Soil hydraulic conductivity in a non-wheel traffic corn row, a wheel traffic corn row, and a reconstructed prairie

Sitha Ketpratoom
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Soil hydraulic conductivity in a non-wheel traffic corn row, a wheel traffic corn row, and a reconstructed prairie

by

Sitha Ketpratoom

A thesis submitted to the graduate faculty
in partial fulfillment of the requirements for the degree of

MASTER OF SCIENCE

Major: Soil Science (Soil Physics)

Program of Study Committee:
Robert Horton, Major Professor
Robert P. Ewing
Matthew J. Helmers
Sally D. Logsdon

Iowa State University
Ames, Iowa
2014

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Soil hydraulic conductivity is important for liquid flow and transport processes in soil. Its value is affected by factors such as soil texture, soil structure, and porosity. These factors are influenced by plants and by human activities such as tillage and traffic compaction. Our study investigates soil hydraulic conductivity in a non-wheel traffic corn row, a wheel traffic corn row, and a reconstructed prairie. Soil hydraulic conductivity was obtained by steady-state tension infiltration measurements, by numerical inversion of the Richards equation, and with pedotransfer functions. The results show that traffic compaction and vegetation affect soil hydraulic conductivity over a range of water tension. At small water tensions, soil hydraulic conductivity of a non-wheel traffic corn row was largest, followed by prairie and a wheel traffic corn row. However, at relatively large water tension, soil hydraulic conductivity of a wheel traffic corn row was largest followed by prairie and non-wheel traffic corn row. Furthermore, the results also show that pedotransfer functions used in this study are not refined enough to detect the effects of traffic compaction and vegetation. Actual field water flow measurements are needed for accurate estimation of soil hydraulic conductivity.
CHAPTER 1. INTRODUCTION

Hydraulic conductivity is an important soil property. Soil hydraulic conductivity varies between soils, and it varies within soils for different conditions. Benjamin et al. (1990) measured physical properties of soils with and without traffic compaction. Traffic compaction reduced saturated hydraulic conductivity of the soils. Logsdon et al. (1992) reported that soil saturated hydraulic conductivity decreased as compaction axle loads increased. Compaction affects pore sizes and pore connections. Compaction reduces the number of macropores and the mean pore size of a soil. Compaction also affects unsaturated hydraulic conductivity. Andreas et al. (2011) used tension infiltrometers to measure the effects of traffic compaction on unsaturated hydraulic conductivity. Horton et al. (1994) reported some effects of compaction on soil hydraulic conductivity. Even though saturated hydraulic conductivity decreases with compaction, unsaturated hydraulic conductivity may be larger in compacted soil than in non-compacted soil for some range of matric potential values. Actual pore size distribution and macropore connections are also affected by the presence of plant roots. Plant roots may occupy pores and block liquid flow. Rasse et al. (2000) studied saturated hydraulic conductivity of bare fallowed soil and soil with growing alfalfa roots using a constant head method (Klute and Dirksen, 1986). The results show that saturated hydraulic conductivity of soil with alfalfa roots is significantly larger than bare fallowed soil. Li and Ghodrati (1994) used a constant head method on soil cores to measure saturated hydraulic conductivity of soil with alfalfa root channels, soil with corn root channels, and soil with no root channels. The results indicate that soil with both alfalfa and corn root channels have larger saturated hydraulic conductivity than soil with no root channel. However, the differences in saturated hydraulic conductivity between the two root types are not
significant. Jiang et al. (2007) reported saturated hydraulic conductivity of soil under corn, soybean, tall fescue, and hay cropping systems using laboratory constant head measurement. A soil predominantly occupied by tall fescue has larger saturated hydraulic conductivity than the others due to connected biopores and low bulk density. Canqui et al. (2010) measured saturated hydraulic conductivity of soil under cropping systems involving three crops (winter wheat, grain sorghum, and soybean) with and without traffic compaction. They found that cropping systems have small impact on hydraulic conductivity, while traffic wheels have large impact on saturated hydraulic conductivity. Literature reports are consistent on compaction reducing saturated hydraulic conductivity. However, literature reports are not consistent on how roots affect hydraulic conductivity. There is a need to further study hydraulic conductivity in cropping systems, especially using in-situ measurements. This study’s interest is to investigate soil saturated and unsaturated hydraulic conductivity representing three conditions, wheel traffic compacted soil between corn rows, non-wheel traffic soil between corn rows, and prairie.

Only a few methods are available for measuring field soil hydraulic conductivity. One of the challenges in measuring hydraulic conductivity is to have a low-noise measurement with reliable results. The tension infiltrometer is a popular non-destructive method for determining field soil hydraulic conductivity. The instrument is used to measure water infiltration rates into soil at different water tensions. Hydraulic conductivities at the selected water tensions can be estimated from the infiltration data. Steady flow methods for estimating saturated and/or unsaturated hydraulic conductivity from infiltration measurements are presented by Wooding (1968), White and Sully (1987), Ankeny et al. (1991), and Reynolds and Elrick (1991). The steady flow methods for determining hydraulic conductivity are restricted to a relatively narrow range of water tensions. Reynolds and Elrick (1991) reported 0 to 20 cm as an appropriate range
of water tensions for tension infiltrometer measurements. This range of water tensions is small compared to the range of soil water conditions in most agricultural fields.

Another way to determine soil hydraulic conductivity is to use transient water flow data and an entire cumulative infiltration curve for numerical inversion of the Richards equation. Šimůnek and van Genuchten (1996) estimated parameters in the van Genuchten hydraulic property model from infiltration data using numerical inversion of the Richards equation. They concluded that steady infiltration rates at selected water tensions are not enough to represent unique soil properties. Šimůnek and van Genuchten (1997) used numerical inversion of water infiltration data at several water tensions. They found that using data from more than one water tension improved the hydraulic property estimations. Šimůnek et al. (1998) implemented their previous idea on field measurements in a sandy loam soil. Their results showed that estimated cumulative infiltration was in agreement with measured cumulative infiltration, and the numerical inversion method could sufficiently estimate soil hydraulic conductivities. However, water retention curves derived from the numerical inversion method were poorly matched with laboratory measurements on soil cores. Šimůnek et al. (1999) did a laboratory study on the numerical inversion method of infiltrometer data. They used pressure transducers and TDR in a loamy sand soil and performed infiltrometer measurements at several water tensions. Cumulative infiltration, pressure potential, and water content data at several water tensions were used for parameter estimation. Numerical inversion results corresponded well to the observed data. The results showed that estimated hydraulic conductivity was in agreement with unsaturated hydraulic conductivity obtained from the Wooding (1968) analysis and from the evaporation analysis of Wind (1968). Our objective is to further test the numerical inversion technique on infiltration measurements made in additional cropping systems.
The inversion method provides soil hydraulic conductivity for a full range of water tensions, which is a wider set of hydraulic conductivities than the steady flow method. However, the inversion method requires a whole day of measurements at each location, and compared to the steady flow method it requires a number of instruments (tensiometers and/or soil water content sensors). A method that requires few resources and relatively small effort to determine hydraulic conductivity is that of pedotransfer functions (PTF). The general idea of a pedotransfer function is to estimate complicated soil physical properties by using basic soil physical properties. Typical properties needed are soil bulk density, soil organic matter, and soil texture. Pedotransfer functions can estimate Brooks and Corey (1964) model parameters and van Genuchten (1980) model parameters. Brooks and Corey (1964) expressed a relationship between hydraulic conductivity and capillary pressure with a power law function. van Genuchten (1980) developed a hydraulic property model based on the Mualem (1976) pore-size model. The pedotransfer functions examined in this study include Rawls et al. (1983), Rawls and Brakensiek (1985), Saxton et al. (1986), Wösten et al. (1999), and Schaap et al. (2001).

The objectives of this study are to compare saturated and unsaturated hydraulic conductivities of non-wheel traffic soil between corn rows, wheel traffic compacted soil between corn rows, and prairie soil. We also compare soil hydraulic conductivity estimated by inverse transient flow method and pedotransfer functions to the tension infiltrometer steady flow method. We hypothesize that, at small water contents, soil under corn with traffic compaction management will have larger hydraulic conductivity than soil under corn receiving no wheel traffic. Compared to the two corn conditions, soil under prairie field is expected to have larger hydraulic conductivity due to availability of biopores created by plant roots. We also hypothesize that the steady flow method, inverse transient flow method, and the pedotransfer functions will
provide unique hydraulic conductivity results for each soil condition due to the impacts of soil management zones and cropping systems. However, we expect that the results of the pedotransfer functions will differ from the results of the other two methods, because pedotransfer functions do not include influences of crop roots and wheel traffic compaction on water flow at the specific locations.
CHAPTER 2. THEORY

1. Steady flow method

There are several procedures capable of estimating soil hydraulic conductivity from tension infiltration measurements. The Ankeny et al. (1991) method is a simple method that generally well-represents soil hydraulic conductivities. The method is based on Wooding’s (1968) solution for water infiltration from a circular pond:

\[ Q = \pi r^2 K(\psi) + 4r \phi(\psi) \]  

where \( Q \) is steady state infiltration (cm\(^3\)/s), \( r \) is radius of the circular pond (cm), \( K(\psi) \) is hydraulic conductivity (cm/s) at a surface matric potential \( \psi \), and \( \phi(\psi) \) is the matrix flux potential (cm\(^2\)/s) given by Gardner (1958):

\[ \phi(\psi) = \int_{\psi_i}^{\psi} K(\psi) \, d\psi \]  

Hydraulic conductivity is assumed to have an exponential relationship with soil water matric potential:

\[ K(\psi) = K_s e^{\alpha \psi} \]  

where \( K_s \) is saturated hydraulic conductivity, and \( \alpha \) is a constant defining the shape of the exponential curve.

If water infiltration measurements are performed at two different water tensions, Eq. (1) will have four unknown parameters: \( K(\psi_1), K(\psi_2), \phi(\psi_1), \) and \( \phi(\psi_2) \). Ankeny et al. (1991) assumed the ratio of \( K(\psi)/\phi(\psi) \) to be a constant, \( A \), throughout the range of measured pressure potentials, so that the number of unknown parameters is reduced to three: \( K(\psi_1), K(\psi_2), \) and \( A \) (Eq. (4) and (5)).
Given the definition of matrix flux potential in Eq. (2) and the hydraulic conductivity relationship in Eq. (3), the difference between matrix flux potential at two different matric potentials is:

\[ \phi(\psi_1) - \phi(\psi_2) = \int_{\psi_2}^{\psi_1} K(\psi) \, d\psi = \int_{\psi_2}^{\psi_1} K_s e^{\alpha \psi} \, d\psi = \frac{K(\psi_1) - K(\psi_2)}{\alpha} \]

The constant \( \alpha \) is a ratio between \( K(\psi_1) - K(\psi_2) \) and \( \phi(\psi_1) - \phi(\psi_2) \), so we can use \( \alpha \) to estimate the constant \( A \). According to the exponential hydraulic conductivity function (Eq. (3)), \( \alpha \) can be calculated if the hydraulic conductivity is known at two matric potentials:

\[ \alpha = \frac{\ln \left( \frac{K(\psi_1)}{K(\psi_2)} \right)}{\psi_1 - \psi_2} \approx A \]

Since hydraulic conductivity at a certain matric potential has a linear relationship with steady state infiltration rate (Eq. (4) and (5)), the constant \( A \) can be estimated:

\[ A \approx \frac{\ln \left( \frac{Q(\psi_1)}{Q(\psi_2)} \right)}{\psi_1 - \psi_2} \]

Once \( A \) is known, \( K(\psi_1) \) and \( K(\psi_2) \) can be calculated with Eqs. (4) and (5).

2. Transient flow method

The Richards equation in cylindrical coordinates is expressed by Warrick (1992) as:

\[ Q(\psi_1) = \left( \pi r^2 + \frac{4r}{A} \right) K(\psi_1) \]

\[ Q(\psi_2) = \left( \pi r^2 + \frac{4r}{A} \right) K(\psi_2) \]
\[
\frac{\partial \theta}{\partial t} = \frac{1}{r} \frac{\partial}{\partial r} \left( rK \frac{\partial h}{\partial r} \right) + \frac{\partial}{\partial z} \left( K \frac{\partial h}{\partial z} \right) + \frac{\partial K}{\partial z} \quad (9)
\]

where \( r \) is radial distance and \( z \) is vertical depth. The unsaturated hydraulic conductivity \( K \) is related to two dependent variables, volumetric water content \( \theta \) and a pressure head \( h \). Eq. (9) can be approximated by discretizing space and time variables as:

\[
\frac{\theta_{r,z,t+1} - \theta_{r,z,t}}{\Delta t} = \frac{1}{r} \frac{\partial}{\partial r} \left( rK \frac{h_{r+1,z,t} - h_{r,z,t}}{\Delta r} \right)_{r+1,z,t} - \frac{\partial}{\partial z} \left( K \frac{h_{r,z+1,t} - h_{r,z,t}}{\Delta z} \right)_{r,z,t} + \frac{K_{r,z+1,t} - K_{r,z,t}}{\Delta z} 
\]

(10)

If water content and pressure head are measured for particular initial and boundary conditions, inverse solutions of Eq. (9) and (10) yield \( K \) that provides the best match of Richards equation to all \( \theta \) and \( h \) throughout time, depth, and radius. In order to find the \( K \) that gives the best match, we need to assume relationships between \( \theta \) and \( h \) for soil hydraulic property functions. The functions used in this study are the van Genuchten – Mualem models:

\[
S_o = \frac{\theta - \theta_r}{\theta_s - \theta_r} = \frac{1}{(1 + |\alpha h|^n)^m}
\]

(11)

\[
K = K_s \left( \frac{\theta - \theta_r}{\theta_s - \theta_r} \right)^l \left\{ 1 - \left[ 1 - \left( \frac{\theta - \theta_r}{\theta_s - \theta_r} \right)^{1/m} \right]^m \right\}^2
\]

(12)

where \( K_s \) is saturated hydraulic conductivity, \( l \) is a pore connectivity parameter, \( \theta_r \) is residual water content, \( \theta_s \) is saturated water content, and \( \alpha, n, \) and \( m (= 1 - 1/n) \) are empirical shape parameters. The six parameters (\( \theta_r, \theta_s, \alpha, n, K_s, l \)) are model characterized soil hydraulic properties. These parameters can be determined by using least squares curve fitting:

\[
\Phi(\theta_r, \theta_s, \alpha, n, K_s, l) = \sum_{i=1}^{x} \sum_{j=1}^{y} w_{ij} \left[ q_i^* - q_i(\theta_r, \theta_s, \alpha, n, K_s, l) \right]^2
\]

(13)
where \( x \) is the number of measurement sets (\( x = 2 \) for infiltration and pressure potential measurement), \( y \) is the number of measurements in a set (\( y = 2000 \) data points for example), \( q_i \) are measured data, \( q_i(\theta_r, \theta_s, \alpha, n, K_s, l) \) are model predictions, and \( v_j \) and \( w_{ij} \) are weights of measurement sets and weights of measured points, respectively. \( \Phi \) is sum of squared errors of the \( q_i \) function. Parameter fitting begins with initially guessed values for the six parameters which yield \( \Phi \). The six parameters are optimized to produce the smallest \( \Phi \). The parameter fitting can be done by the program HYDRUS (2D/3D) (PC-Progress s.r.o., Korunni, Prague, Czech Republic) developed by Šimůnek et al. (1999). HYDRUS (2D/3D) software uses the Levenberg-Marquardt algorithm to determine an optimum value for each parameter by minimizing the sum of squared errors \( \Phi \). The set of parameters \( \theta_r, \theta_s, \alpha, n, K_s, l \) that yields the lowest \( \Phi \) is the estimated parameter set of the soil.

3. Pedotransfer functions

Two water retention models were used, those of van Genuchten (1980) and Brooks and Corey (1964). The van Genuchten model is shown in Eq. (11). The Brooks and Corey (1964) relationship between water content, \( \theta \), and water tension, \( h \), is:

\[
S_e = \frac{\theta - \theta_r}{\phi - \theta_r} = \left(\frac{h_b}{h}\right)^\lambda, \quad h > h_b
\]
\[
= 1, \quad h \leq h_b
\]

where \( \theta_r \) is residual water content, \( \phi \) is soil porosity, \( h_b \) is air-entry pressure, and \( \lambda \) is a pore size distribution parameter. Parameters in these two models can be used to estimate soil hydraulic conductivity. van Genuchten soil hydraulic conductivity is calculated using Eq. (12). The Brooks and Corey soil hydraulic conductivity is defined as:
Water retention parameters can be obtained by fitting Eqs. (11) and (14) to water content and water tension data. Another approach to estimate soil hydraulic parameters is to use basic soil properties such as soil texture and soil bulk density with a pedotransfer function. Pedotransfer functions used in this study include Rawls et al. (1983), Rawls and Brakensiek (1985), Saxton et al. (1986), Wösten et al. (1999), and Schaap et al. (2001).

### 3.1 Rawls et al. (1983)

Rawls et al. (1983) used a USA nationwide soil survey database to develop equations to estimate soil water content at 12 water tensions with percent sand, percent clay, organic matter content, and bulk density of the soil. The equation is: \( \theta = a + b \cdot \text{sand} + c \cdot \text{clay} + d \cdot \text{OC} + e \cdot \rho_b \).

Table 1 shows coefficients for Rawls et al. (1983) values at each water tension.

<table>
<thead>
<tr>
<th>h(cm)</th>
<th>a</th>
<th>b</th>
<th>c</th>
<th>d</th>
<th>e</th>
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<tr>
<td>200</td>
<td>0.4180</td>
<td>-0.0021</td>
<td>0.0035</td>
<td>0.0232</td>
<td>-0.0859</td>
</tr>
<tr>
<td>330</td>
<td>0.3486</td>
<td>-0.0018</td>
<td>0.0039</td>
<td>0.0228</td>
<td>-0.0768</td>
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<tr>
<td>600</td>
<td>0.2819</td>
<td>-0.0014</td>
<td>0.0042</td>
<td>0.0216</td>
<td>-0.0612</td>
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<tr>
<td>1000</td>
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<td>0.0043</td>
<td>0.0202</td>
<td>-0.0517</td>
</tr>
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<td>2000</td>
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<td>4000</td>
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<td>-0.0007</td>
<td>0.0045</td>
<td>0.0160</td>
<td>-0.0315</td>
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<td>7000</td>
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<td>-0.0005</td>
<td>0.0045</td>
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<td>-0.0004</td>
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<td>15000</td>
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<td>-0.0004</td>
<td>0.0044</td>
<td>0.0122</td>
<td>-0.0182</td>
</tr>
</tbody>
</table>

Table 1: Coefficients for the Rawls et al. (1983) pedotransfer function.

Using the 12 pairs of \((\theta, h)\) from Rawls et al. (1983), van Genuchten parameters can be estimated through parameter fitting.
3.2 Rawls and Brakensiek (1985)

Rawls and Brakensiek (1985) developed equations to estimate Brooks-Corey parameters using USA nationwide soils:

\[ h_b = \exp(5.34 + 0.185clay - 2.484\phi - 0.002clay^2 - 0.044sand\phi + 0.001sand^2\phi^2 \\
- 0.009clay^2\phi^2 - 0.00001sand^2clay + 0.009clay^2\phi - 0.0007sand^2\phi \\
+ 0.000005clay^2sand \\
+ 0.500\phi^2clay) \]  

\( (16) \)

\[ \lambda = \exp(-0.784 + 0.018sand - 1.062\phi - 0.00005sand^2 - 0.003clay^2 + 1.111\phi^2 \\
- 0.031sand\phi + 0.0003sand^2\phi^2 - 0.006clay^2\phi^2 - 0.000002sand^2clay \\
+ 0.008clay^2\phi - 0.007\phi^2clay) \]  

\( (17) \)

\[ \theta_r = -0.048 + 0.0009sand + 0.005clay + 0.029\phi - 0.0002clay^2 - 0.001sand\phi \\
- 0.0002clay^2\phi^2 + 0.0003clay^2\phi - 0.002\phi^2clay \]  

\( (18) \)

where \( sand, silt, clay \) are mass percents of sand, silt, and clay in soil, respectively, and \( \phi \) is soil porosity.

3.3 Saxton et al. (1986)

Saxton et al. (1986) developed pedotransfer functions based on USA nationwide soils. If Eq. (14) is written in the form \( h = A\theta^B \), Saxton et al. (1986) estimated the parameters \( A \) and \( B \) to be:

\[ A = 100\exp(-4.396 - 0.0715clay - 0.000488sand^2 - 0.00004285sand^2clay) \]  

\( (19) \)

\[ B = -3.140 - 0.00222clay^2 - 0.00003484sand^2clay \]  

\( (20) \)

where \( sand \) is percent sand, and \( clay \) is percent clay of the soil.
3.4 Wösten et al. (1999)

Wösten et al. (1999) used European soils to develop pedotransfer functions estimating van Genuchten parameters. Input data for Wösten et al. (1999) functions are percent silt, percent clay, percent organic matter, bulk density, and depth of the soil.

\[
\theta_s = 0.7919 + 0.001691 \text{clay} - 0.29619 \rho_b - 0.000001491 \text{silt}^2 + 0.0000821 OM^2 \\
+ \frac{0.02427}{\text{clay}} + \frac{0.01113}{\text{silt}} + 0.01472 \ln(\text{silt}) - 0.0000733 OM \text{clay} \\
- 0.000619 \rho_b \text{clay} - 0.001183 \rho_b OM - 0.0001664 \text{topsoil} \cdot \text{silt} 
\] (21)

\[
\alpha = \exp \left( -14.96 + 0.03135 \text{clay} + 0.0351 \text{silt} + 0.646 OM + 15.29 \rho_b - 0.192 \text{topsoil} \\
- 4.671 \rho_b^2 - 0.000781 \text{clay}^2 - 0.00687 OM^2 + \frac{0.0449}{OM} + 0.0663 \ln(\text{silt}) \\
+ 0.1482 \ln(OM) - 0.04546 \rho_b \text{silt} - 0.4852 \rho_b OM + 0.00673 \text{topsoil} \\
\cdot \text{clay} \right) 
\] (22)

\[
n = 1 + \exp \left( -25.23 - 0.021995 \text{clay} + 0.0074 \text{silt} - 0.1940 OM + 45.5 \rho_b - 7.24 \rho_b^2 \\
+ 0.0003658 \text{clay}^2 + 0.002885 OM^2 - \frac{12.81}{\rho_b} - \frac{0.1524}{\text{silt}} - \frac{0.01958}{OM} \\
- 0.2876 \ln(\text{silt}) - 0.0709 \ln(OM) - 44.6 \ln(\rho_b) - 0.02264 \rho_b \text{clay} \\
+ 0.0896 \rho_b OM + 0.00718 \text{topsoil} \cdot \text{clay} \right) 
\] (23)

where \text{sand, silt, clay} are percent of sand, silt, and clay in soil, respectively. \(\rho_b\) is bulk density. \(OM\) is organic matter content. \text{topsoil} is an ordinal variable having the value of 1 or 0. Wösten et al. (1999) classify their pedotransfer functions by layer/horizon to be \text{topsoil} and \text{subsoil}.

The pedotransfer function uses 1 for \text{topsoil} and 0 for \text{subsoil}.
3.5 Schaap et al. (2001)

Schaap et al. (2001) developed a program, ROSETTA, estimating van Genuchten parameters. The program has different levels of parameter estimation depending on input data as follows:

- Soil textural classes
- Sand, silt, clay percentages
- Sand, silt, clay percentages and bulk density
- Sand, silt, clay percentages, bulk density, and water retention value at 330 cm
- Sand, silt, clay percentages, bulk density, and water retention values at 330 and 15000 cm

More input data should lead to greater accuracy in estimated properties.
CHAPTER 3. MATERIALS AND METHODS

1. Study area

The study area was located in Boone County, IA, USA (41°55′N, 93°45′W) at the Iowa State University COBS (Comparison Of Biofuel Systems) research site. Soil at the site is classified as Clarion soil (fine-loamy, mixed, superactive, mesic Typic Hapludoll). Study areas used for measurements are traffic compacted soil and non-traffic compacted soil in a corn field, and soil in a prairie field. The corn field has a 2-year rotation of corn and soybean. The prairie area is a combination of various species of prairie with no fertilizer applied. The cropping systems have been used since 2008. Infiltration measurements were performed after fall harvest in 2012.

2. Field measurements

2.1 Infiltrometer

A drawing of the tension disk infiltrometer is shown in Fig. 1. The infiltrometer consists of a bubble tower, a Mariotte column, and a soil contact base. The bubble tower is used to control water tension via adjustment of an air entry port. The Mariotte column supplies water for infiltration. The soil contact base is a circular disk used to distribute water from the Mariotte column to the soil. Diameters of the Mariotte column and the soil contact base are 5 and 25.5 cm, respectively.
Figure 1: Diagram of a tension infiltrometer. Figure from Ankeny et al. (1988).
Pressure transducers are positioned in the Mariotte column to measure pressure at the top and bottom of the column. Water level in the Mariotte column is directly related to the difference between the top and the bottom pressure, thus water infiltration with time can be measured by connecting the transducers to a data logger. A Campbell 21X data logger was used for the measurements (Campbell Scientific Inc., North Logan, Utah). The pressure transducers were calibrated in our lab with a manometer at pressures between 0 and 300 cm of water. Voltage outputs have a linear relationship with pressures applied to the transducers with $R^2 \geq 0.9999$.

### 2.2 Tensiometers

Tensiometers were inserted into soil beneath the infiltrometers at depths of 5 cm and 7 cm, and at a distance from the center equal to the radius of the infiltrometer contact base. Pressure transducers used on the tensiometers were connected to the data logger. Soil matric potential was measured simultaneously with each infiltration measurement. Data were collected every 5 seconds.

### 3. Laboratory measurements

One or two days after ceasing infiltration measurements, undisturbed soil cores and disturbed soil samples were collected at each measured site. Soil cores were 7.6 cm in diameter and 7.6 cm high. Undisturbed soil cores were brought to the laboratory to measure soil saturated hydraulic conductivity, soil water retention, and soil bulk density. Disturbed soil samples were used to measure soil particle size distribution and soil organic matter content.

The soil cores were water saturated in a vacuum chamber before making saturated hydraulic conductivity measurements. The $K_s$ was measured by a constant head method (Klute
and Dirksen, 1986). After constant head measurements were finished, soil cores were placed into pressure chambers for water retention measurements. Soil water content was measured at pressures of 0, 6, 13, 20, 50, 100, 200, 330, and 500 cm of water. Disturbed soil samples were also used to determine soil water contents at 5000 and 9000 cm of water using pressure plate measurements. After finishing the pressure chamber measurements, soil cores were oven-dried at 110 °C to determine water content and soil bulk density. Disturbed soil samples were used to measure soil texture by sieving and pipette methods. Soil organic matter contents were obtained by the loss on ignition method (Konen et al., 2002).

4. Soil hydraulic conductivity estimation

4.1 Field steady flow method

Soil water infiltration was measured at tensions of 0, 3, 6, and 15 cm of water. The first water tension used in the study was 0 cm followed by 3, 6, and 15 cm. Infiltration times at 0, 3, and 6 cm tensions were 20-60 minutes. For the 15 cm tension, the infiltration time was 1-2 hours or greater. Three replications of infiltration were made for each soil condition at 0, 3, and 6 cm. Infiltration at 15 cm water tension was not done at every measurement site because of the large infiltration times. Thus, at 15 cm tension there are two replications for the corn treatments, and one replication for prairie.

The Ankeny et al. (1991) approach was used to determine soil hydraulic conductivity using steady infiltration rates at each water tension. Since the saturated hydraulic conductivity can be estimated from two steady state infiltration rates and there are four infiltration rates (0, 3, 6, and 15 cm water) in the calculation, we calculate average hydraulic conductivity from two adjacent results. For example, we used steady state infiltration rates at 0 and 3 cm to calculate
soil hydraulic conductivity at the 3 cm water tension. Then we calculated another soil hydraulic conductivity value at 3 cm with the steady state infiltration rates at 3 and 6 cm water tensions. The two values for 3 cm were averaged to provide the soil hydraulic conductivity at 3 cm.

### 4.2 Field transient flow method

The 2D axisymmetric flow domain was set to 50 by 50 cm$^2$. The calculation was done using a rectangular finite element mesh. The domain was discretized into 17 horizontal layers and 17 vertical sections as shown in Fig. 2.

![Figure 2: Domain layers.](image)

The matric potentials used for parameter fitting are either matric potential at the 5 cm depth (Node 1) or at the 7 cm depth (Node 2). Nodes labeled 3 are positions where water flowed
from the infiltrometer into the soil. The layers are concentrated at the top of the soil profile and at a distance where tensiometers are placed to enhance the effectiveness of the calculations. The smaller and more numerous the elements, the longer the calculation time. The bottom layer was set to have free drainage, and the left and right vertical boundaries were set to have no flux. The top layer was separated into two parts: a variable head boundary where infiltration occurs and an atmospheric boundary where no infiltration occurred.

The initial condition is the pressure head reading of the transducer at the beginning of the measurement. Six parameters of the van Genuchten – Mualem model, $\theta_r$, $\theta_s$, $\alpha$, $n$, $K_s$, $l$, were fitted. The matric potential readings that represented water flow for the current boundary heads were included in the inverse analysis.

4.3 Pedotransfer functions

Soil properties were estimated by the ROSETTA program from Schaap et al. (2001), and CalcPTF from Guber and Pachepsky (2010). Input data for ROSETTA are percentages of sand, silt, and clay, plus soil bulk density and soil water content at 330 cm of water tension. Input data for CalcPTF are soil bulk density, soil organic matter, depth of the soil, and percentages of sand, silt, and clay. Results from ROSETTA are parameters in the Mualem – van Genuchten model including $K_o$, the empirical matching saturated hydraulic conductivity. Results from CalcPTF are parameters in the Mualem – van Genuchten model and the Brooks – Corey model (1964). CalcPTF uses the Wösten et al. (1999) and Rawls et al. (1983) functions to estimate the parameters in the Mualem – van Genuchten model. Pairs of water content and water tension from Rawls et al. (1983) were fitted with a FORTRAN code (VGpar.for) in CalcPTF. CalcPTF also uses Saxton et al. (1986) and Rawls and Brakensiek (1985) functions to estimate the Brooks –
Corey model parameters. CalcPTF does not estimate $K_s$ for the Mualem – van Genuchten hydraulic conductivity equation. Thus, for these parameters, we used the laboratory-measured $K_s$ to estimate unsaturated hydraulic conductivity.
CHAPTER 4. RESULTS AND DISCUSSION

1. Steady flow method

At the 0 cm water tension, soil in the corn field without wheel traffic had the highest steady-state infiltration rates, while the soil receiving traffic compaction had the lowest steady-state infiltration rates. There were several visible macropores in the measured infiltration areas of the non-wheel traffic soils, but almost no pores were visible in the wheel traffic areas. The zero tension infiltration rates of prairie soil were intermediate to those of the non-wheel traffic and wheel traffic soils. A probable reason that prairie soil did not have the larger infiltration rate is that plant roots blocked some of the soil pores hindering water movement. A distinguishing characteristic of the prairie soil was that many plant roots were present near the soil surface. The average root mass of the prairie soils in the top 5 cm in 2012 was 3.6 Mg/ha, while the average root mass of the soils from the corn field was 0.1 Mg/ha (Dietzel and Liebman, 2014).

Representative cumulative infiltrations for 0 cm of water tension are shown in Fig. 3. The cumulative infiltrations at 0 cm imply that plant roots and wheel traffic compaction affect water movement in these soils.

At 3 cm water tension, infiltration rates of all of the soils were less than at 0 cm water tension. The non-wheel traffic soil still had the highest infiltration rate, followed by the prairie soil and the wheel traffic soil. Fig. 4 shows the cumulative infiltration at 3 cm water tension. One of the non-traffic wheel soils and one of the prairie soils had about the same cumulative infiltration as the the 3 cm tension wheel traffic values.
At 6 cm water tension, the values of the cumulative infiltration of each soil were quite similar. They can be separated into three groups, the larger, the intermediate, and the smaller cumulative infiltrations, as they appear in Fig. 5. The soils with no wheel traffic compaction belong to the larger and the intermediate cumulative infiltrations for 6 cm tension. The wheel
traffic soils and the prairie soils were observed in all of the three groups. Differences in cumulative infiltrations between each system are not obvious at the 6 cm water tension.

Figure 5: Cumulative infiltration at 6 cm water tension.

At the 15 cm water tension, cumulative infiltrations of the soils were similar. Fig 6 shows the cumulative infiltration of the soils at 15 cm water tension. The plot shows fluctuations due to bubbling occurring in the infiltrometer. It is notable that one of the wheel traffic soils had the largest cumulative infiltration within the 15 cm tension measurement. Moreover, prairie soils seem to have the smallest cumulative infiltration at this tension. Cumulative infiltration at the 6 cm and 15 cm water tension for the soils were more similar than they were at 0 cm and 3 cm water tension. The pore sizes that primarily contribute to water flow at the 6 cm and 15 cm water tension are not the same as the pore sizes that primarily contribute to water flow at the 0 cm and 3 cm water tensions, because water will not fill a large pore at high water tension.
Hydraulic conductivities calculated from the measured infiltration rates were analyzed in statistical program JMP (JMP 11.0.0, Statistical Analysis Systems, Cary, NC). According to the analysis, soil hydraulic conductivity at 0, 3, and 6 cm water is log-normally distributed. The 15 cm tension has not enough information for the analysis. The results are displayed in Fig. 7. The error bar is standard deviation of the data. Average hydraulic conductivity at 0 cm water tension of the non-wheel traffic soil is more than 15 times larger than the wheel traffic soil, and is more than 6 times larger than the prairie soil. Hydraulic conductivities of the wheel traffic soils and non-wheel traffic soil at 15 cm water tension are not significantly different, while one of the prairie soils had lower hydraulic conductivities compared to other treatments. The results indicate that traffic compaction and prairie roots affect soil hydraulic conductivity.
2. Transient flow method

Figs. 8 and 9 show matric potential and cumulative infiltration at each soil location. Matric potential readings for the non-wheel traffic corn corresponded well to the infiltration data. Estimated cumulative infiltration and matric potential matched well with the measured cumulative infiltration and matric potential. However, not all of the soil located in area of traffic corn and in prairie showed agreement between measured cumulative infiltration and measured matric potential. Wheel traffic corn 2 and prairie 3 had small matric potential relative to cumulative infiltration (Fig. 8 (e) and (i)). An explanation for this result is either there was measurement error or that there was non-uniform flow due to soil heterogeneity. The problem resulted in unrealistic parameter estimations. Table 2 shows the estimated van Genuchten–Mualem parameters for each soil and laboratory measured saturated hydraulic conductivity.
Parameter estimation simulations for wheel traffic corn 2 and prairie 3 did not converge to the matric potential inputs.

<table>
<thead>
<tr>
<th>soils</th>
<th>$\theta_r$</th>
<th>$\theta_s$</th>
<th>$\alpha$ (1/cm)</th>
<th>$n$</th>
<th>$l$</th>
<th>$K_s$ (cm/s)</th>
<th>lab $K_s$ (cm/s)</th>
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</thead>
<tbody>
<tr>
<td>non wheel traffic corn 1</td>
<td>0</td>
<td>0.5</td>
<td>0.163</td>
<td>1.3</td>
<td>-2.25</td>
<td>0.0084</td>
<td>0.0058</td>
</tr>
<tr>
<td>non wheel traffic corn 2</td>
<td>0</td>
<td>0.5</td>
<td>0.396</td>
<td>1.6</td>
<td>-1.79</td>
<td>0.0171</td>
<td>0.0094</td>
</tr>
<tr>
<td>non wheel traffic corn 3</td>
<td>0</td>
<td>0.6</td>
<td>0.287</td>
<td>1.46</td>
<td>-0.55</td>
<td>0.0134</td>
<td>0.0109</td>
</tr>
<tr>
<td>wheel traffic corn 1</td>
<td>0</td>
<td>0.5</td>
<td>0.131</td>
<td>1.41</td>
<td>-5.42</td>
<td>0.0008</td>
<td>0.0053</td>
</tr>
<tr>
<td>wheel traffic corn 2</td>
<td>NC</td>
<td>NC</td>
<td>NC</td>
<td>NC</td>
<td>NC</td>
<td>NC</td>
<td>0.0026</td>
</tr>
<tr>
<td>wheel traffic corn 3</td>
<td>0</td>
<td>0.5</td>
<td>0.154</td>
<td>1.31</td>
<td>-5.82</td>
<td>0.0004</td>
<td>0.0052</td>
</tr>
<tr>
<td>prairie 1</td>
<td>0.01</td>
<td>0.47</td>
<td>0.077</td>
<td>1.48</td>
<td>-0.01</td>
<td>0.0017</td>
<td>0.0083</td>
</tr>
<tr>
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<td>0.5</td>
<td>0.194</td>
<td>1.36</td>
<td>-5.44</td>
<td>0.0028</td>
<td>0.0051</td>
</tr>
<tr>
<td>prairie 3</td>
<td>NC</td>
<td>NC</td>
<td>NC</td>
<td>NC</td>
<td>NC</td>
<td>NC</td>
<td>0.0051</td>
</tr>
</tbody>
</table>

Table 2: Estimated soil hydraulic parameters. NC: no convergence.

Estimated hydraulic conductivities were in agreement with the Ankeny et al. (1991) hydraulic conductivity values. Fig. 10 shows the estimated hydraulic conductivity using numerical inversion and Ankeny et al. (1991) method for each treatment.
Figure 8: Measured and estimated pressure potential of each soil. (a), (b), and (c) represent non-wheel traffic corn 1, 2, and 3 respectively. (d), (e), and (f) represent wheel traffic corn 1, 2, and 3 respectively. (g), (h), and (i) represent prairie 1, 2, and 3 respectively.
Figure 9: Measured and estimated cumulative infiltration of each soil. (a), (b), and (c) represent non-wheel traffic corn 1, 2, and 3 respectively. (d), (e), and (f) represent wheel traffic corn 1, 2, and 3 respectively. (g), (h), and (i) represent prairie 1, 2, and 3 respectively.
Figure 10: Soil hydraulic conductivity using numerical inversion and Ankeny et al. (1991) method for (a) non-wheel traffic corn, (b) wheel traffic corn, and (c) prairie.
For wheel traffic corn and prairie, agreement between the inverse method and the Ankeny et al. (1991) method was not as good as for non-wheel traffic corn. Saturated hydraulic conductivity of the wheel traffic corn 2 and prairie 3 did not match as well compared to the non-wheel traffic site. The poor matches may be due to abnormalities in the matric potential reading. The numerical soil was assumed to be homogeneous. However, the actual field soil may not be homogeneous. Soil in the traffic area may not have received uniform compression. Soil under the prairie may not have the same root distribution over the entire volume. The heterogeneity of the soil may cause water infiltration to be non-uniform, resulting in non-uniform matric potential readings and non-representative inverse calculations.

At low tensions, non-wheel traffic corn tended to have larger saturated hydraulic conductivity than the other two treatments. However, at higher water tensions, wheel traffic corn had larger hydraulic conductivity than the non-wheel traffic corn (Fig. 11).

![Figure 11: Soil unsaturated hydraulic conductivity of non-wheel traffic corn, wheel traffic corn, and prairie using numerical inversion method.](image-url)
3. Pedotransfer functions

Laboratory measured soil properties are shown in Table 3. Although soil texture is similar at all locations, there are major differences in soil bulk density. Non-wheel traffic corn has the smallest soil bulk density. Prairie bulk density is smaller than wheel traffic corn, but larger than non-wheel traffic corn. Bulk density is related inversely to saturated hydraulic conductivity.

<table>
<thead>
<tr>
<th>soils</th>
<th>%sand</th>
<th>%silt</th>
<th>%clay</th>
<th>%OM</th>
<th>BD (g/cm³)</th>
<th>Porosity (cm³/cm³)</th>
<th>θ@330 cm of water</th>
<th>Ks (cm/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>non wheel traffic corn 1</td>
<td>47</td>
<td>33</td>
<td>20</td>
<td>5.07</td>
<td>1.30</td>
<td>0.51</td>
<td>0.23</td>
<td>0.0058</td>
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<td>45</td>
<td>35</td>
<td>20</td>
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<td>1.34</td>
<td>0.49</td>
<td>0.17</td>
<td>0.0094</td>
</tr>
<tr>
<td>non wheel traffic corn 3</td>
<td>52</td>
<td>30</td>
<td>18</td>
<td>4.46</td>
<td>1.35</td>
<td>0.49</td>
<td>0.17</td>
<td>0.0109</td>
</tr>
<tr>
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<td>60</td>
<td>25</td>
<td>15</td>
<td>4.00</td>
<td>1.54</td>
<td>0.42</td>
<td>0.23</td>
<td>0.0053</td>
</tr>
<tr>
<td>wheel traffic corn 2</td>
<td>58</td>
<td>27</td>
<td>15</td>
<td>4.12</td>
<td>1.49</td>
<td>0.44</td>
<td>0.20</td>
<td>0.0026</td>
</tr>
<tr>
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<td>34</td>
<td>19</td>
<td>4.80</td>
<td>1.49</td>
<td>0.44</td>
<td>0.23</td>
<td>0.0052</td>
</tr>
<tr>
<td>prairie 1</td>
<td>50</td>
<td>34</td>
<td>16</td>
<td>4.35</td>
<td>1.39</td>
<td>0.47</td>
<td>0.18</td>
<td>0.0083</td>
</tr>
<tr>
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<td>29</td>
<td>18</td>
<td>4.22</td>
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<td>0.44</td>
<td>0.17</td>
<td>0.0051</td>
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<tr>
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<td>27</td>
<td>15</td>
<td>3.71</td>
<td>1.44</td>
<td>0.46</td>
<td>0.18</td>
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</tr>
</tbody>
</table>

Table 3: Laboratory measured soil properties. OM is organic matter content. BD is bulk density.

Soil properties in Table 3 were used as input to ROSETTA (Schaap et al., 2001) and CalcPTF. Outputs are soil water retention parameters in the van Genuchten (1980) model and the Brooks and Corey (1964) model. Water retention parameters from each pedotransfer function were used to calculate water content at a water tension. Figure 12 presents average values comparing estimated water retention curves and measured water content at a particular water
tension. The plots show that estimated water retention curves mostly overestimate water contents. The model that seems to provide the closest estimation is ROSETTA. This can be expected since one of the input data for the ROSETTA is water content at a pressure of 330 cm of water. Table 4 shows root means square error of water retention points of each model.

<table>
<thead>
<tr>
<th></th>
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<th></th>
<th></th>
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</tr>
</thead>
<tbody>
<tr>
<td>non traffic corn 1</td>
<td>0.09</td>
<td>0.10</td>
<td>0.03</td>
<td>0.05</td>
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<td>0.06</td>
<td>0.02</td>
<td>0.04</td>
<td>0.04</td>
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<tr>
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<td>0.11</td>
<td>0.02</td>
<td>0.08</td>
<td>0.05</td>
</tr>
<tr>
<td>prairie 2</td>
<td>0.09</td>
<td>0.10</td>
<td>0.02</td>
<td>0.08</td>
<td>0.04</td>
</tr>
<tr>
<td>prairie 3</td>
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<td>0.07</td>
<td>0.02</td>
<td>0.05</td>
<td>0.03</td>
</tr>
</tbody>
</table>

Table 4: Root mean square error of water retention points predicted by each function.

The estimated water retention parameters were used to calculate unsaturated hydraulic conductivity of each soil (see Appendix A.3). The Wösten et al. (1991) model provided the best pedotransfer function estimates of soil hydraulic conductivity. The average percentage difference between hydraulic conductivity estimated by Wösten et al. (1991) and Ankeny et al. (1991) is around 400%. Saxton et al. (1983) has average difference of 1000%. ROSETTA (Schaap et al., 2001) has average difference of 2600%. Rawls and Brakensiek (1985) have average difference of 58000%. Saxton et al. (1986) has average difference of 138000%. The differences show that soil hydraulic conductivity in this study is more suitable to the Mualem – van Genuchten model than the Brooks – Corey model.
Figure 12: Average volumetric water content of (a) non-wheel traffic corn row, (b) wheel traffic corn row, and (c) prairie at different water tension.
Figure 13: Soil hydraulic conductivity using Wösten et al. (1999) function and Ankeny et al. (1991) method at (a) non-wheel traffic corn, (b) wheel traffic corn, and (c) prairie.
Comparisons of hydraulic conductivity estimated by the Wösten et al. (1991) and Ankeny et al. (1991) methods are shown in Fig. 13. Non-wheel traffic soil, wheel traffic soil, and prairie soil values calculated by pedotransfer functions have similar trends. The results show that the pedotransfer functions are not good at distinguishing between soil treatments. For non-wheel traffic corn the closest results are between Wösten et al. (1999) and Ankeny et al. (1991). The results imply that, although pedotransfer functions are easy to use to estimate soil hydraulic conductivity, they may not be very accurate and they do not accurately reflect the effects of traffic compaction and plant roots.
CHAPTER 5. CONCLUSIONS

In this study soil hydraulic conductivity is determined for a non-wheel traffic corn row, a wheel traffic corn row, and a prairie area using the Ankeny et al. (1991) method, an inversion method, and several pedotransfer functions. The objectives of the study were to compare soil hydraulic conductivity between treatments, and to compare hydraulic conductivity from the inverse method and pedotransfer functions to values from the Ankeny et al. (1991) method.

The results show that traffic compaction and vegetation affect soil hydraulic conductivity. Near saturation, soil between corn rows without wheel compaction had largest hydraulic conductivity compared with other treatments. The inverse method showed that, at high water tensions, corn without wheel traffic had smaller hydraulic conductivity than corn with wheel traffic compaction. The results imply that non-wheel traffic soil in the study is better than compacted wheel traffic soil for liquid transport at small water tensions, but that compacted soil is better than non-compacted soil for liquid transport at large water tensions. Prairie soil had smaller hydraulic conductivity than soil between corn rows without traffic compaction, but it had larger hydraulic conductivity than soil between corn rows with traffic compaction. Prairie soil having smaller hydraulic conductivity than a non-wheel traffic corn row was unexpected. One possible explanation for the results is that prairie roots blocked some soil pores, thus hindering water flow.

Field-measured cumulative infiltration and soil matric potential can be used to estimate soil unsaturated hydraulic conductivity using numerical inversion of the Richards equation. Hydraulic conductivities determined from the transient flow method using numerical inversion are consistent with results from the Ankeny et al. (1991) method. The pedotransfer
functions did not distinguish differences in soil hydraulic conductivity caused by traffic compaction or vegetation differences. The Wösten et al. (1999) pedotransfer function provided the closest estimations of hydraulic conductivity to those from the Ankeny et al. (1991) method, but the pedotransfer function estimations were quite different from the field results based on tension infiltration measurement. Even though the results from the inverse method were in agreement with those of the Ankeny et al. (1991) method at small water tensions, the results at high water tension were not independently confirmed. The findings of this study raise the following questions:

1. What impact do roots have on soil hydraulic conductivity, and how does it vary with water tension?
2. How accurate are the inverse method values of soil hydraulic conductivity at large water tensions?
REFERENCES


Soil hydraulic conductivity estimated from numerical inversion method.

Figure 13: Non-wheel traffic corn soil hydraulic conductivity using numerical inversion and Ankeny et al. (1991) method. (a), (b), and (c) are non-wheel traffic corn 1, 2, and 3, respectively.
Figure 14: Wheel traffic corn soil hydraulic conductivity using numerical inversion and Ankeny et al. (1991) method. (a) and (b) are wheel traffic corn 1 and 3, respectively.
Figure 15: Prairie soil hydraulic conductivity using numerical inversion and Ankeny et al. (1991) method. (a) and (b) are prairie 1 and 2, respectively.
APPENDIX B

Laboratory measured and estimated water retention curves.

Figure 16: Volumetric water content of non-wheel traffic corn row at different water tensions.

Figure 16: Volumetric water content of non-wheel traffic corn row at different water tensions.
Figure 17: Volumetric water content of wheel traffic corn row at different water tensions.
Figure 18: Volumetric water content of prairie locations at different water tensions.
APPENDIX C

Soil hydraulic conductivity estimated from pedotransfer functions.

Figures 19-23 display soil hydraulic conductivity calculated from each pedotransfer function. ROSETTA (Schaap et al., 2001) displayed differences between each treatment at large water tensions, but estimates similar hydraulic conductivity at small water tensions. Rawls et al. (1983) gave differences between each treatment at small water tensions, but similar hydraulic conductivity were observed at large water tensions. Wösten et al. (1999) did not give differences between each treatment at small or large water tensions.

The Wösten et al. (1999) function has the closest soil hydraulic conductivity to the results of the Ankeny et al. (1991) method for the soil in this study. Figures 24-26 show a comparison between Wösten et al. (1999) and Ankeny et al. (1991) results.

Figure 19: Estimated hydraulic conductivity from ROSETTA (Schaap et al., 2001).
Figure 20: Estimated hydraulic conductivity from Wösten et al. (1999) functions.

Figure 21: Estimated hydraulic conductivity using Rawls et al. (1983) functions.
Figure 22: Estimated hydraulic conductivity using Rawls and Brakensiek (1985) functions.

Figure 23: Estimated hydraulic conductivity using Saxton et al. (1986) functions.
Figure 24: Non-wheel traffic corn soil hydraulic conductivity using the Wösten et al. (1999) pedotransfer function and Ankeny et al. (1991) method. (a), (b), and (c) are non-wheel traffic corn 1, 2, and 3 respectively.
Figure 25: Wheel traffic corn soil hydraulic conductivity using pedotransfer function and Ankeny et al. (1991) method. (a), (b), and (c) are wheel traffic corn 1, 2, and 3 respectively.
Figure 26: Prairie soil hydraulic conductivity using pedotransfer functions and Ankeny et al. (1991) method. (a), (b), and (c) are prairie 1, 2, and 3 respectively.