Comparison of Tension Infiltrometer, Pressure Infiltrometer, and Soil Core Estimates of Saturated Hydraulic Conductivity

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ABSTRACT

Saturated hydraulic conductivity (K_{SAT}) is an important soil property that is difficult to measure. Positive-head tension infiltrometer (TI) and single-ring pressure infiltrometer (PI) techniques show promise for measuring K_{SAT}, but there have been few field tests or comparisons with other methods. The TI, PI, and classical undisturbed soil core (SC) methods for measuring K_{SAT} were compared on single-grain sand, structured loam, and cracking-clay loam soils under conventional tillage (CT), no-tillage (NT), and native woodlot (WL) managements. Of the 27 between-method correlations (3 methods $\times$ 3 soils $\times$ 3 managements), only four were significant ($P < 0.05$). The TI method yielded lower K_{SAT} values under high-permeability conditions ($K_{SAT} \geq 10^{-4}$ ms^{-1}) relative to the other methods, as evidenced by lower geometric mean K_{SAT} (K_{GM}), lower maximum K_{SAT} (K_{MAX}), and lower minimum K_{SAT} (K_{MIN}) values. The 0.10-m diam. by 0.10-m-long SC method cores may have been too small to yield representative estimates of K_{SAT} in the cracking-clay loam and in the NT and WL managements of the sand and loam, as indicated by high coefficients of variation (CVs), inconsistent K_{GM} values, or high K_{MAX} values relative to the other methods. Erratic K_{MAX} and K_{MIN} values, along with high CVs, suggest that the 0.10-m-diam. PI ring may have been too small to adequately sample the cracking clay loam soil under CT and NT management. Further work appears warranted for developing K_{SAT} measurement methods, interpreting K_{SAT} results, and determining appropriate K_{SAT} methods for various soil types and conditions.

Saturated hydraulic conductivity (K_{SAT}) is a critically important soil property for many agronomic, engineering, and environmental activities. For example, it is essential in many water-solute transport and crop-growth models (e.g., Clemente et al., 1994; Smith et al., 1995; Van Dam et al., 1997), and it is used extensively in the measurement and evaluation of soil physical quality (e.g., Gregorich et al., 1993). It is also a key parameter in the design and performance assessment of irrigation and drainage systems (e.g., Luthin, 1978), earthen waste impoundments (e.g., Youngs et al., 1995), waste water leach fields (e.g., Ward and Morrison, 1984), and many other agricultural, geotechnical, and environmental structures.

Because of the importance of K_{SAT}, many methods have been developed over time for its measurement in the field and laboratory (e.g., Klute and Dirksen, 1986; Reynolds, 1993a, 1993b, 1993c). Unfortunately, these methods often yield substantially dissimilar K_{SAT} values, since this parameter is extremely sensitive to sample size, flow geometry, sample collection procedures, and various soil physical–hydrological characteristics (e.g., Bouma, 1983). In addition, most (perhaps all) K_{SAT} methods are neither appropriate nor accurate for all applications, soil types, or soil conditions (e.g., Bouma, 1983). Methods for measuring K_{SAT} should therefore be evaluated carefully before use to ensure that they provide practicable results.

For the last decade, the tension infiltrometer (TI) method (Perroux and White, 1988; Ankeny et al., 1991; Reynolds and Elrick, 1991) has gained popularity for in situ measurement of near-saturated and saturated soil hydraulic properties (e.g., Everts and Kanwar, 1992; Mohanty et al., 1998). This is primarily because it is simple and fast; and it causes little disturbance of the soil macrostructure, which controls near-saturated and saturated flow (e.g., Elrick and Reynolds, 1992; White et al., 1992).

Using the TI to measure K_{SAT} presents two difficulties, however. First, the classical TI theory, which is based on the Wooding (1968) and/or the Philip (1969) infiltration analyses, does not apply to the ponded infiltration conditions necessary for measuring K_{SAT} (Reynolds and Elrick, 1991; Reynolds and Zebchuk, 1996). Second, the contact sand needed to ensure good hydraulic connection between the infiltrometer and the soil (Perroux and White, 1988) can introduce flow impedance effects at the high infiltration rates associated with zero-ponded and ponded conditions (Reynolds and Zebchuk, 1996).

One approach to circumventing the TI analysis problem is to extrapolate from negative pressure head (h) measurements to zero pressure head using an assumed hydraulic conductivity–pressure-head relationship, $K(h)$, such as the empirical Gardner (1958) and van Genuchten (1980) functions (Messing and Jarvis, 1993; Jarvis and Messing, 1995). The accuracy of such a procedure, of course, depends on the accuracy of the assumed $K(h)$ relationship, which will vary with both the soil type and the soil macrostructure at each measurement site (Messing and Jarvis, 1993). The contact sand impedance problem might be dealt with by simply not using contact sand for positive h. This presents procedural difficulties, however, if an ascending series of negative h values are being applied (for measuring near-saturated hydraulic parameters) before positive h, since this would require interrupting the infiltration process to remove the contact sand. Reynolds and Zebchuk (1996) developed an

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Abbreviations: CT, annual conventional tillage cropping; CV, coefficient of variation; K_{GM}, geometric mean K_{SAT}; K_{MAX}, maximum K_{SAT}; K_{MIN}, minimum K_{SAT}; K_{SAT}, saturated hydraulic conductivity; NT, annual no-tillage cropping; PI, single-ring pressure infiltrometer; S_{SAT}, sorptivity for ponded infiltration; SC, undisturbed soil core; TI, positive-head tension infiltrometer; WL, never cropped or cultivated native woodlot.

approximate steady-flow–shallow ponded head analysis for the TI, as well as procedures for accounting for flow impedance by the contact sand. Laboratory and numerical simulation tests (Reynolds and Zebchuk, 1996) indicated that these innovations are accurate, but field tests and comparisons with other methods have not been conducted.

The pressure infiltrometer (PI) method (Reynolds, 1993a; Reynolds and Elrick, 1990) is a single-ring, steady-flow technique for measuring K_{SAT} in situ. Advantages of the method include relatively rapid and simple measurements, no requirement for contact sand, and analysis procedures that account for flow divergence effects caused by flow geometry and soil capillarity (Reynolds and Elrick, 1990). Potential limitations, however, include relatively small sample (ring) size, soil disturbance during ring insertion, and possible *short circuit* or edge flow along the ring wall (Reynolds, 1993a). Although the PI method is potentially well suited for measuring the K_{SAT} of agricultural soils, it has so far received little field testing or comparison with other methods.

The intact or undisturbed soil core (SC) method (e.g., Klute and Dirksen, 1986) is one of the classical techniques for measuring K_{SAT}. Like the PI method, the SC method has potential limitations related to small or inadequate sample size, soil disturbance during core collection, and possible short circuit flow through macropores or along the core wall (e.g., McIntyre, 1974; Bouma, 1980). On the other hand, the SC method is simple, inexpensive, convenient, and based on a direct application of Darcy's Law, which defines K_{SAT}. Despite potential limitations, the SC method remains one of the most popular means for measuring K_{SAT}, and it is often used as a benchmark for evaluating other methods.

The objectives of this study were to (i) compare the little-tested TI and PI techniques described earlier to the classical SC method for measuring K_{SAT}, and (ii) obtain information suggesting soil textural and structural conditions for which each method may not yield representative estimates of K_{SAT}. To cover many of the common soil textures and structures in agricultural environments, the three methods were compared in single-grain sand, structured loam, and cracking clay loam soils under annual conventional till cropping, annual no-till cropping, and never cropped or cultivated native vegetation.

MATERIALS AND METHODS

Field Sites

Three field sites were selected to cover the range of near-surface textures and structures found in many humid-region agricultural soils, including a structureless single-grain sand, a structured loam, and a cracking clay loam (Table 1). At each field site, adjacent plots under annual conventional tillage cropping, annual no-tillage cropping, and native woodlot vegetation were selected for K_{SAT} measurement. Conventional tillage (CT) consisted of moldboard plowing in the spring (Delhi and Rockwood sites) or fall (Woodslee site), followed by secondary discing and harrowing immediately before planting. No-tillage (NT) used standard no-till equipment and procedures, with the only soil disturbance being that caused by the no-till planter. The woodlot (WL) plots were vegetated with native deciduous trees and grasses. The CT and NT plots were well established at each field site and the WL plots had not been cropped or cultivated in living memory (Table 1). The cropped plots (CT, NT) had either a corn–soybean–winter wheat [*Zea mays* (L.)–*Glycine max* (L.) Merr.–*Triticum aestivum* (L.)] rotation (Delhi and Rockwood sites) or a corn–soybean rotation (Woodslee site), with the K_{SAT} measurements being taken in non-trafficked crop interrows during the soybean phase of the rotations.

Measurement Methods

The TI estimates of K_{SAT} were obtained using the Mariotte-based apparatus and multiple head–single disc procedures described in Reynolds (1993a), Reynolds and Elrick (1991), and Reynolds and Zebchuk (1996). The TI membrane was 0.20 m in diam. and consisted of a 270-mesh (53-μm equivalent pore size) phosphor bronze sieve screen. Hydraulic contact between the TI membrane and soil was established and maintained using a 0.01-m thickness of glass bead contact material (Table 2) held in place by a 0.25-m-diam. retaining ring (Reynolds and Zebchuk, 1996). A nylon guard cloth (53-μm equivalent pore size) was placed between the soil and the contact material to prevent slumping of the air-dry contact material into soil cracks and macropores during its initial placement and when $h \geq 0$. Pressure heads of ≈ -0.15, -0.10, -0.05, -0.03, -0.01, 0, $+0.01$, and $+0.02$ m of water were established in ascending order on the soil surface, and the corresponding quasi-steady flow rates measured (see Reynolds and Zebchuk, 1996, for procedural details). Flow rates were deemed *quasi-steady* when the rate of fall of the water level in the TI reservoir was constant for at least 10 min (discussed further under Results and Discussion). The K_{SAT} values were determined using the two positive h values (0.01, 0.02 m) and the *positive-head* procedure described in Reynolds and Zebchuk (1996). Although the negative heads and corresponding flow rate measurements are not required for the K_{SAT} calculation, they were included here because the TI is normally used for simultaneous determination of both saturated and near-saturated hydraulic properties.

The PI estimates of K_{SAT} were determined using the apparatus and procedures described in Reynolds (1993b) and Reynolds and Elrick (1990). A stainless steel ring (0.10-m diam., 0.11-m length, 2.6-mm wall thickness) was inserted 0.10 m into the soil, and the PI base plate and Mariotte reservoir were attached. No contact material or guard cloth was placed on the soil surface. Two pressure heads were established on the soil in succession and in ascending order. The set pressure heads varied from 0.085 to 0.138 m for the first head, and from 0.210 to 0.418 m for the second head, depending on the flow rate encountered (i.e., lower heads were set for faster flow rates to reduce water consumption). As with the TI method, flow rates were considered quasi-steady when the rate of fall of water level in the reservoir was constant for at least 10 min. The K_{SAT} values were determined using the single-head or multiple-head procedures described in Reynolds (1993b).

Soil core estimates of K_{SAT} were obtained by using stainless steel rings (same rings as used for the PI method) to extract 0.10-m-diam. by 0.10-m-long intact (undisturbed) soil cores and applying the classical constant-head or falling-head methods (Klute and Dirksen, 1986; Reynolds, 1993c). Apparatus similar to that described in Reynolds (1993c) was used, except that the end caps were attached to the flanged stainless steel rings using an O-ring and four wing bolts. This ensured that

Table 1. Selected field site information.

Field site name and location	Soil name and type	U.S. soil classification	Soil texture in top 100 mm: Sand	Silt	Clay	Soil structure in top 100 mm	Duration of land management: CT†	NT‡	WL§
			— % by wt. —				— yr —		
Delhi 42°52′ N, 80°31′ W	Fox sand	Psammentic Hapludalf	90	5	5	*Structureless* (loose, single-grain). Few biopores and roots; occurrence increases from CT to NT to WL.	>15	6	>50
Rockwood 43°38′ N, 80°11′ W	Guelph loam	Mollic Hapludalf	36	48	16	*Structured* (friable, aggregates 1- to 5-mm width). Biopores, roots, and aggregates present; few in CT and NT, abundant in WL.	≈17	9	>50
Woodslee 42°13′ N, 82°44′ W	Brookston clay loam	Typic Argiaquoll	28	35	37	*Cracking* (massive matrix, shrinkage-crack polygons 10- to 100-mm diam., crack widths ≤10 mm when soil dry). Biopores and roots present; few in CT, more in NT, abundant in WL. Also granular peds in WL.	14	14	>50

† CT, annual conventional tillage cropping.
‡ NT, annual no-tillage cropping.
§ WL, never cropped or cultivated native woodlot.

the seal between the end cap and ring would remain watertight even under the large hydraulic-head gradients (up to 10) that were required for some falling-head tests. The soil cores were saturated in stages for a 4-d period using temperature-equilibrated (22°C) water before measuring K_{SAT}.

Field Procedures

The K_{SAT} measurements were made inside open-ended rectangular sheetmetal frames (≈0.9 × 0.6 × 0.15 m) located 0.6 to 3.0 m apart on each land management practice (CT, NT, WL) at each of the three field sites. The frames were inserted 0.03 m into the soil and covered with white plywood before and between the K_{SAT} measurements. The covered frames served essentially the same purpose as the tent arrangement of Messing and Jarvis (1993) and Jarvis and Messing (1995), that is, to minimize changes in antecedent soil water content and soil surface conditions as a result of rainfall, overland flow, daytime evaporation, and evening condensation during the 2- to 3-wk periods required at each field site to collect the K_{SAT} measurements. The measurements were taken during July and August, after the initial transient effects of tillage and planting had dissipated, the crop roots were well established, and when rainfall at the field sites is low and infrequent.

Within each sheetmetal frame, the K_{SAT} measuring sequence had three steps:

(i) The TI method applied on a relatively level spot within the sheetmetal frame where local surface irregularities were ±5 mm or less. The soil surface was not scraped, leveled, brushed, or vacuumed before installation of the retaining ring, guard cloth, and contact material. The retaining ring, contact material, and guard cloth were removed after completing the measurements, and the frame recovered with plywood.

(ii) After a 2- to 5-d drainage period, the plywood cover was removed from the frame and the PI method applied on the TI infiltration surface (i.e., within the wetted circle left by the TI measurement). The PI ring was left in place after the measurements were completed. The frame was then recovered with plywood.

(iii) After a 1- to 5-d drainage period, the plywood cover was again removed and the PI ring extracted as an undisturbed soil core. The core was analyzed in the laboratory using the SC method.

Saturated hydraulic conductivity measurements were replicated 7 to 12 times with each method (TI, PI, SC) on each land management practice (CT, NT, WL) at each field site (Delhi, Rockwood, Woodslee) for a total of 267 measurements. At each field site and for each method, water with major ion concentrations similar to that of the soil water was used to minimize possible changes in the antecedent soil structure due to aggregate slaking and clay-particle dispersion. All measurements were taken at the soil surface. The K_{SAT} values were not adjusted for possible temperature (water viscosity) or air entrapment effects.

Analyses

The K_{SAT} values from the three methods were compared on the basis of mean value, maximum value, minimum value, coefficient of variation, and the Pearson correlation coefficient. Lognormal statistical distributions were assumed, as is common for in situ and undisturbed core measures of K_{SAT} (e.g., Warrick and Nielson, 1980). The K_{SAT} data were consequently natural log–transformed (ln-transformed) before statistical comparison; geometric means were calculated rather than arithmetic means; and the coefficient of variation was calculated using an appropriate lognormal relationship (Hastings and Peacock, 1975, p. 84). Correlations among the three methods were conducted on a station-by-station basis within each land management practice and field site (27 separate correlations) using the ln-transformed K_{SAT} values. The term K_{GM} is used to represent the geometric mean K_{SAT} value, K_{MAX}

Table 2. Selected characteristics of the contract material used in the tension infiltrometer (TI) measurements (adapted from Reynolds and Zebchuk, 1996).

Material type and size	Sand	Silt	Clay	Air-entry value	Water-entry value	K_{SAT} ($h \geq -0.15$ m)
	— % —			— m —		$\times 10^4$ m s^{-1}
Glass spheres, 75- to 150-μm diam.	99.87† (±0.60)	0.13 (±0.08)	0.00	−0.58 (±0.015)	−0.30 (±0.030)	1.09 (±0.08)

† Arithmetic mean, values in brackets are plus and minus one standard deviation.

Table 3. Station-wise Pearson correlation coefficients (*R* value) plus statistical significance (*P* value) among the tension infiltrometer (TI), pressure infiltrometer (PI), and intact soil core (SC) methods for measuring K_{SAT} (n = 7–12). Correlations performed using the ln-transformed K_{SAT} data. Italicized *P* values are <0.05.

Land management	Method comparison	Fox sand		Guelph loam		Brookston clay loam	
		R value	*P* value	*R* value	*P* value	*R* value	*P* value
Annual conventional tillage (CT)	SC vs. TI	+0.1355	0.6912	−0.4747	0.2346	−0.8150	*0.0480*
	SC vs. PI	+0.3449	0.2722	−0.4389	0.3245	+0.1762	0.7384
	PI vs. TI	+0.3476	0.2948	+0.8970	*0.0010*	+0.0319	0.9459
Annual no-tillage (NT)	SC vs. TI	−0.0638	0.8521	+0.7761	*0.0139*	+0.6331	0.0920
	SC vs. PI	−0.1523	0.6548	+0.5157	0.1553	+0.6393	0.0879
	PI vs. TI	+0.0311	0.9235	+0.1144	0.7531	+0.8612	*0.0128*
Native woodlot (WL)	SC vs. TI	+0.3088	0.3555	+0.5716	0.1388	−0.0690	0.8600
	SC vs. PI	+0.2433	0.4460	+0.4459	0.1965	+0.3428	0.3664
	PI vs. TI	+0.2158	0.5239	+0.5806	0.1313	+0.3386	0.3727

to represent the maximum K_{SAT} value, K_{MIN} for the minimum K_{SAT} value, and CV for coefficient of variation.

RESULTS AND DISCUSSION

Time to Quasi-Steady Flow

Since the TI and PI are steady-flow methods that go through an initial transient phase, the accuracy of the K_{SAT} determination will depend partially on the degree to which quasi-steady flow was achieved. This was assessed here by comparing measured equilibration times with the equilibration times predicted by the Philip (1986) t_{grav} calculation,

$$t_{grav} = (S_{SAT}/K_{SAT})^2 \qquad [1]$$

where S_{SAT} (ms$^{-1/2}$) is sorptivity and K_{SAT} (ms^{-1}) is saturated hydraulic conductivity for ponded infiltration into unsaturated soil.

As expected, the measured equilibration times were highly variable for both the TI and PI methods, with CVs varying from 20 to 64% at each pressure head. The TI required 10 to 20 min to equilibrate at each of the two positive pressure heads, while the PI generally required 20 to 30 min at the first head and 15 to 20 min at the second head. Despite the variability, correspondence with t_{grav} was favorable. The estimated t_{grav} for the TI method was 17.2 ± 11.5 min, while that for the PI was 14.7 ± 14.2 min. Quasi-steady flow therefore appears to have been achieved adequately for both the TI and PI methods.

Correlations Among Methods

Only 4 of the 27 correlations between K_{SAT} values are significant at $P < 0.05$ (Table 3, italicized values). One of the significant correlations is negative while the other three are positive, and no pattern is evident among the significant correlations. Lack of correlation occurs despite frequent statistical equivalence ($P < 0.05$) of K_{GM} values (Table 4). In addition, no significant correlations occur between the PI and SC methods, or in the structureless sand soil (Table 3).

The general lack of correlation between the TI method and the other two methods might be related to sample size and/or flow geometry and/or soil disturbance. The TI infiltrates through a much larger soil area (49 087 mm^2) than the PI and SC methods (7854 mm^2), and may therefore sample more macropores and other soil heterogeneities. Flow is three-dimensional in the TI method, as opposed to one-dimensional (or predominantly one-dimensional) in the PI and SC methods, which may affect K_{SAT} results if macropores, etc. have induced substantial vertical–horizontal anisotropy into

Table 4. Comparison of K_{SAT} measurements obtained using the tension infiltrometer (TI), pressure infiltrometer (PI), and intact soil core (SC) methods. K_{GM} is geometric mean K_{SAT} value; K_{MAX} is maximum K_{SAT} value; K_{MIN} is minimum K_{SAT} value; CV is coefficient of variation.

Method	Annual conventional tillage (CT)					Annual no-tillage (NT)					Native woodlot (WL)				
	N†	K_{GM}	K_{MAX}	K_{MIN}	CV	N	K_{GM}	K_{MAX}	K_{MIN}	CV	N	K_{GM}	K_{MAX}	K_{MIN}	CV
		$\times10^{-5}$ m s^{-1}			%		$\times10^{-5}$ m s^{-1}			%		$\times10^{-5}$ m s^{-1}			%
							Fox sand								
TI	11	3.13b‡	6.83	1.27	59.6	12	2.57b	5.31	1.18	47.3	11	2.11b	6.18	0.98	53.1
PI	12	9.46a	17.85	3.10	51.1	12	5.36a	9.93	1.61	58.1	12	21.67a	38.95	7.12	57.8
SC	12	7.97a	16.50	3.81	48.6	11	8.14a	38.70	3.32	73.7	12	21.59a	59.30	4.49	95.5
							Guelph loam								
TI	10	1.56a	7.74	0.18	163.9	10	4.20a	15.98	2.39	68.2	8	4.51b	9.98	0.81	97.4
PI	9	1.48a	4.39	0.26	101.8	10	6.90a	15.69	1.74	79.5	10	23.80a	81.59	12.20	63.8
SC	8	1.15a	6.57	0.15	218.6	9	3.38a	34.30	0.18	344.9	10	32.38a	88.20	8.56	84.3
							Brookston clay loam								
TI	9	1.03a	2.14	0.59	44.5	8	2.33ab	5.10	0.95	62.8	9	6.31b	12.27	1.96	83.5
PI	8	0.132ab	1.08	0.019	362.4	9	1.89b	126.25	0.028	5058.2	10	7.22b	18.30	3.57	53.3
SC	7	0.0252b	4.34	x§	1.4E5	9	13.63a	68.70	1.46	206.6	9	25.19a	78.20	10.80	81.0

† Number of measurements.
‡ Mean values within a column and soil type followed by the same letter are not significantly different at $P < 0.05$.
§ Minimum value = 2.41×10^{-9} ms^{-1}.

the infiltration process. Although not observed during the measurements, insertion of the ring for the PI and SC methods may have caused varying degrees of artefact soil crack creation, which would not occur for the TI method.

The lack of correlation between the PI and SC methods is difficult to explain. Both methods have essentially the same sample size, flow geometry, and sample collection technique (insertion of a metal ring). They even sample virtually the same soil volume, since the SC cores were obtained by extracting the PI rings and their contained soil. One might have expected the PI and SC methods to at least correlate in the sand soil, as its uniformity and single-grain structure (Table 1) should resist alteration by the insertion and extraction of a ring.

Viewing of *x–y* comparison plots of K_{SAT} by the three methods (i.e., TI and PI vs. SC) indicates that the general lack of statistical correlation (Table 3), despite frequent statistical equivalence of K_{GM} values (Table 4), is due primarily to the lack of trend in the data or extensive scatter about the 1:1 line (data not shown). The general lack of statistically significant correlation or even trends among the TI, PI, and SC methods appears to confirm the findings of others (e.g., Bouma, 1980, 1982, 1983), that K_{SAT} is extremely sensitive to even relatively small differences in sample size, flow geometry, and soil structure.

Tension Infiltrometer Results

The TI method yielded a significantly lower K_{GM} ($P < 0.05$), as well as lower K_{MAX} and K_{MIN} values, when K_{GM} by the other methods was greater than about 0.8×10^{-4} ms^{-1} (Table 4). For lower permeabilities (i.e., $K_{SAT} \leq 0.8 \times 10^{-4}$ ms^{-1}), the TI method yielded K_{GM}, K_{MAX}, and K_{MIN} values that were comparable to one or both of the other methods. This behavior suggests that either the TI method (as used in this study) underestimated K_{SAT} under high permeability conditions (i.e., $K_{SAT} > 0.8 \times 10^{-4}$ ms^{-1}), or the other two methods were overestimating. If the TI method underestimated, possible reasons might include the following: restriction at high flow by the Mariotte air and/or water supply tubes; impedance by the TI membrane and/or guard cloth and/or contact material; inaccuracy in the positive-head method for K_{SAT} calculation; three-dimensional vs. one-dimensional flow geometry effects; or restricted operation of surface-vented macropores, cracks, or other preferential flow zones under the TI infiltration surface.

Restriction by the Mariotte air and/or water supply tubes is unlikely because the same Mariotte system was used for the PI method. In addition, laboratory tests of the TI apparatus showed no measurable restriction effects by the air and water supply tubes, membrane, or guard cloth at flow rates exceeding those measured in this study. Although a previous laboratory and numerical simulation study (Reynolds and Zebchuk, 1996) did indeed find impedance effects by the contact material (Table 2) under rapid-flow conditions, procedures developed in that study were used here to take those effects into account. Underestimates resulting from inaccuracy in the K_{SAT} calculation method are also unlikely because the method was developed specifically for small ponded head conditions in the TI; and the method was established in a numerical simulation study (Reynolds and Zebchuk, 1996) to be accurate within ±10% for K_{SAT} ranging from 10^{-4} to 10^{-8} ms^{-1}. In addition, the K_{SAT} values determined by this procedure were consistently greater than or equal to the K_{SAT} values obtained by extrapolation from slightly negative pressure heads using the Gardner (1958) exponential $K(h)$ relationship (e.g., Messing and Jarvis, 1993; Jarvis and Messing, 1995). Saturated hydraulic conductivity underestimates resulting from the primarily 3-D hemispherical flow field of the TI vs. the predominantly 1-D vertical flow of the PI and SC also do not seem likely because the underestimates (Table 4) occur more extensively in the relatively uniform and structureless sand soil, rather than in the more heterogeneous structured loam and cracking clay loam soils (Table 1).

Restricted operation of surface-vented macropores, cracks, and other preferential-flow zones under the TI may, however, be a mechanism that could cause underestimates in K_{SAT}. Although the TI can be set to produce a known positive pressure head at the contact material–soil interface (using, for example, the procedures in Reynolds and Zebchuk, 1996), it may still be possible for small, isolated areas at the interface to have a lower (than set) pressure head directly above preferential-flow zones. These localized areas of reduced pressure head would be caused by hydraulic head loss through the contact material (impedance) as a result of very rapid flow through the preferential-flow zones. If the head loss was sufficient to cause the pressure head immediately above the preferential-flow zone to be reduced substantially from the value set by the TI, this would in turn reduce the flow through the preferential-flow zone relative to what would occur if no contact material were present. Given that preferential-flow zones (especially surface-vented macropores and cracks) occupying as little as 3% of the infiltration surface can conduct as much as 90% of the measured flow (Mohanty et al., 1996), then even a few preferential-flow zones with restricted flow may be sufficient to cause a substantial reduction in measured flow rate, and hence a significantly lower estimate of K_{SAT}. A careful investigation of the hydraulics at the contact material–soil interface under the TI would be required to establish both the existence and importance of this kind of restricted flow through preferential-flow zones.

Undisturbed Soil Core Results

In the sand and loam soils, the K_{GM} values from the SC method were statistically equivalent to those from the PI method, and higher than those from the TI method (Table 4). In the clay loam, however, the SC method produced both higher and lower K_{GM} values than the other methods (Table 4). In addition, the SC method often produced the largest K_{MAX}, K_{MIN}, and CV values of the three methods, regardless of soil type, and especially in the NT and WL managements (Table 4).

The higher K_{GM}, K_{MAX}, and K_{MIN} values may reflect rapid *pipe* flow through worm holes, old root channels, and cracks that extend all the way through the cores (e.g., Bouma, 1982). Such macropores were often visible on both ends of the cores, and their frequency of occurrence was, as expected, greater in the NT and WL managements. On the other hand, the lower K_{GM} and K_{MIN} values in the CT management of the clay loam soil may have been the result of slow flow after swelling-induced closure of shrinkage cracks during core saturation (e.g., Jarvis and Messing, 1995). There was no evidence of flow surface smearing or compaction in these cores.

The high–low behavior of K_{GM}, K_{MAX}, and K_{MIN} in the clay loam (Table 4) suggests that although the SC cores were larger than usual (0.10-m diam. $\times$ 0.10-m length), they may still have been too small to adequately sample that soil. This is perhaps not surprising, given that the clay loam soil developed 10- to 100-mm-diam. shrinkage crack polygons with crack widths up to 10 mm (Table 1). Bouma (1983) recommended that detached soil samples should be large enough to contain at least 20 soil peds, which implies that cores from the clay loam soil needed to be at least twice the size used here (i.e., 0.20-m diam. $\times$ 0.20-m length). Bouma (1982) and Wu et al. (1992) appear to have obtained representative K_{SAT} results in a structured clay and a macroporous loam, respectively, using intact soil cores that were 0.30 m in diam. by 0.25 to 0.30 m long. Unfortunately, such large cores are impractical for many studies.

The representativeness of the SC method in the NT and WL managements of the sand and loam soils may also be somewhat in question, given that the method consistently yielded higher K_{MAX} values than the other two methods for those conditions (Table 4). As mentioned above, these high K_{MAX} values are probably the result of rapid pipe flow through worm holes and old root channels, which extend through the entire length of the core.

Pressure Infiltrometer Results

The PI method yielded K_{GM} values that were statistically equivalent to one or both of the other methods in all nine soil type–land management combinations (Table 4). The K_{MAX}, K_{MIN}, and CV values yielded by the PI were also comparable, for the most part, to those from one or both of the other methods. Although this does not necessarily validate the PI method over the other methods, possible reasons for the high level of internal consistency relative to the other methods include (i) lack of membrane, contact material, or guard cloth to cause possible flow impedance effects; (ii) reduced impact of soil swelling because the relatively rapid PI measurements (30–50 min duration) were completed before substantial swelling could occur; and (iii) reduced effect of pipe flow through macropores because the soil core remains attached to the underlying soil profile. It is noted, however, that the PI method produced erratic K_{MAX} and K_{MIN} values, as well as high CV values for the CT and NT managements in the cracking clay loam. As with the SC method, this may suggest that the soil volume sampled by the PI method was too small for the structural conditions in the CT and NT managements on the clay loam soil. Another possibility might be air entrapment effects caused by rapid wetting of the soil within the confines of the PI ring, although one might expect air entrapment effects to occur in all of the managements rather than in just the CT and NT managements of the clay loam.

CONCLUSIONS

Comparing techniques for measuring the K_{SAT} of intact soil is an imprecise, perhaps even dubious, enterprise because there is no independent K_{SAT} datum or benchmark upon which evaluations and judgments can be made. It is nonetheless important to make such comparisons because they provide one of the few sources of information that practitioners can draw upon to select K_{SAT} methods that are appropriate for their circumstances. The following comments regarding the TI, PI, and SC techniques are consequently offered, notwithstanding the above caveat.

The TI, PI, and SC methods often yielded different measures of K_{SAT} under the conditions tested. Only 4 of the 27 between-method correlations were significant at $P < 0.05$ (Table 3); and in only two of the nine soil type–management combinations (CT and NT managements in the loam soil) did all three methods yield statistically equivalent ($P < 0.05$) K_{GM} values (Table 4). There was also a general lack of consistency or pattern among the K_{GM}, K_{MAX}, K_{MIN}, and CV values yielded by the three methods (Table 4).

The TI method yielded estimates of K_{GM} that were comparable to those of one or both of the other methods when K_{SAT} was less than about 10^{-4} ms^{-1} (Table 4). Under higher permeability conditions, however, the TI method gave lower K_{GM}, K_{MAX}, and K_{MIN} values than the other methods (Table 4). The reason for this is not clear, but may be related to restricted flow through preferential-flow zones (especially surface-vented worm holes, old root channels, and cracks) as a result of localized flow-impedance effects in the contact material used for the TI measurements (Table 2). The TI may have yielded the most representative estimates of K_{SAT} in the CT and NT managements of the cracking clay loam because it gave CVs that were substantially lower than those of the other methods.

Although the SC method cores were larger than usual at a 0.10-m diam. by 0.10-m length, they may still have been too small to yield representative K_{SAT} values in the cracking clay loam soil, as evidenced by high CV values and both higher and lower K_{GM} values relative to the other methods (Table 4). The SC method may have given representative estimates of K_{GM} in the structureless sand and structured loam soils (Table 4); however, the consistently higher K_{MAX} values in the NT and WL managements of these soils may indicate that the cores were smaller than ideal under those conditions, owing to probable pipe flow through macropores.

The PI method gave K_{GM} values that were statistically equivalent to the K_{GM} from one or both of the other methods in all nine soil type–land management combinations (Table 4). Erratic K_{MAX} and K_{MIN} values, as well as high CV values, suggest that the PI method may not have yielded representative K_{GM} values in the CT and NT treatments of the cracking clay loam soil. For all other soil type and land management combinations, the PI method yielded K_{GM}, K_{MAX}, K_{MIN}, and CV values that were comparable to one or both of the other methods.

This study supports the argument of Bouma (1983) that soil textural–structural conditions are critically important factors determining both the magnitude of K_{SAT} and the best method(s) for measuring K_{SAT}. Further work is clearly needed in developing K_{SAT} measurement methods, interpreting K_{SAT} results, and in determining the most appropriate method(s) for both the soil conditions and the intended application of the K_{SAT} data.

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