NC STATE UNIVERSITY
DEPARTMENT of SOIL SCIENCE

Tillage Effects on Soil Physical Quality Inferred from Indicators and Pore Volume Density Critical Limits

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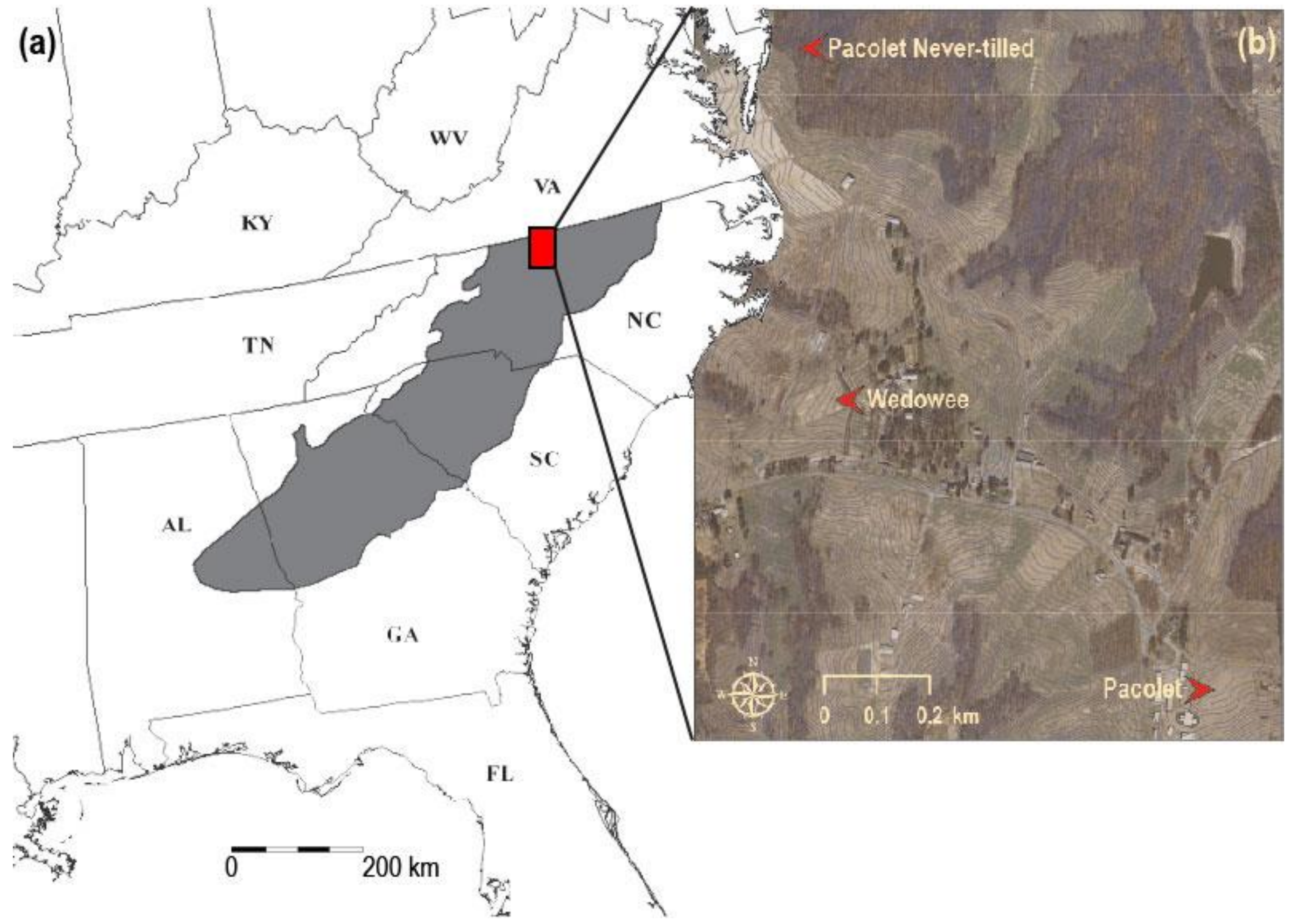
ACADEMICS ▲ RESEARCH ▲ EXTENSION

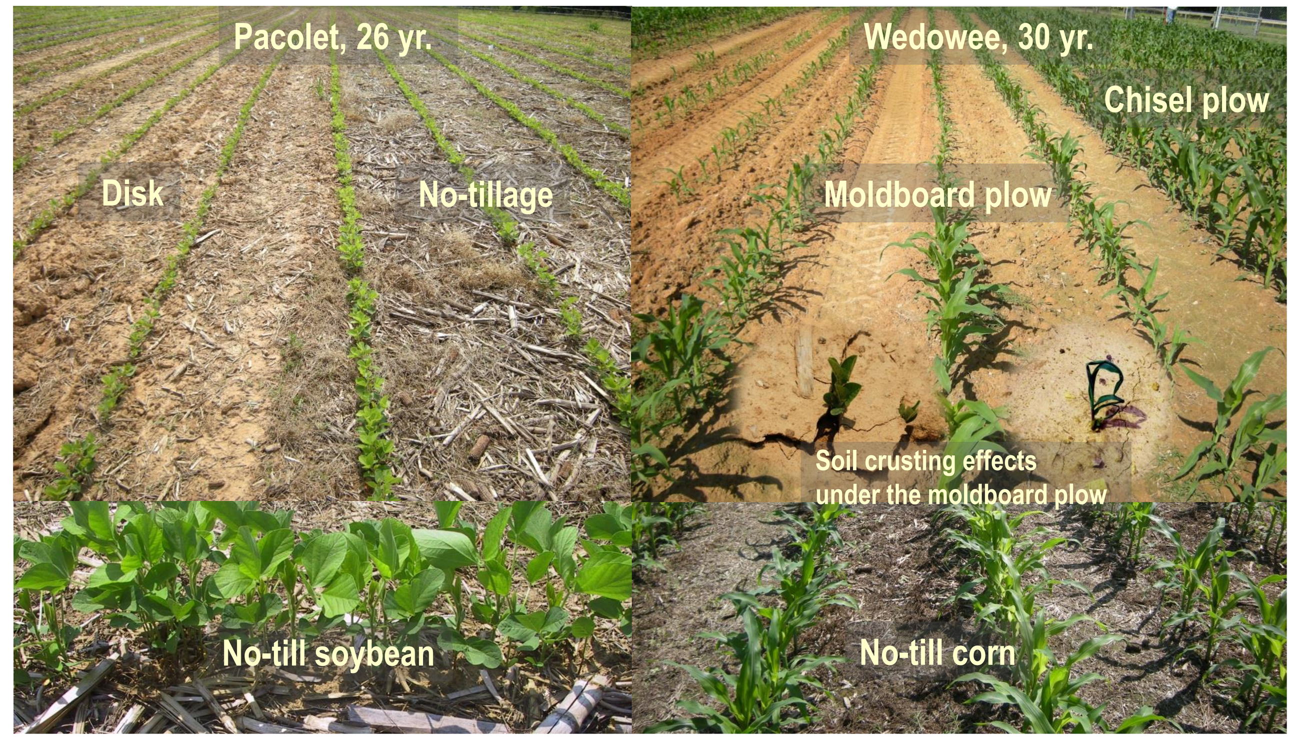
Rationale

The concept of soil quality attempts to quantify soil properties relative to some "ideal" or "critical" range for that soil as a way of encouraging good land husbandry, better productivity and environmental stewardship. Important indicators of soil physical quality include macroporosity, plant-available water, air capacity, relative field capacity, bulk density, organic C and soil structure. These indicators quantify, directly or indirectly, the soil's ability to store and transmit plant-essential water, air, and nutrients. Novel approaches to quantify soil physical quality include Dexter's "S-index" (Dexter and Czyż, 2009), and pore volume density critical limits (Reynolds et al., 2009) which depend on information from the soil water retention curve (SWRC). However, few studies have tested the validity of SWRC-inferred indicators in southern Ultisols where non-inversion and no-tillage planting systems have been successfully deployed in corn and soybean cropping systems for well over three decades.

Here, we examine the relationship between Dexter's "S-index" and plant-available water capacity, and the critical limits of pore volume density function indicators after Reynolds et al. (2009) in two, tilled and never-tilled, Typic Kanhapludult soils in the North Carolina Piedmont.

Figure 1.





Research Methods

○ Design and Treatments: Two, long-term tillage experiments, both on fine, kaolinitic, thermic Typic Kanhapludults at the Upper Piedmont Research Station, Reidsville, Rockingham County, NC (**Figure 1a,b**).

- Experiment 1: "Wedowee Tillage Plots" established in 1984 on a Wedowee sandy loam with nine tillage treatments replicated four times: fall or spring moldboard plowing, fall or spring chisel plowing with or without disking, spring disking only, no-tillage, and no-tillage with shallow under-row (UR) subsoiling.
- Experiment 2: "Pacolet Tillage Plots" established in 1988 on a Pacolet sandy loam soil involves alternating, on an annual basis, conventional and no-tillage, and no-tillage with shallow cultivation compared to continuous conventional and no-tillage systems.
- Reference Site: "Pacolet Never-tilled (NT)", an old-growth (100+ yr) hardwood forest Pacolet sandy loam. Soil at this site was assumed to represent a 'virgin' untilled or reference Ultisol with respect to physical quality.

○ Cropping System: Continuous corn (*Zea mays* L.) or a corn-soybean (*Glycine max* L. Merr.) rotation. In all plots, traffic (foot and machinery) has been confined in the same interrows year after year.

○ Soil Sampling and Analysis: Surficial (0-76 mm) soil samples were collected from the untrafficked crop interrow in stainless steel cylinders 76 mm diameter by 76 mm high with an Uhland drive head and hammer assembly. For the reference site: ten, independent 0-76 mm and 76-152 mm deep samples were taken representing surficial A_O (mineral-organic, "Pacolet NT A_o") and underlying mineral A ("Pacolet NT A_1") horizons, respectively.

Water release was measured by saturating and desorbing soil in a pressure outflow system at -10, -50, -100, -330, -400, -500 hPa. After oven-drying, bulk soil mass was measured. Oven-dry soil was ground to pass a 2-mm sieve, re-saturated and desorbed at -1,000, -5,000, and -15,000 hPa for ≥120 hr in a pressure plate apparatus. After correcting for course fragments, bulk density was calculated as the ratio of oven-dry soil mass to cylinder volume.

○ Data and Evaluation: Water release data was fit to the van Genuchten function:

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

Where: θ_{sat} = soil volumetric water content (%) at saturation.
θ_{res} = residual water content (%) as ψ approaches infinity.
α = proportional to the inverse of the air-entry suction (hPa^{-1}).
n = shape parameter (dimensionless) related to the slope of the water release curve subject to the Mualem constraint $m = (1 - 1/n)$
θ_ψ = volumetric water content (%) at ψ matric potential (hPa)

The adjustable parameters θ_{sat}, θ_{res}, α, and n were estimated by Levenberg-Marquardt non-linear optimization with the NLIN procedure in SAS 9.2. Slope of the soil water release curve (SWRC, Dexter's "S-index") was computed by Eq.[1]; normalized pore volume density by Eq.[2]; pore volume density location parameters d_{mean}, d_{median}, d_{mode} by Eqs.[3], [4], [5]; and shape parameters d_{SD}, $d_{kurtosis}$, $d_{skewness}$ by Eqs.[6], [7], [8] given in Table 1.

Total plant-available water (PAW_T) was calculated between -50, -100, -330 and -15,000 hPa (58, 30, 9μm – 0.2μm equivalent pore diameters) and structural plant-available water (PAW_S) between -50, -100, -330 and 1,000 hPa (58, 30, 9μm – 3μm equivalent pore diameters) from water release data.

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Interpretive Summary

For |S| x PAW panels in Figure 2:

○ Dexter's "S-index" was positively (P_{all}≤0.0001) related to PAW_T and PAW_S at h = -50, -100, and -330 hPa in the Wedowee and Pacolet Plots (n=52) and in the Pacolet NT reference soil (n=20). See panels in **Figure 2**.

○ Regression slopes in **Figure 2** decreased invariantly with rising soil water tension, as generally did intercepts and adjusted coefficients of determination (R^2); the Δ_{slope} was greater between -50 and -100 hPa compared to -100 and -330 hPa. Our interpretation is that Dexter's "S-index" is more sensitive to pore water associated with course soil structure than fine structure.

○ Regression slopes and intercepts were greater, and Δ_{slope} between -50 and -100 hPa and -100 and -330 hPa was less in the Pacolet NT reference soil compared to the tilled Wedowee and Pacolet soils, probably due to higher C levels and structural porosity in the Pacolet NT reference A_o horizon. See **Figure 2** panels, annotations.

○ Dexter's "S-index" was generally a better predictor of PAW_S compared to PAW_T. This is significant because we hypothesize that low-tension (≤ -1,000 hPa) structural PAW is a reliable indicator of soil physical quality compared to PAW at higher (e.g., > -1,000 hPa) tension head.

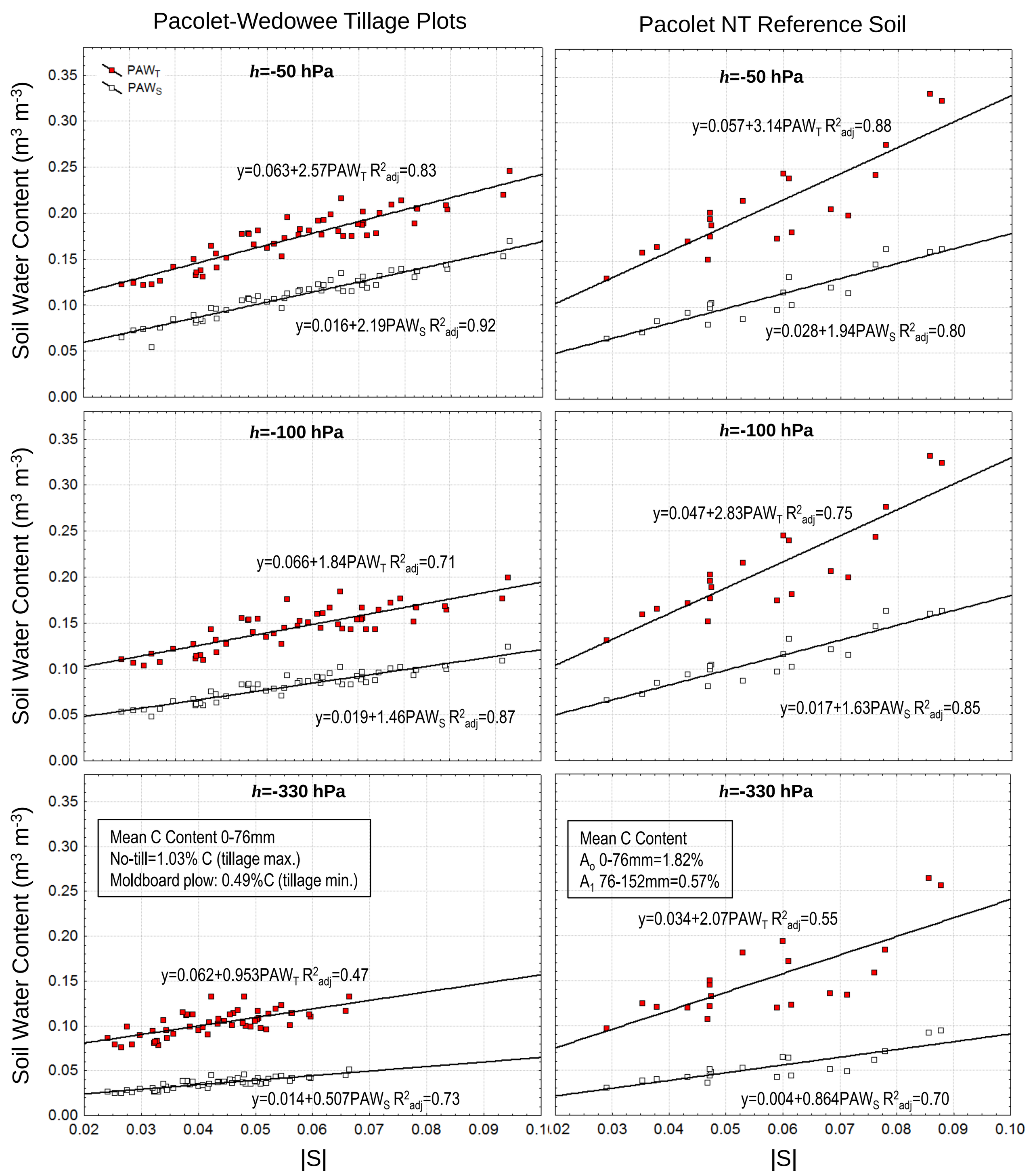

Figure 2. Relationship between the slope of the soil water release curve (Dexter's "S-index") and total and structural PAW in tilled Pacolet and Wedowee and never-tilled Pacolet sandy loam soils under rising soil water tension.

Interpretive Summary con't.

For $I^*(h)$ panels in Figure 3a,b and Table 1 and 2 information:

○ Location and shape parameters in the tilled and no-tilled Wedowee and Pacolet soils, and in the Pacolet NT reference soil, fell mainly outside the optimal range; optimal values for all tillage-soil combinations are highlighted in red in **Table 2**. See **Table 1** for definitions.

○ The highest "S-index" value (=better relative physical quality) occurred in the Pacolet NT A_o horizon; Pacolet no-tillage, and Wedowee fall and spring moldboard plow produced the lowest "S-index" value (=poor relative physical quality). See **Table 2**.

○ The largest d_{mode} occurred in the Pacolet NT A_o horizon (139μm); the smallest d_{mode} occurred under Pacolet no-tillage (16.9μm) and in the Pacolet NT A_1 horizon (11.8μm). Our interpretation is that large d_{mode} values indicate greater density of macropores and small d_{mode} values indicate a preponderance of fine structural pores, both related to bulk density (See **Figure 3a**).

○ In a Wedowee soil the maximum d_{mode} occurred under fall chisel plow tillage (116μm) and the minimum d_{mode} under no-tillage (40.7μm). See **Figure 3b**.

○ **Figure 3a** shows a close correspondence of normalized pore volume density functions $I^*(h)$ in the Pacolet NT A_1 horizon and under Pacolet no-tillage, despite relatively large differences in measured bulk density. We hypothesize that development of pore size distribution in some upland NC Ultisols depends on soil factors other than bulk density.

○ For all tillage and soil combinations $d_{mean} < d_{mode}$, indicating a greater excess of small pores relative to a lognormal distribution. **See Figures 3a** and **3b**, and **Table 2**.

Table 1. Equations for Dexter's "S index" and related pore volume density location and shape parameters.

Eq. #	Expression	Indicator Parameter	Definition
[1]	$S = -n(\theta_{sat} - \theta_{res})\left[\frac{2n-1}{n-1}\right]^{[(1/n)-2]}$	Dexter's "S-index"	Slope of the SWRC curve at the inflection point
[2]	$I^*(h) = \frac{m(\alpha h)^n\left[1+m^{-1}\right]^{(m+1)}}{\left[1+(\alpha h)^n\right]^{(m+1)}}; 0 \le I^*(h) \le 1$ h = tension head at the inflection point on the SWRC.	Pore volume density function	Relative lognormal frequency of pore volume density (distribution).
[3]	$d_{mean} = \exp\left(\frac{\ln d_{0.16} + \ln d_{0.50} + \ln d_{0.84}}{3}\right)^{\dagger}$	Mean	Statistical measure of central tendency (geometric)
[4]	$d_{median} = \frac{2980\alpha}{(0.5^{-1/m}-1)^{1/n}}; \theta = 0.50(50\% \text{ saturation})$	Median	50% quartile
[5]	$d_{mode} = \frac{2980\alpha}{\left(\theta_i^{-1/m}-1\right)^{1/n}}$ where $\theta_i = \left[1+(\alpha h_i)^n\right]^{-m}$	Mode	Most frequently occurring pore diameter
[6]	$d_{SD} = \exp\left(\frac{\ln d_{0.84} - \ln d_{0.16}}{4} + \frac{\ln d_{0.95} - \ln d_{0.05}}{6.6}\right); 1 \le d_{SD} < \infty$	Standard deviation	Indicates relative variation in pore diameter
[7]	$d_{kurtosis} = \frac{\ln d_{0.05} - \ln d_{0.95}}{2.44(\ln d_{0.25} - \ln d_{0.75})}; 0.41 \le d_{kurtosis} < \infty$	Kurtosis	Indicates more (>1) or less (<1) central peakness relative to lognormal curve
[8]	$d_{skewness} = \frac{1}{2}\left[\frac{\ln d_{0.16} + \ln d_{0.84} - 2(\ln d_{0.50})}{(\ln d_{0.84} - \ln d_{0.16})} + \frac{\ln d_{0.05} + \ln d_{0.95} - 2(\ln d_{0.50})}{(\ln d_{0.95} - \ln d_{0.05})}\right]; -1 \le d_{skewness} \le +1$	Skewness	Indicates symmetry; positive→negative values = pore density curve skewed right→left respectively.

† where $d_{0.16}, d_{0.84}$ etc. are given by: $d_\theta = \frac{2980\alpha}{\left(\theta^{-1/m}-1\right)^{1/n}}; 0 \le \theta \le 1$

Further Reading

Dexter, A.R. and E.A. Czyż. 2007. Applications of S-theory in the study of soil physical degradation and its consequences . Land Degrad. Develop. 18:369-381.

Reynolds, W.D., Drury, C.F., Tan, C.S., Fox, C.A., and X.M. Yang. 2009. Use of indicators and pore volume-function characteristics to quantify soil physical quality. Geoderma 152:252-263.

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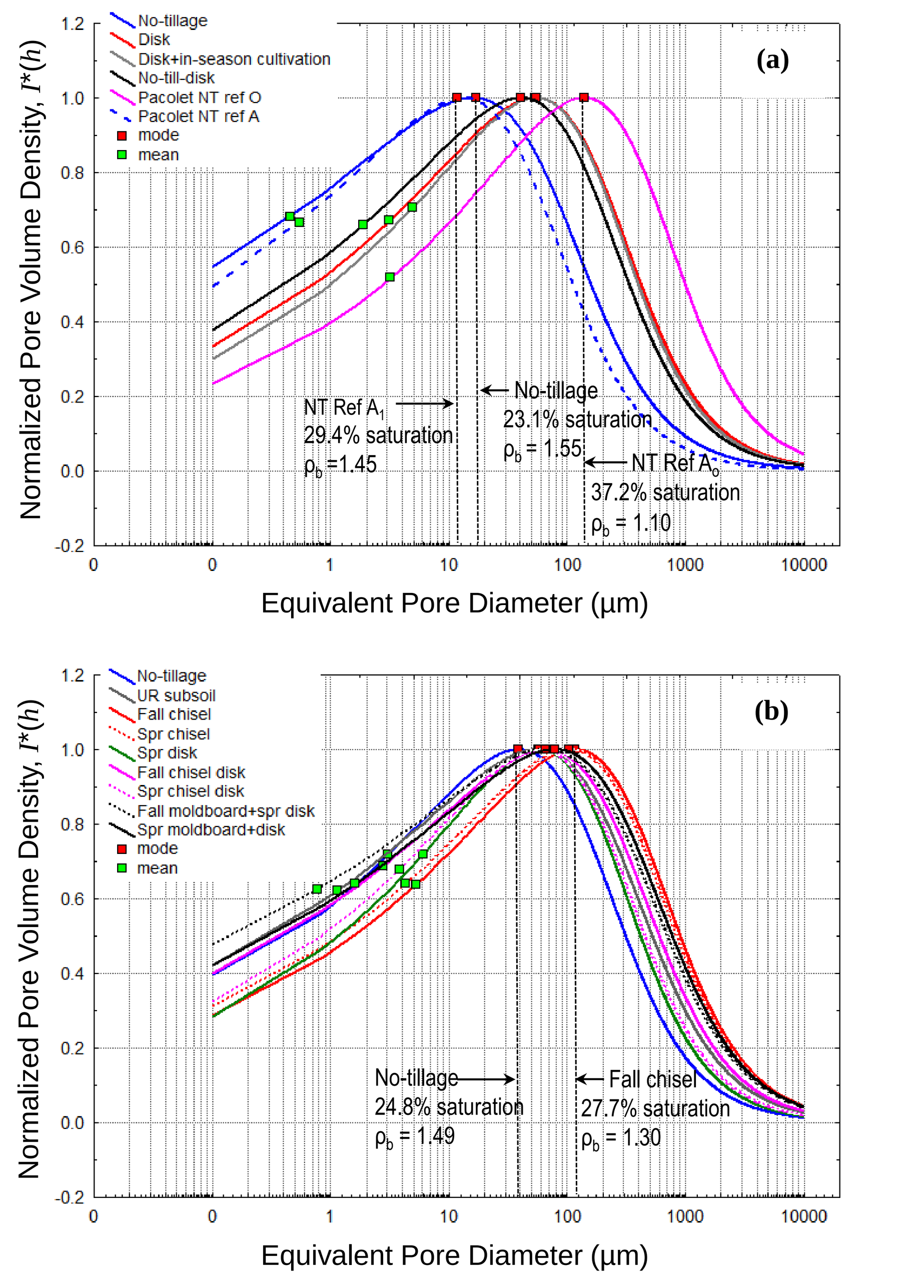

Figure 3. Mean normalized pore volume density function $I^*(h)$ for (**a**) Pacolet tillage plots (n=4), Pacolet NT reference A_o (n=10) and A_1 (n=10) horizons; and (**b**) Wedowee tillage plots (n=4). Vertical dashed lines indicate the d_{mode} location and % saturation coinciding with the peak of $I^*(h)$ representing the most frequently occurring pore diameter on the x axis.

Table 2. Dexter's "S index", and pore volume shape and location parameters for Pacolet tillage plots and Pacolet reference soil, and Wedowee tillage plots, compared to the "optimal range".

Treatment	|S|	Location Parameters				Shape Parameters	
		d_{mode}	d_{mean}	d_{median}	d_{SD}	Skewness	Kurtosis
Pacolet tillage	---	--------	μm e.p.d.	--------	---	---	---
No-tillage	0.030	16.9	1.37	0.46	1167	-0.42	1.14
No-tillage/disk	0.048	40.5	5.06	1.93	125	-0.39	1.15
Disk	0.048	53.1	7.72	3.15	95	-0.39	1.15
Disk+cultivation	0.055	54.7	10.5	4.93	72	-0.38	1.15
Pacolet reference							
NT A_O horizon	0.069	139	8.42	3.23	266	-0.37	1.15
NT A_1 horizon	0.045	11.8	1.32	0.54	2139	-0.40	1.14
Wedowee tillage							
No-tillage	0.041	40.7	6.75	3.05	136	-0.39	1.15
UR subsoil	0.036	51.9	3.48	1.14	409	-0.41	1.14
F. chisel	0.047	116	11.9	5.32	393	-0.39	1.14
Spr. chisel	0.048	104	10.6	4.27	206	-0.39	1.14
Spr.disk	0.054	58.1	12.2	6.02	135	-0.37	1.15
F. chisel+spr. disk	0.042	67.0	7.28	2.78	827	-0.41	1.14
Sp. Chisel+disk	0.048	58.5	9.08	3.82	93	-0.38	1.15
F. moldboard+spr. disk	0.032	65.5	2.95	0.77	2468	-0.42	1.13
Spr. Moldboard+disk	0.033	73.2	4.72	1.62	1128	-0.42	1.14
Optimal range	>0.035	60-140	3-7	0.7-2	400-1000	-0.43 -0.41	1.13-1.14