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Scaling of near-saturated hydraulic conductivity measured using disc infiltrometers

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Abstract. A function relating unsaturated soil hydraulic conductivity K and soil water pressure head h is most important for understanding water flow and chemical transport in the vadose zone. Furthermore, the $K(h)$ function near saturation is critical for describing flow in macropores and other structural voids. The usefulness of similar media scaling and functional normalization to describe the near-saturated hydraulic conductivity function $K(h)$ measured in situ at 296 spatial locations across a heterogeneous agricultural field was tested. Disc (ponded and tension) infiltrometers were used to measure $K(h)$ at different field positions (corn row, no traffic interrow, and traffic interrow) cutting across different soil types (Nicollet and Clarion loam derived from glacial till material). The $K(h)$ data ranged several orders of magnitude for different field positions and soil types and were found to be statistically different between different field positions. Using a Gardner type $K(h)$ function, relative hydraulic conductivity values, and a hybrid of similar media scaling and functional normalization concepts, all disc infiltrometer data sets were coalesced to a single reference curve. Poor to moderately correlated K and h scale factors did not show any significant spatial structure across the field. A novel finding is that saturated hydraulic conductivities (K_{sat}) could be successfully used as the scale factor for the near-saturated $K(h)$ functions (e.g., 0–15 cm soil water tension) under all field positions and soil types at the experimental field.

1. Introduction

Among others, *Warrick et al.* [1977] and *Jarvis and Messing* [1995] suggested that further research should be carried out with respect to both experimental technology and scaling concepts for an optimum coevolution of techniques addressing soil heterogeneity. More recently, in situ measurement of near-saturated hydraulic conductivity ($K(h)$) using disc (ponded and tension) infiltrometers has opened up new avenues to assess spatial variability of hydraulic properties of field soils. These in situ $K(h)$ measurements are better suited to represent (near-saturated) flow and transport scenarios in the field than $K(h)$ measurements obtained using detached soil cores in the laboratory [*Mohanty et al.*, 1994a]. Near-saturated $K(h)$ measurements are important for understanding the influence of macropores and other structural voids in the soil water regime of field soils and useful for multidomain models for soil hydraulic properties. The effects of soil structure and macropores might be more reliably predicted, as shown by *Mohanty et al.* [1997]. Spatial variability of these $K(h)$ measurements using different geostatistical and/or scaling concepts need to be studied further for different soils, crops, tillage practices, traffic conditions, and other extrinsic/intrinsic field variables. *Mohanty et al.* [1994b, 1996] used geostatistical techniques to analyze disc infiltrometer $K(h)$ data under different soil and traffic conditions. To date, only *Jarvis and Messing* [1995] used a similar media scaling technique to analyze disc infiltrometer $K(h)$ data obtained by means of four to six disc infiltrometer experiments at each of six different soil types in Sweden.

The objective of our study was to test the appropriateness of similar media and functional normalization scaling approaches for describing disc infiltrometer–measured near-saturated $K(h)$ data under different soil types and field positions. Moreover, we investigated whether a hybrid of similar media and functional normalization scaling approaches was applicable to $K(h)$ data that cut across different soil types and field positions in a large field. A large data set, totaling up to 296 disc infiltrometer data near Boone, Iowa, was used for this study.

2. Materials and Methods

Infiltration measurements were made along two parallel transects running orthogonal to the crop rows in field 5 at the Agronomy and Agricultural Engineering Research Center near Boone in central Iowa. Soil type in this field is predominantly silt loam belonging to the Clarion-Nicollet-Webster soil association (Figure 1a). Webster is a fine-loamy, mixed, mesic Typic Haplaquoll at the valley, and Clarion is a fine-loamy, mixed, mesic Typic Hapludoll located at the top of the hill. Nicollet, which is a fine-loamy, mixed, mesic Aquic Hapludoll, lies in midlevel positions between the other two. The soils were developed from calcareous glacial till (Des Moines lobe, Wisconsin age) with surface texture ranging from loam to sandy loam. All measurements were limited to a plot under no-tillage management of continuous row corn production for 8 years prior to our experiment. This study was conducted in May 1990 during the planting season.

An automated disc infiltrometer [*Ankeny et al.*, 1988; *Ankeny*, 1992] was used for obtaining a large number of measurements needed for determining spatial variability of hydraulic conductivity. The small disc size (7.62 cm diameter) of the infiltrometer was useful for measuring infiltration rates in different narrow soil management zones (e.g., crop row, interrow, trafficked interrow). Ponded [*Prieksat et al.*, 1992] and tension

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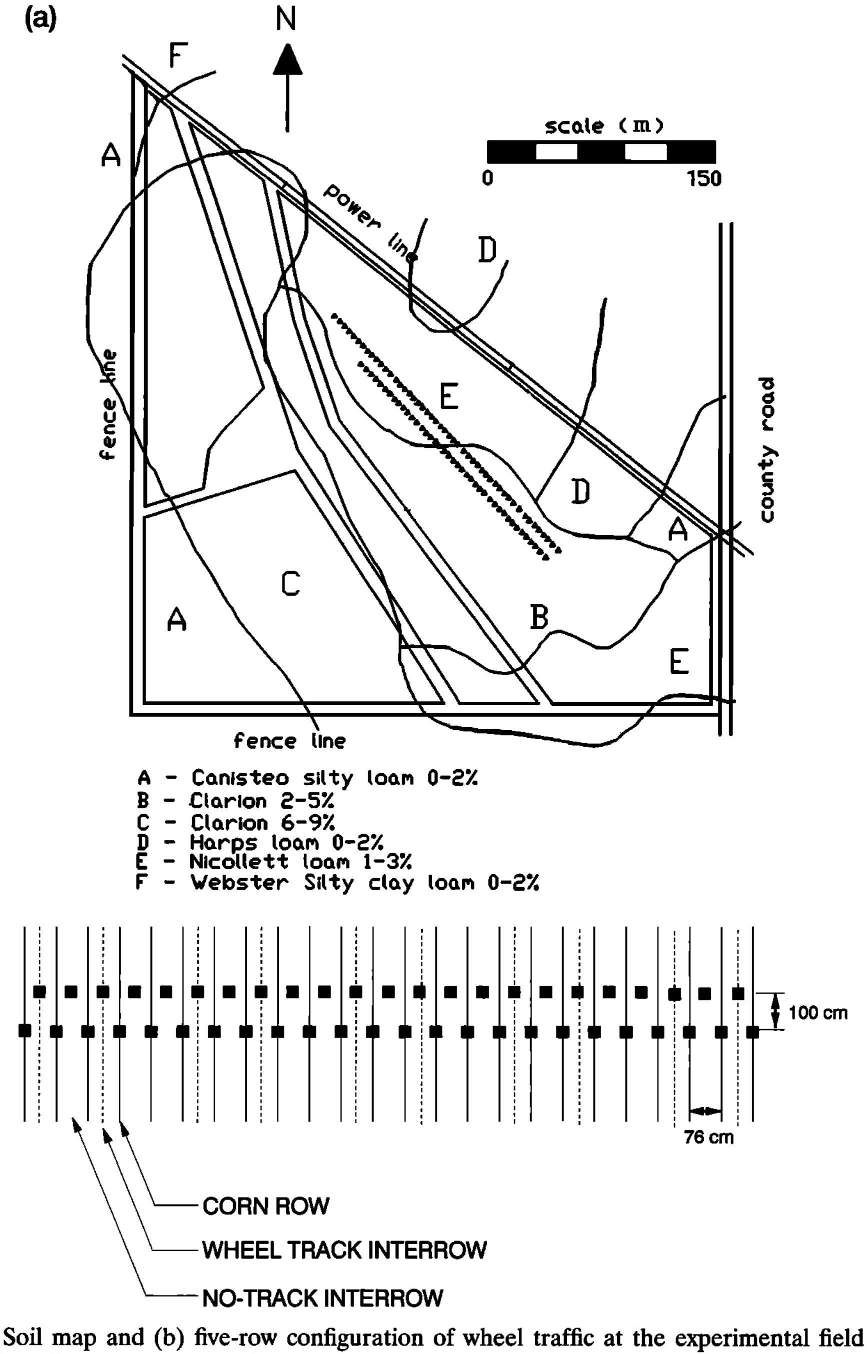

Figure 1. (a) Soil map and (b) five-row configuration of wheel traffic at the experimental field site near Boone, Iowa. Sampling transects are shown as two parallel lines across the center of the field running in SE-NW direction in Figure 1a. Solid squares indicate the infiltration measurement sites arranged on two parallel transects in Figure 1b [after *Mohanty et al.*, 1994b].

infiltrometers [*Ankeny et al.*, 1988; *Ankeny*, 1992] were used to measure infiltration rates along two parallel transects orthogonal to the crop rows. The two parallel transects, one for corn row and one for interrow measurement locations, were located 1 m apart to avoid any foot traffic at the measuring sites during the field experiment. The ponded infiltrometer maintains a thin layer of water (approximately 0 ~ 1 mm depth) above the contact surface, while the tension infiltrometer creates a soil water tension at the contact surface with a precision of 0 ~ 10 mm. The infiltrometers were run in sequence at the same positions at 0-, 30-, 60-, and 150-mm water tensions, for 25 min, with automatic recording of the infiltration volume using pressure transducers and data loggers, at regular time intervals. The infiltration measurements at the 296 sites were completed in less than a week, thus minimizing temporal variability in the data. Eighteen automated infiltrometers were used to accomplish all measurements in this short period of time. Tension infiltrometer readings were taken at 160 corn row sites and 136 interrow sites (including trafficked and nontrafficked locations).

Figure 1b shows the five-row configuration of preplanting and harvesting traffic. The distance between consecutive rows and consecutive interrows was 76 cm. Infiltration measurements were made at the center of the corn rows and interrows. At each measurement location an area approximately 25–30

Table 1. Summary Statistics of $K(h)$ for Different Field Positions (Corn Row, No-Track Interrow, and Wheel Track Interrow) and Soil Types (Nicollet Loam and Clarion Loam)

Moments	Tension 0 mm	30 mm	60 mm	150 mm
	Corn Row, Nicollet Loam			
N	70	75	66	59
Mean K (ln K), μm/s	110.3 (4.37)	7.05 (1.75)	2.43 (0.732)	0.94 (−0.379)
Maximum K, μm/s	723.2	27.5	11.4	4.4
Minimum K, μm/s	7.9	0.97	0.23	0.1
Coefficient of variation of K (ln K), %	93.4 (19.9)	66.1 (37.4)	72.1 (97.8)	78.5 (208.4)
W normal* for K (ln K)	0.732 (0.965)	0.882 (0.990)	0.830 (0.987)	0.822 (0.980)
	Corn Row, Clarion Loam			
N	77	80	77	75
Mean K (ln K), μm/s	110.9 (4.27)	6.75 (1.72)	2.84 (0.845)	1.14 (−0.095)
Maximum K, μm/s	531.5	27.43	11.37	4.3
Minimum K, μm/s	2.97	0.82	0.21	0.036
Coefficient of variation of K (ln K), %	1.54 (24.2)	70.1 (37.2)	68.2 (78.9)	67.1 (793.9)
W normal* for K (ln K)	0.833 (0.962)	0.824 (0.998)	0.833 (0.953)	0.829 (0.861)
	Corn Row, Field			
N	147	155	143	134
Mean K (ln K), μm/s	110.6 (4.32)	6.89 (1.73)	2.65 (0.792)	1.05 (−0.222)
Maximum K, μm/s	723.2	27.54	11.38	4.39
Minimum K, μm/s	2.97	0.82	0.21	0.036
Coefficient of variation of K (ln K), %	92.1 (22)	67.9 (37.1)	70.1 (87.16)	71.9 (351.1)
W normal* for K (ln K)	0.798 (0.969)	0.848 (0.981)	0.829 (0.969)	0.830 (0.941)
	No-Track Interrow, Field			
N	54	72	72	59
Mean K (ln K), μm/s	66.3 (3.49)	4.2 (1.05)	2.0 (.368)	0.7 (−0.698)
Maximum K, μm/s	317.7	14.6	7.9	2.9
Minimum K, μm/s	2.8	0.1	0.2	0.03
Coefficient of variation of K (ln K), %	125.5 (35.55)	79.7 (94.50)	80.3 (24.75)	76.9 (122.3)
W normal* for K (ln K)	0.706 (0.963)	0.881 (0.947)	0.848 (0.958)	0.866 (0.965)
	Wheel Track Interrow, Field			
N	27	35	33	17
Mean K (ln K), μm/s	27.3 (3.04)	1.6 (0.212)	0.6 (−0.878)	0.2 (−2.59)
Maximum K, μm/s	89.7	4.6	1.9	0.8
Minimum K, μm/s	3.9	0.2	0.04	0.002
Coefficient of variation of K (ln K), %	76.5 (26.34)	64.3 (371.97)	78.2 (91.17)	120.5 (59.54)
W normal* for K (ln K)	0.864 (0.972)	0.938 (0.938)	0.849 (0.977)	0.710 (0.880)

*Normality test using the Shapiro-Wilk W statistic.

cm diameter was cleared to a depth of 2–3 cm and leveled. Two layers of cheesecloth were placed on the soil surface before wetting to minimize slaking of soil into the macropores. Flow measurements were taken from low to high tension (0 to 150 mm) on a 7.62-cm-diameter circle on the cleared soil surface, which allowed an evaluation of surface position (treatment) effects on the distribution of different pore sizes. By adopting a wet to dry (i.e., 0- through 150-mm tension) measurement sequence, the wetting front advances as rapidly as possible, and the assumption of unit gradient below the device should be closely approximated. However, it is important to note that the drainage sequence might lose any important information related to soil water hysteresis at the field site. A total of 147, 155, 143, and 134 measurements were available from corn rows at 0-, 30-, 60-, and 150-mm tensions, respectively. Similarly, 54, 72, 72, and 59 data points were available for nontrafficked interrows, and 27, 35, 33, and 17 for trafficked interrows. Except for a few unsuccessful measurement sites because of bad transducer connections, leaks in the disc membrane, or operator error in measurement setup, these numbers covered all surface positions (i.e., corn rows and interrows) in the entire field under study. Because of the rather limited number of measurements under interrows, we did not categorize them under different soil types, as opposed to the case of corn rows.

Ankeny [1992] presented a complete description of design, setup, calibration, operation, and data analysis procedures for the tension and ponded infiltrometers used in this study. For completeness we briefly present the hydraulic conductivity calculation procedure from the three-dimensional infiltration rates below.

Wooding [1968] proposed the following algebraic approximation of steady state unconfined saturated infiltration rates into soil from a circular source of radius r:

$$Q = \pi r^2 K + 4r\phi_m \tag{1}$$

where Q $[L^3T^{-1}]$ is the volumetric flow rate, K $[LT^{-1}]$ is the saturated hydraulic conductivity, and ϕ_m $[L^2T^{-1}]$ is a matrix flux potential where

$$\phi(0) = \int_{h_i}^{0} k(h)\, dh \tag{2}$$

where $k(h)$ $[LT^{-1}]$ is the hydraulic conductivity/pressure head relationship and h_i $[L]$ is the initial water potential of the

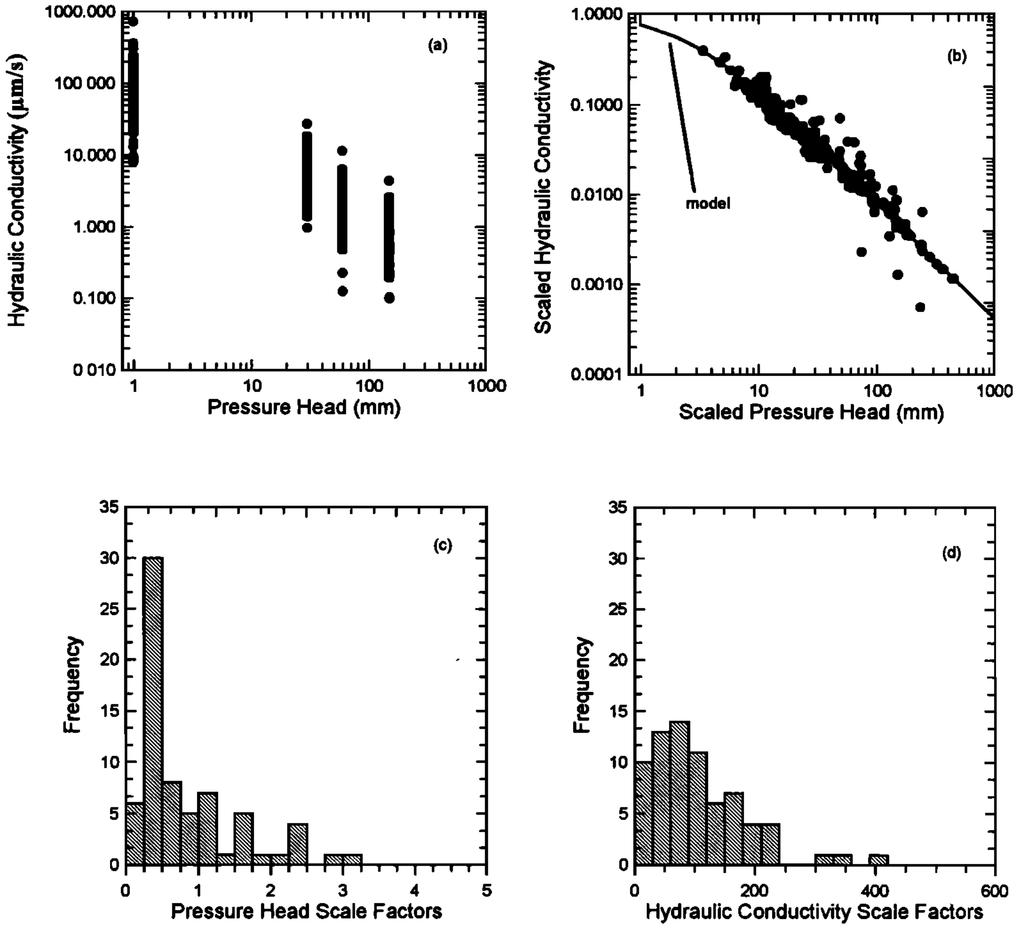

Figure 2. Scaling results for unsaturated hydraulic conductivity $K(h)$, measured under corn rows in Nicollet soil: (a) raw data, (b) scaled data, (c) histogram of pressure head scale factors, and (d) histogram of hydraulic conductivity scale factors.

unwetted soil. Rewriting (2) for a general infiltrating boundary tension or supply potential h_0 yields

$$\phi(h_0) = \int_{h_i}^{h_0} K(h)\,dh \qquad h_i \le h_0 \le 0 \qquad (3)$$

Substituting (3) into (1) allows (1) to be applied for arbitrary supply potential h_0. Accordingly, if two infiltrating flow rates $Q(h_1)$ and $Q(h_2)$ are measured at supply potential h_1 and h_2 then we obtain two equations and four unknowns:

$$Q(h_1) = \pi r^2 K(h_1) + 4r\phi(h_1) \qquad (4)$$

$$Q(h_2) = \pi r^2 K(h_2) + 4r\phi(h_2) \qquad (5)$$

The unknowns are $K(h_1)$, $K(h_2)$, $\phi(h_1)$, and $\phi(h_2)$. To solve for these unknowns, we must obtain at least two more equations. One of these is obtained by assuming the relationship

$$A = K/\phi = \text{const} \qquad (6)$$

between h_1 and h_2 [*Philip*, 1985].

The basis for an additional equation was adapted from *Elrick et al.* [1988] and is given by

$$\phi(h_1) - \phi(h_2) = \Delta h[K(h_1) + K(h_2)]/2 \qquad (7)$$

The system of four equations, (4), (5), (6), and (7), can now be solved for the four unknowns, $K(h_1)$, $K(h_2)$, $\phi(h_1)$, and $\phi(h_2)$, using simultaneous equation procedures. The above approach allowed us to calculate hydraulic conductivity from any pair of unconfined infiltration rates taken on the ponded and tension infiltrometers. Further procedural details are given by *Ankeny et al.* [1991].

3. Scaling Analysis

Miller and Miller [1956] introduced the concept of geometric similitude and similar media scaling in soil physics. This approach relies on the definition of a characteristic length scale that is related to particle sizes and pore dimensions in particular geometric arrangements. During the last several decades, scaling theory has evolved and is increasingly being used in different soil/hydrologic problems including, among others, soil hydraulic property determination of heterogeneous fields, estimation of infiltration, drainage, runoff, water balance, and crop water uptake, and predicting chemical transport under variably saturated conditions. Some of the better known scaling studies include *Warrick et al.* [1977], *Peck et al.* [1977], *Sharma and Luxmoore* [1979], *Simmons et al.* [1979a, b], *Luxmoore and Sharma* [1980], *Youngs and Price* [1981], *Tillotson and Nielsen* [1984], *Jury et al.* [1987], *Hopmans et al.* [1988], *Vogel et al.* [1991], *Ahuja and Williams* [1991], *Shouse et al.* [1992], *Clausnitzer et al.* [1992], *Warrick and Hussen* [1993], *Shouse et al.* [1995], and *Rockhold et al.* [1996]. *Tillotson and*

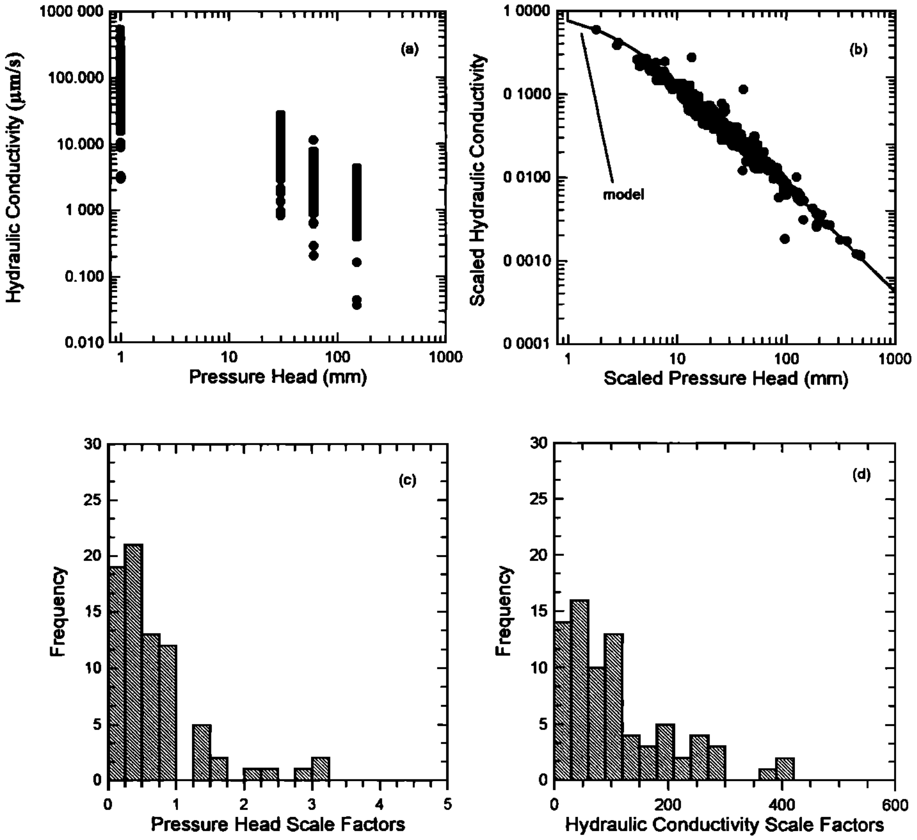

Figure 3. Scaling results for unsaturated hydraulic conductivity $K(h)$, measured under corn rows in Clarion soil: (a) raw data, (b) scaled data, (c) histogram of pressure head scale factors, and (d) histogram of hydraulic conductivity scale factors.

Nielsen [1984] gave a good review of different scaling methods including dimensional analysis, inspectional analysis, and functional normalization. *Hopmans* [1987] and *Vogel et al.* [1991] compared different methods to scale soil hydraulic properties. In most of the above studies, scaling characterizes the spatial variability of soil properties, thus facilitating numerical or other solution procedures.

In this study we scaled the near-saturated $K(h)$ data collected under different soil types, field positions, and across the entire field, using relative hydraulic conductivity ($K_{\mathrm{rel}}(h) = K(h)/K_{\mathrm{sat}}$) against h as proposed by *Jury et al.* [1987]. Relative hydraulic conductivity was used to alleviate any gravity-dominated macropore flow near saturation because of soil structural features that have little or no influence on water flow under unsaturated conditions. More recently, among others, *Mohanty et al.* [1997] found that the soil hydraulic conductivity measured with the disc infiltrometer between 0- and 3-cm tension can be several orders of magnitude higher than the hydraulic conductivity at 3-cm tension, while the water content in the same range remained nearly unchanged. They proposed a matching point between the gravity-dominated macropore flow region and the capillarity-dominated matrix flow region, and for joining separate functions in the two flow regions. Also, they suggested that the soil water retention and hydraulic conductivity functions are independent of each other in the macropore flow region. Earlier, using the same set of data as in this study, *Mohanty et al.* [1996] showed little or no correlation between the saturated and unsaturated K values. In their scaling study, *Jarvis and Messing* [1995, Table 3] used somewhat similarly a two-line exponential model to describe the K in a macropore-mesopore system; this model was found to minimize the mean square errors (MSE) compared to a single-exponential model or the unimodal Mualem–van Genuchten model. These research findings support the argument by *Jury et al.* [1987] for using relative hydraulic properties, instead of the hydraulic properties themselves, for estimating the scaling factors. However, in the following sections, our scaling approach should be distinguished from *Jury et al.* [1987] in that we did not use any further scaling beyond the K_{rel} calculation. In other words K_{sat} is viewed as a (physical) scale factor for hydraulic conductivity based on the similar media concept. Here we suggest that for the near-saturated K, the similar media concept is not necessarily limited to geometrical similarity as in the work by *Miller and Miller* [1956], but may entail more of a combination of dynamic, kinematic, and geometric similarity represented by K_{sat}. In contrast, *Jury et al.* [1987] used an additional empirical factor to scale K resembling a functional normalization scheme [*Tillotson and Nielsen*, 1984].

Different approaches including the field average, a somewhat arbitrary site in the field, or other previously or independently collected data sets, have been used in the scaling literature to define the reference hydraulic parameters. In this study, several arbitrarily selected ($K_{\mathrm{rel}}(h)$, h) data sets from our field site were used to define the reference model. Using nonlinear regression, the formulation by *Gardner* [1960] (as cited by *Hillel* [1980, p. 200])

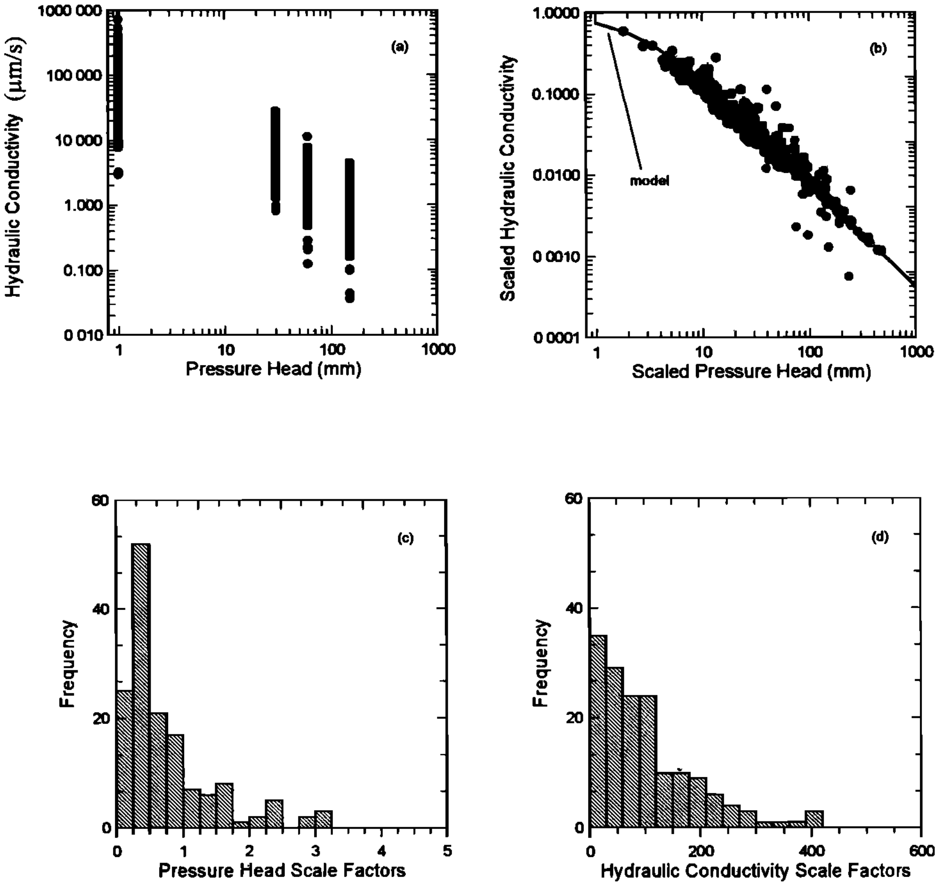

Figure 4. Scaling results for unsaturated hydraulic conductivity $K(h)$, measured under corn rows in Nicollet and Clarion soils: (a) raw data, (b) scaled data, (c) histogram of pressure head scale factors, and (d) histogram of hydraulic conductivity scale factors.

$$\frac{K(h)}{K_{\mathrm{sat}}} = K_{\mathrm{rel}}(h) = \frac{1}{[1 + (h/h_c)^n]} \qquad (8)$$

was found to describe the data sets better than the function $K(h)/K_{\mathrm{sat}} = \exp(-\lambda h)$ by *Gardner* [1958] and the van Genuchten–Mualem function [*van Genuchten*, 1980]. In these equations, λ and n are empirical constants, and h_c is the suction head at which $K_{\mathrm{rel}} = 0.5$. Although (8) gives a better fit to $K_{\mathrm{rel}}(h)$, it is important to mention here that the *Wooding* [1968] procedure for estimating $K(h)$ (described in the previous section) is based on the assumption of *Gardner*'s [1958] exponential relationship for $K(h)$. Subsequently, one arbitrary $[K_{\mathrm{rel}}(h), h]$ set was chosen as the reference, and function (8) was fitted by nonlinear regression, giving $h_c = 2.41$ cm, and $n = 1.29$. Paired $[K_{\mathrm{rel}}(h), h]_{i=1\cdots N,\, x=1\cdots X}$ data points were subsequently scaled to the reference curve using the functional normalization of h [*Tillotson and Nielsen*, 1984]. The (empirical) scale factor α_x for a certain infiltration sequence at site x consisting of N data points (i.e., tension steps) was then found by minimizing the sum of squared differences (SS) between the reference relative hydraulic conductivity curve and the scaled data points:

$$\mathrm{SS} = \sum_{i=1}^{i=N} [\alpha_x h_i - h_i^{\mathrm{ref}}]^2 \qquad (9)$$

A simple computational protocol was developed to calculate α_x. Mathematically,

$$\alpha_{i,x} = \frac{h_{i,x}^{\mathrm{ref}}}{h_{i,x}} \qquad i = 1, \cdots, N \qquad \forall x \qquad (10)$$

$$\alpha_x = \frac{1}{N} \sum_{i=1}^{i=N} \alpha_{i,x} \qquad \forall x \qquad (11)$$

By analogy, $K_{\mathrm{sat},x}$ used for calculating the $K_{\mathrm{rel},x}$ can be viewed as a scale factor for K, whereas α_x is a scale factor for h. Henceforth, we will use the terminology "scale factor for hydraulic conductivity" and $K_{\mathrm{sat},x}$ interchangeably. Once α_x for a spatial location (x) is known, scaled $h_{i,x}^*$ $(= \alpha_x h_{i,x})$ are calculated for all tension steps $(i = 1, \cdots, N)$.

As mentioned earlier, our scaling procedure is neither strictly similar media scaling based according to geometric similitude as in the work by *Miller and Miller* [1956] nor functional normalization based according to empiricism. It is somewhat a hybrid of similar media scaling and functional normalization.

4. Results and Discussion

Summary statistics for $K(h)$ are presented in Table 1 for both the Nicollet and Clarion soils; results are for different

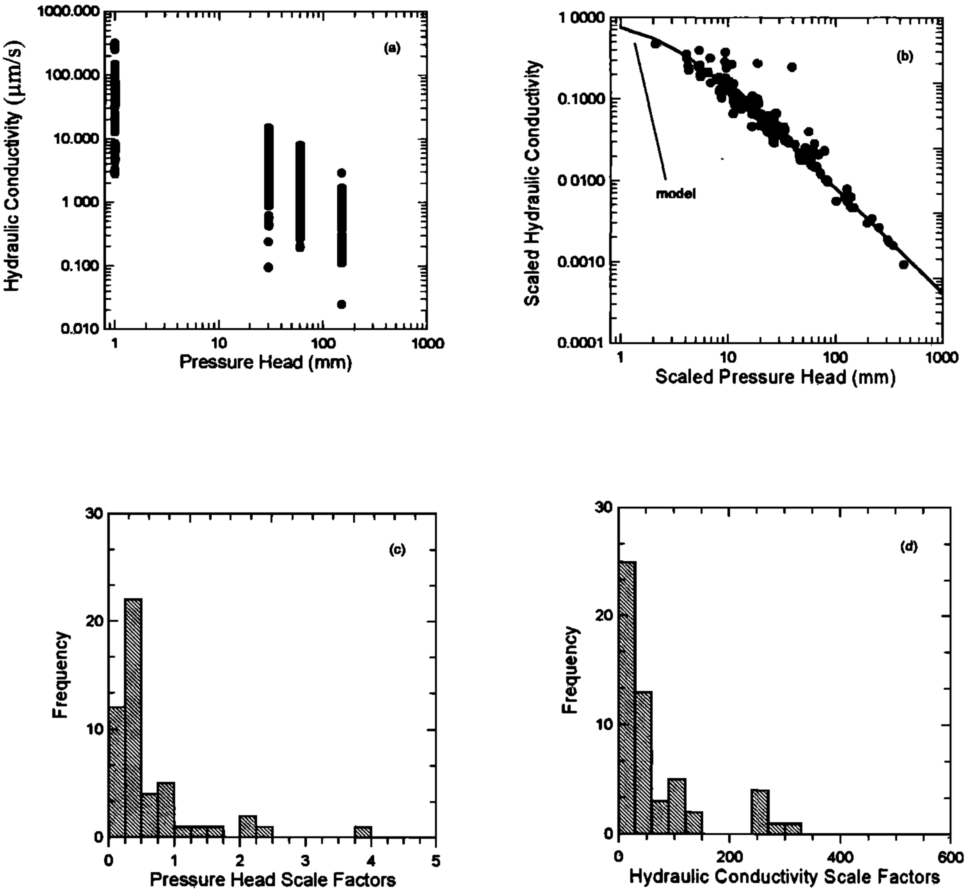

Figure 5. Scaling results for unsaturated hydraulic conductivity $K(h)$, measured under no-traffic interrows in Nicollet and Clarion soils: (a) raw data, (b) scaled data, (c) histogram of pressure head scale factors, and (d) histogram of hydraulic conductivity scale factors.

field positions including corn rows, nontrafficked interrows, and trafficked interrows. In all cases, as judged from Shapiro-Wilk tests (i.e., W statistics [*Shapiro and Wilk*, 1965]), $K(h)$ data were found to be better represented by lognormal distributions (Table 1). For all invoked soil water pressure heads, the mean $K(h)$ was highest for the corn rows, lowest for the wheel track interrows, and intermediate for the no-track interrows. Moreover, a multiple-mean comparison (Duncan's test) showed that relative $K(h)$ at the three field positions were statistically significant ($P = 0.99$). Differences in $K(h)$ between Nicollet and Clarion soil were statistically not significant. We suggest that the soil-induced variability in $K(h)$ was either removed or suppressed by the variability imposed by the agricultural practice (i.e., row cropping, wheel traffic) at the field site. A geostatistical analysis of the $K(h)$ data under all three field positions showed a nugget effect indicating no spatial structure [*Mohanty et al.*, 1994b]. Furthermore, for different soil and traffic conditions, proportional effects [*Journel and Huijbregts*, 1978, p. 187] in the mean and variance of $K(h)$ were found.

Results obtained by scaling $K_{\mathrm{rel}}(h)$ data with reference to the Gardner model are shown for corn rows in Nicollet soil (Figure 2), corn rows in Clarion soil (Figure 3), corn rows cutting across the Nicollet and Clarion soils (Figure 4), no-traffic interrows cutting across the Nicollet and Clarion soils (Figure 5), traffic interrows cutting across the Nicollet and Clarion soils (Figure 6), and all data cutting across Nicollet and Clarion soils and pertaining to all three field positions (Figure 7). Visual examination of the raw and scaled data showed that scaling coalesced the $K(h)$ data very well and matched the reference Gardner model in all six cases, except for a few outliers. Note that only one set of model parameters was used for all different soil types and field positions. Table 2 presents mean square error (MSE) values of $K(h)$ both before and after scaling, with respect to the reference model. MSE is defined as the average difference between measured or scaled K and the model $\hat{K}$,

$$\mathrm{MSE} = \left[\frac{1}{X} \frac{1}{N} \sum_{x=1,t=1}^{X,N} (K_{t,x} - \hat{K}_{t,x})^2 \right] \tag{12}$$

The scaling procedure reduced the MSE for all six cases by 81–96%. Under corn rows, scaling reduced MSE by 94% for Nicollet soil, by 91% for Clarion soil, and 92% across the entire field. For no-traffic and wheel traffic interrows, MSE was reduced by 81% and 96%, respectively. Across the entire field under study, including both soil types and three field positions, scaling reduced MSE by 89%. The MSE values following scaling were satisfactorily small in all cases. These findings signify the important advantage of scaling in describing the apparent field-scale variability of the hydraulic conductivity. Results obtained here are important in deterministic and stochastic flow/transport studies as demonstrated by *Hopmans et al.* [1988] and *Rockhold et al.* [1996].

Table 3 presents several statistics of the pressure head scale

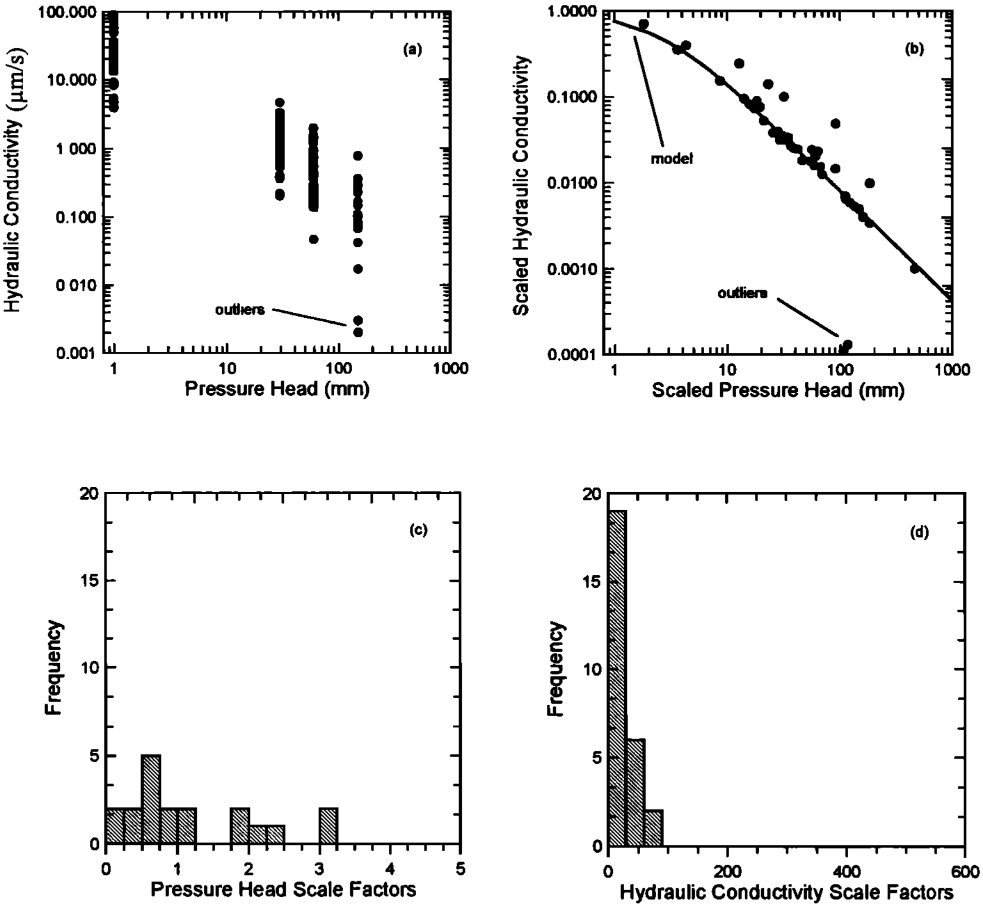

Figure 6. Scaling results for unsaturated hydraulic conductivity $K(h)$, measured under wheel traffic interrows in Nicollet and Clarion soils: (a) raw data, (b) scaled data, (c) histogram of pressure head scale factors, and (d) histogram of hydraulic conductivity scale factors.

factors (α) under different soil types, field positions, and the entire field. The mean α was found to be highest for trafficked interrows, lowest for no-trafficked interrows, and intermediate for corn rows. The coefficients of variance (CVs) for α ranged between 78% and 155% and were found to be somewhat inversely related to the mean α. Figures 2–7 show probability density functions (pdf) for the pressure head scale factors (α) and hydraulic conductivity scale factors (K_{sat}). In general, both scale factors followed a lognormal distribution better than a normal distribution based on the Shapiro-Wilk test (W normal score; Table 3). K and h scale factors were found to be poorly to moderately correlated at different field positions and soil types: corn rows in Nicollet soil ($r^2 = 0.436$), corn rows in Clarion soil ($r^2 = 0.680$), corn rows cutting across the Nicollet and Clarion soils ($r^2 = 0.542$), no-traffic interrows cutting across the Nicollet and Clarion soils ($r^2 = 0.434$), traffic interrows cutting across the Nicollet and Clarion soils ($r^2 = 0.048$), and all data cutting across Nicollet and Clarion soils and pertaining to all three field positions ($r^2 = 0.352$). Geostatistical analyses of log-transformed K and h scale factors at all field positions and soil types revealed no spatial structure in the estimated semivariograms (Figures 8 and 9). The definition of semivariogram can be found in any standard geostatistics text [e.g., *Journel and Huijbregts*, 1978]. Estimated semivariograms were computed up to half of the total lag distance for individual field positions or soil types. Except for wheel track interrows, all semivariogram estimations were based on at least 30 data pairs at all lags.

Table 2. Mean Square Errors (MSEs) for Different Soil Types, Field Positions, and the Entire Field, Both Before and After Scaling

Condition(s)	Raw Data	Scaled Data	Reduction in MSE, %
Corn row, Nicollet loam	0.004080	0.000246	94
Corn row, Clarion loam	0.006438	0.000563	91
Corn row, field	0.005298	0.00041	92
No trafficked interrow, field	0.010437	0.002005	81
Trafficked interrow, field	0.032078	0.001206	96
Pooled data for the entire field	0.00955	0.00085	89

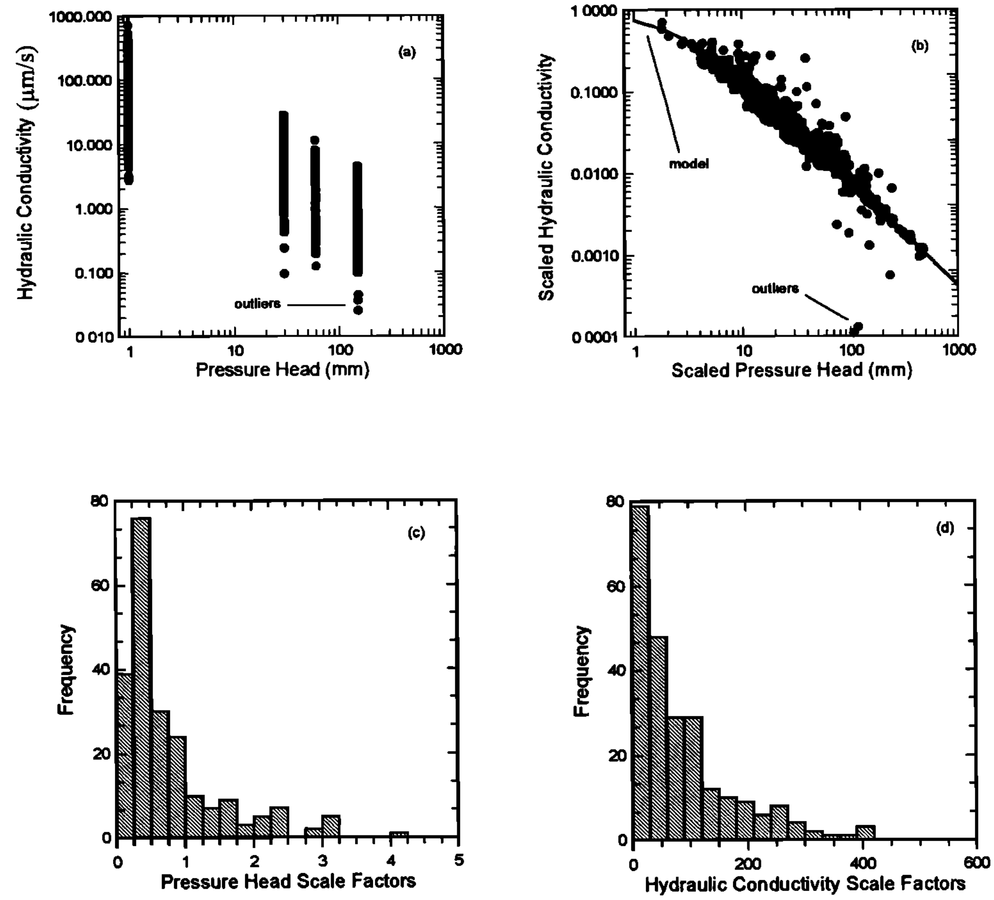

Figure 7. Scaling results for unsaturated hydraulic conductivity $K(h)$, measured under all three field positions and both soil types: (a) raw data, (b) scaled data, (c) histogram of pressure head scale factors, and (d) histogram of hydraulic conductivity scale factors.

The frequency distributions (Figures 2–7) and spatial correlation structure (Figures 8 and 9) of these scale factors (K_{sat} and α) describe variability in the field, thus resulting in considerably simplified and more convenient mathematical description for possible use in modeling the hydrologic behavior of our heterogeneous field site. It should, however, be pointed out that our results are limited to hydraulic conductivity of surface soil. Nevertheless, surface hydraulic conductivity is very important for macroporous soil (as in this case), where macropore area/contribution is generally higher than in deeper horizons. Using the calculated scale factors, we will address field-scale flow and transport modeling in the vadose zone in a follow-up paper.

The results in this paper indicate that near-saturated $K(h)$ data collected using disc infiltrometers in a large field near Boone, Iowa, cutting across different soil types and field positions could be effectively scaled to a reference (Gardner) model using a hybrid of similar media–functional normalization scaling approaches. The significance of this finding is that effective dynamic, kinematic, and geometrical similarities re-

Table 3. Summary Statistics of Pressure Head Scale Factor (α) for Different Soil Types, Field Positions, and the Entire Field

	Treatment*					
Moment	1	2	3	4	5	6
N	71	75	146	50	19	215
Mean α (ln α)	0.788 (−0.486)	0.704 (−0.684)	0.768 (−0.587)	0.694 (−0.832)	1.18 (−0.194)	0.789 (−0.610)
Maximum α	3.00	3.18	3.18	7.21	3.07	7.21
Minimum α	0.113	0.09	0.09	0.07	0.06	0.06
CV for α (ln α), %	84 (163)	95 (117)	90 (136)	155 (103)	78 (513)	104 (138)
W normal† for α (ln α)	0.793 (0.954)	0.737 (0.971)	0.758 (0.965)	0.487 (0.955)	0.878 (0.917)	0.716 (0.979)

CV denotes coefficient of variance.

*Treatments: 1, corn row, Nicollet loam; 2, corn row, Clarion loam; 3, corn row, field; 4, no trafficked interrow, field; 5, trafficked interrow, field; 6, pooled data for the entire field.

†Normality test using the Shapiro-Wilk W statistics.

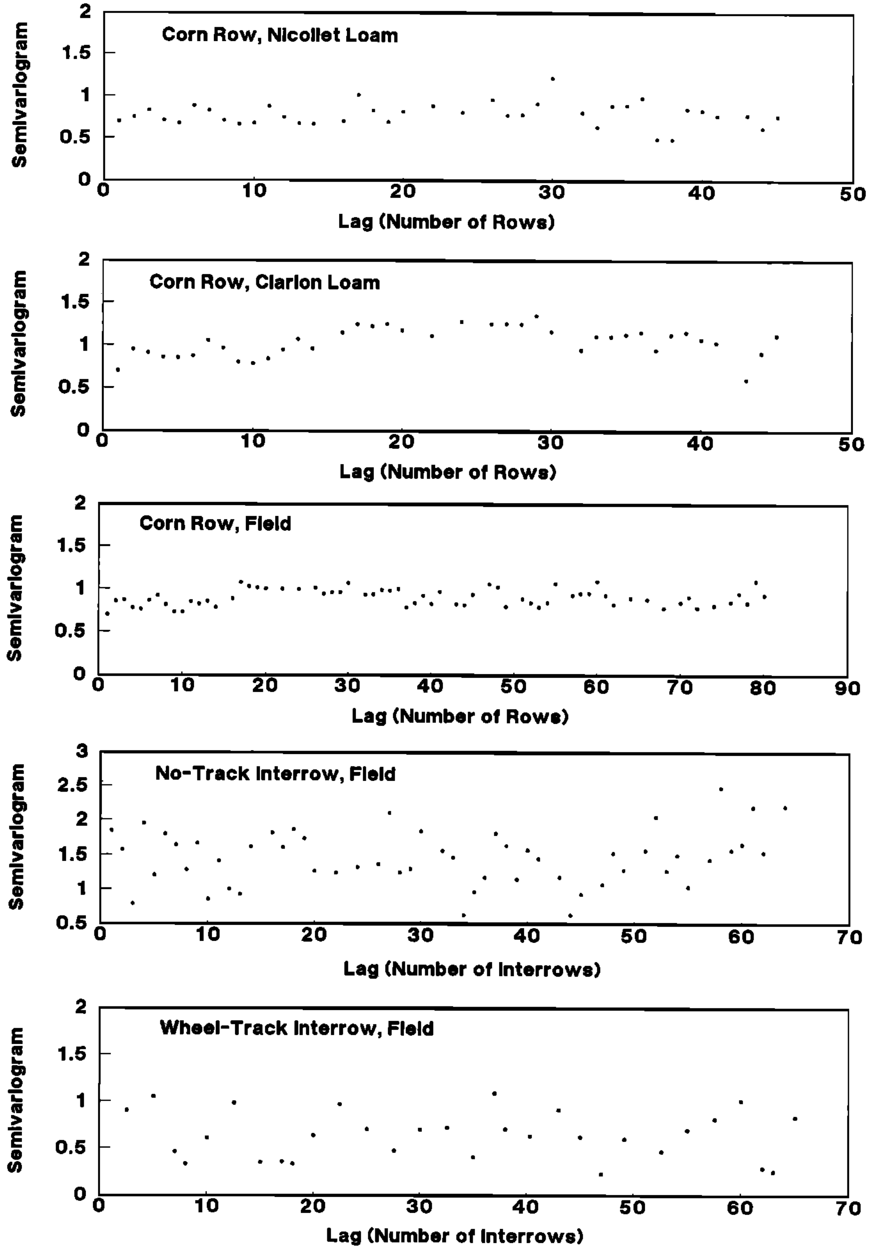

Figure 8. Experimental semivariograms of the log-transformed K scale factors ($\ln K_{sat}$) for different field positions and soil types.

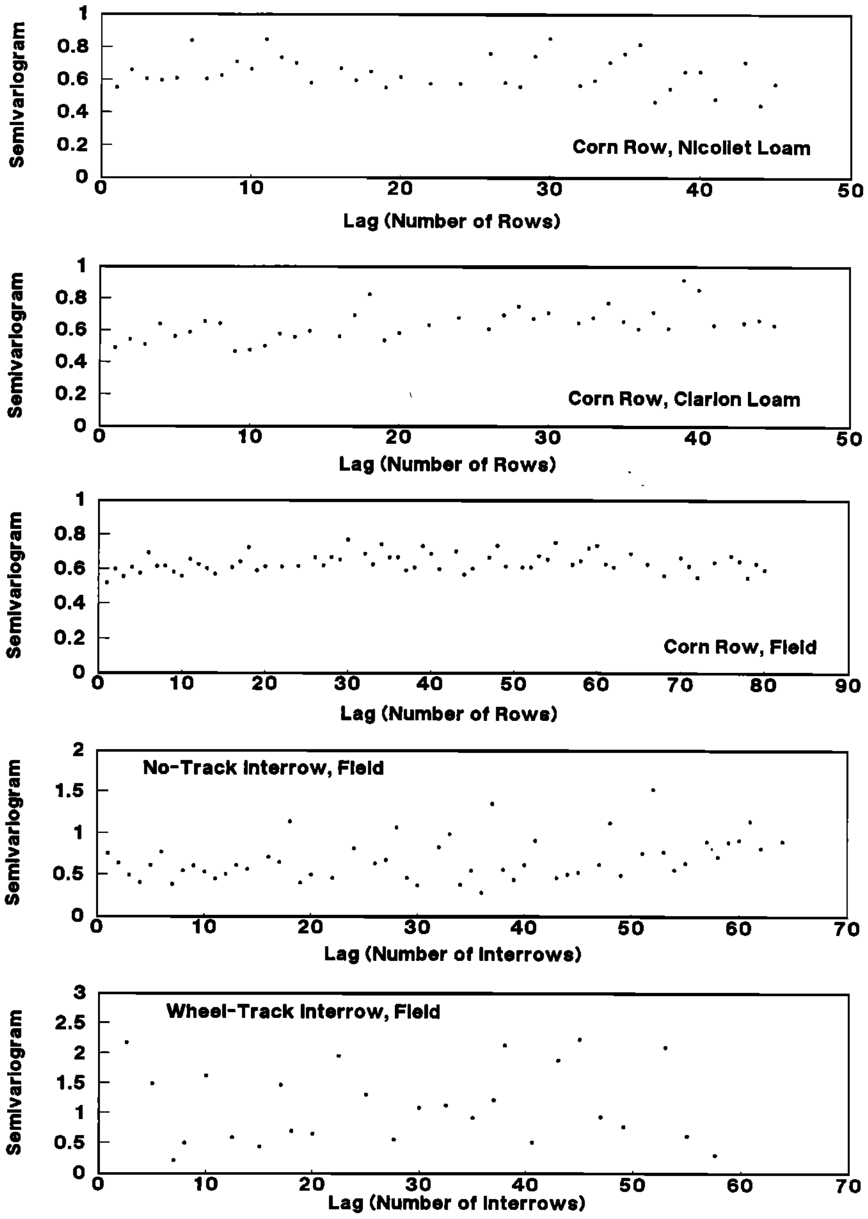

Figure 9. Experimental semivariograms of the log-transformed h scale factors ($\ln \alpha$) for different field positions and soil types.

mained intact in the soil pore system across the field even after human-induced disturbance (e.g., row cropping, wheel traffic). As the disc infiltrometer technique is limited to the near-saturation soil water tension range (e.g., 0 ~ 20 cm), this could be augmented by other methods (e.g., multistep outflow experiment, pressure plate apparatus); using the soil sample right below the disc infiltrometer measurement [e.g., *Mohanty et al.*, 1997] could prove to be a useful technique for covering K for most soil water tension ranges. These characteristics of the soils at our field site (in terms of their particle, pore, and aggregate arrangements) can be used to advantage in field-scale hydrologic modeling by reducing the number of soil hydraulic parameters for describing field-scale heterogeneity.

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