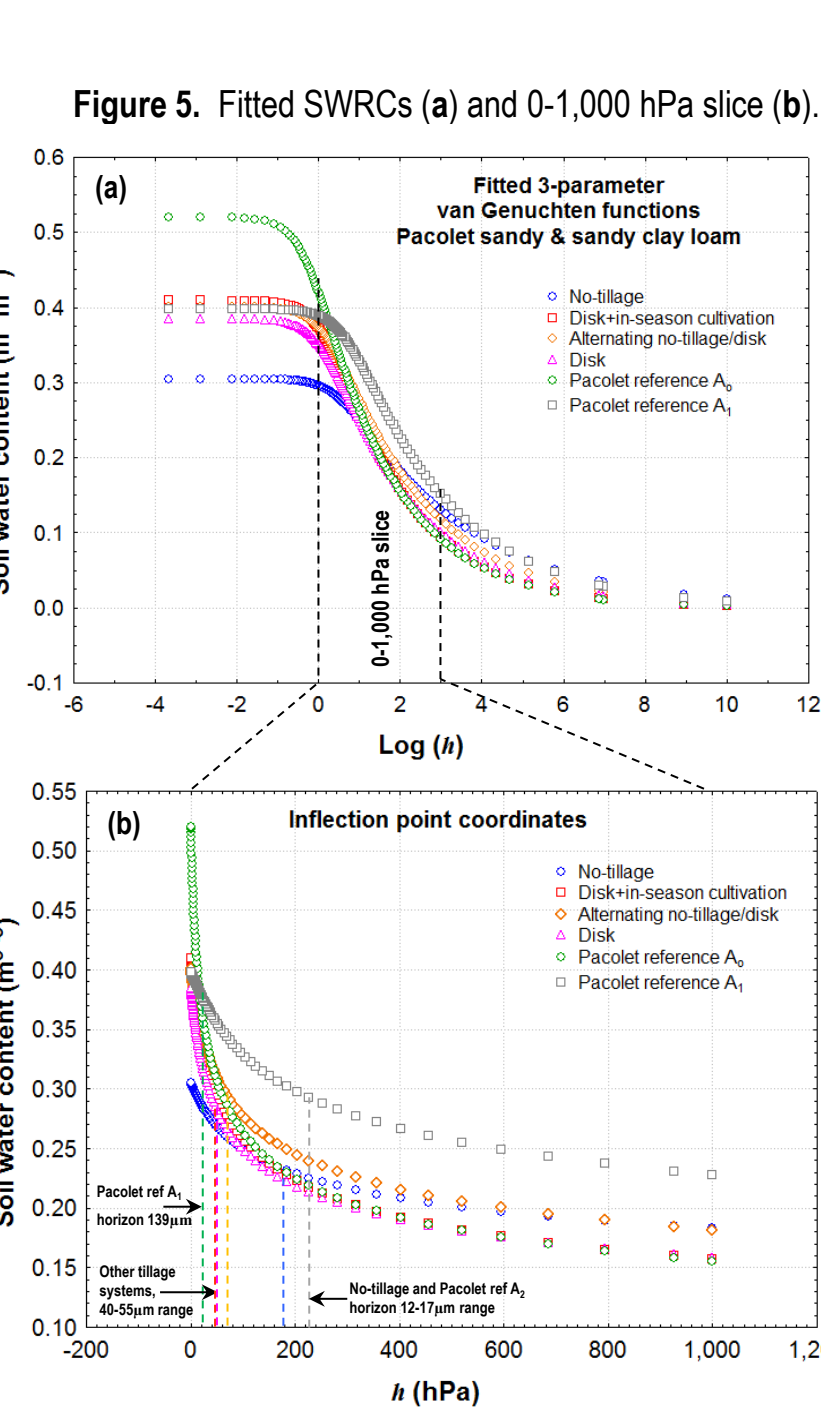


Figure 5. Fitted SWRCs (a) and 0-1,000 hPa slice (b).

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, not soil type.
- Despite altering some important physical properties under long-term no-tillage and non-inversion tillage, average corn and soybean grain yield has been equal to or better than clean tillage over a quarter-century. We infer that residue cover is the prime factor driving corn and soybean productivity in upland NC Piedmont Ultisols, not tillage-induced changes in pore size distribution and attendant soil quality indicators.

Further Reading

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