SYSTEMATIC VARIABILITY OF SOIL HYDRAULIC CONDUCTIVITY ACROSS THREE VERTISOL CATENAS

A Thesis

by

LEONARDO DANIEL RIVERA

Submitted to the Office of Graduate Studies of
Texas A&M University
in partial fulfillment of the requirements for the degree of

MASTER OF SCIENCE

August 2010

Major Subject: Soil Science

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Approved by:

Chair of Committee,	Cristine Morgan
Committee Members,	Kevin McInnes
	Charles Tom Hallmark
	Georgianne Moore
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ABSTRACT

Systematic Variability of Soil Hydraulic Conductivity Across Three Vertisol Catenas.
(August 2010)
Leonardo Daniel Rivera, B.S., Texas A&M University
Chair of Advisory Committee: Dr. Cristine Morgan

Soil hydraulic properties, such as saturated hydraulic conductivity (K_s), have high spatial variation, but little is known about how to vary a few measurements of K_s over an area to model hydrology in a watershed with complex topography and multiple land uses. Variations in soil structure, macropores (especially in soil that shrink and swell), land use, and soil development can cause large variations in K_s within one soil type. Characterizing the impacts of soil properties that might vary systematically with land use and terrain attributes on K_s rates would provide insight on how management and human activity affect local and regional hydrology. The overall objective of this research was to develop a strategy for using published infiltration and K_s measurements by the Natural Resources Conservation Service for watershed hydrology applications in a Vertisol, and to extend this knowledge toward developing recommendations for future infiltration measurements. To achieve this goal, soil infiltration measurements were collected across three catenas of Houston Black and Heiden clays (fine, smectitic, thermic Udic Haplusterts) under three land uses (improved pasture, native prairie, and conventional tillage row crop). Measurement locations were selected to account for variation in terrain attributes.

Overall, K_s values were not significantly different across different landscape positions; however, in fields under similar land uses, K_s values were found to be lower in the footslope positions and higher in the backslope positions. The pedotransfer function, ROSETTA, provided estimates of 64% of the overall variability in K_s while also providing accurate estimates of the mean of K_s when particle size distribution and bulk density are used as inputs in the model. Through the use of multiple regression analysis, soil antecedent water content, bulk density, clay content, and soil organic carbon along with two indicator variables for the catenas were highly correlated ($r^2 = 0.59$) with K_s. The indicator variables explained 17% of the variation in K_s that could not be explained by measured soil properties. It is recommended that when NRCS measures K_s on benchmark soils, especially high clay soils, that they collect particle size distribution, bulk density, organic carbon, and antecedent water content data.

DEDICATION

I would like to dedicate this thesis to my wife, Lindsey, and my mother, Ida, for the never ending support they gave me while working on this research. My mother has been nothing but a prime example to me of how to love life, work hard, and cherish the people around you.

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CHAPTER I

INTRODUCTION: THE IMPORTANCE OF RESEARCH

Fundamental knowledge of the mechanisms of water movement through soil under is essential for sound land management. The rate at which water flows through soil is used in most models that simulate water flow, solute transport, and runoff. The flux density of water through soil is proportional to the gradient in soil water potential. For vertical flow of water in soil, Darcy's law can be written as the following:

$$J_w = -K \cdot \frac{d(\psi_P + \psi_m + \psi_g)}{dz}, \qquad [1]$$

where J_w is the volumetric flux density of water ($m^3\ m^{-2}\ s^{-1}$) or ($m\ s^{-1}$), K is the hydraulic conductivity ($m^3\ m^{-2}\ s^{-1}$) or ($m\ s^{-1}$), ψ_p is the pressure water potential (m), ψ_m is the matric water potential (m), ψ_g is the gravitational water potential (m), z is the vertical space coordinate (m), and $\frac{d\left(\psi_P + \psi_m + \psi_g\right)}{dz}$ is the water potential gradient ($m\ m^{-1}$). The geometry and size distribution of the soil pores have a strong influence on the magnitude of K. The hydraulic conductivity can be related to the saturated hydraulic conductivity (K_s) and the degree of saturation by:

$$K = K_s \cdot f(\theta/\theta_s) \qquad [2]$$

where θ is the volumetric soil water content ($m^3\ m^{-3}$), θ_s is the volumetric soil water content at saturation ($m^3\ m^{-3}$), $f(\theta/\theta_s)$ is a function that decreases from a value of 1 as

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the soil desaturates. With this relationship $K = K_s$ when $\theta/\theta_s = 1$. Different forms of this function have been proposed (e.g., Brooks and Corey, 1964; van Genuchten, 1980; Campbell, 1985).

The rate that water infiltrates into the soil is related to K_s. The infiltration rate i ($m^3\ m^{-2}\ s^{-1}$) or ($m\ s^{-1}$) into an initially unsaturated soil is governed by the combined influence of gradients in matric and gravitational potentials which can be approximated (Philip, 1957) as:

$$i = 0.5 \cdot S \cdot t^{-0.5} + A \qquad [3]$$

where i is the infiltration rate ($m^3\ m^{-2}\ s^{-1}$) or ($m\ s^{-1}$), S is the sorptivity of the soil ($m^3\ m^{-2}\ s^{-1/2}$) or ($m\ s^{-1/2}$), t is time since the commencement of infiltration (s), and A is the steady state infiltration rate ($m^3\ m^{-2}\ s^{-1}$) or ($m\ s^{-1}$), i.e., when $t >> 0$, $0.5 \cdot S \cdot t^{-0.5} << A$. In addition, the soil becomes saturated and the gradient in matric potential becomes very small near the surface as $t>>0$, so the water potential gradient in Darcy's law becomes the gradient in gravitational potential (i.e., $-1\ m\ m^{-1}$) such that:

$$i \cong A \cong J_w = -K_s \cdot \frac{d\psi_g}{dz} = -K_s \cdot (-1) = K_s. \qquad [4]$$

Since the hydraulic conductivity is related to K_s, the distribution of K_s across a landscape is needed to simulate water flow in soil within a watershed. The magnitude of saturated hydraulic conductivity of soil measured on small samples is log-normally distributed and related to physical properties of that soil sample (Mapa, 1995; Reynolds and Zebchuk, 1996; Lin et al., 1998; Baldock and Nelson, 2000). The United States Department of Agriculture (USDA) – Natural Resource Conservation Service (NRCS) Soil Survey Staff in Texas is currently developing a database containing information on physical and chemical soil properties of NRCS benchmark soils (www.tx.nrcs.usda.gov/soil/index.html). The NRCS's goal is to populate this database with measured properties and to provide practitioners with realistic information for land management decisions and for assessing ecosystem services. One of the physical properties that will populate this database will be K_s. The published value of K_s for a particular soil series will be based on the average of three infiltration measurements made using a 30-cm inner ring diameter, double-ring infiltrometer (Reynolds et al., 2002b).

Many hydrology modeling exercises are implemented to investigate the effect of changes in land use or management on surface hydrology (Zhi et al., 2009; Pisinaras et al., 2010; Shimelis et al., 2010). Values of K_s are most often assumed to be constant within a single soil series or mapping unit for purposes of hydrology modeling (Setegn et al., 2010), although it is recognized that K_s varies with land use, landscape position, bulk density, and other soil properties within the mapping unit. One method of addressing this issue of spatial uncertainty is to utilize pedotransfer functions (Rawls et al., 1991; van Genuchten and Leij, 1992; Leij and van Genuchten, 1999; Lin et al., 1999b; Schaap et al., 2001) to assign variability to K_s across the landscape. Development of a protocol to combine measurements of K_s on a soil series, pedotransfer function estimates of K_s, and knowledge on how K_s within a soil series varies across a watershed would be a useful step for more realistic parameterization of surface hydrology models.

Much of the USDA prime farmland and urban development in Texas are located on Vertisols of the Texas Blackland Prairies (e.g., Dallas-Fort Worth, Austin, and San Antonio) and the Texas Coast Prairie (e.g., Houston). The goal of this study is to develop a protocol for applying published K_s values to site-specific management applications for two benchmark soils in the Texas Blackland Prairies Major Land Resource Area an area dominated by Vertisols. Vertisols are soils with high clay content (>35%) throughout the soil profile and a high shrink-swell potential which sets them apart from other soils. Vertisols are generally considered to have low infiltration and K_s values. Structure and bulk density can be spatially and temporally variable across these soils and are significantly affected by land use causing high spatial variations in K_s (Gupta et al., 2006; Sobieraj et al., 2002; Lin et al., 1998; Lin et al., 1999a; Lin et al., 1999b). Because structure development and maintenance of that structure in shrink-swell soils is affected by vegetation, a Vertisol is a good candidate for developing a protocol for assigning the variability of K_s across a watershed with one dominant soil series mapped along with multiple land uses and management.

CHAPTER II

LITERATURE REVIEW

Variation of soil saturated hydraulic conductivity (K_s) is governed by physical and morphological properties such as texture, structure, and macroporosity, especially in soils with high clay content and having differences in initial soil moisture and root density (Lin, 1995; Lin et al., 1999a). Variability of K_s can be measured with in situ measurements or on intact soil cores brought into the laboratory (Reynolds et al., 2002b). Field-based methods can capture more information about macropore structures than methods utilizing cores. In addition, field-based measurements capture more realistic effects of air entrapment and tortuosity than do laboratory-based measurements (Reynolds and Elrick, 1985).

Sources of variability in K_s across one soil type may be random or systematic. Random variability of K_s within a single soil mapping unit is, in part, due to the random distribution of some macropores in soil (Lin et al., 1998; Gupta et al., 2006). Systematic variability of K_s is derived from systematic variability of soil properties created across a catena during soil formation (Jenny, 1946). Systematic variability can be described in part with empirical or mechanistic models. For example, it is recognized that K_s values vary with soil porosity and porosity is related to soil bulk density that varies within a mapping unit of a soil series. Soil bulk density has been related to soil organic carbon, soil structure and water content for clayey soils (Mapa, 1995; Baldock and Nelson, 2000).

Measurement Methods

A variety of laboratory and field methods of measuring K_s are available. Laboratory measurements are typically conducted on undisturbed soil cores collected from the field. Methods of measuring K_s on soil cores include the constant head method, the falling head method, and the steady flow method (Reynolds et al., 2002a). The constant head and the falling head methods are meant to complement each other; the constant head method is capable of measuring K_s ranges from about 1 to $1\text{x}10^{-5}$ cm s^{-1} while the falling head method is capable of measuring K_s ranges from about $1\text{x}10^{-4}$ to $1\text{x}10^{-7}$ cm s^{-1}. The main disadvantage of using laboratory methods is that the measured K_s value could differ appreciably from what it would have been had the soil sample remained hydraulically connected to the underlying horizons. When soil cores are collected, open-ended macropores are sometimes created from dead-end pores. These open-ended segments of dead-end pores lead to overestimates of K_s. Similarly, hydraulically active macropores are sometimes truncated within a soil core, leading to underestimates of K_s (Reynolds et al., 2002a).

Field-based methods provide a means of quantifying K_s of an intact soil profile. Field methods of measuring K_s include the single-ring and double-ring infiltrometers, and the constant-head well-permeameter. Values of K_s determined from these methods are based on three-dimensional flow analysis. The single-ring infiltrometer utilizes an open-ended cylinder driven into the ground. The double-ring infiltrometer consists of concentric open-ended cylinders driven into the ground, the outer open-ended cylinder is meant to limit lateral flow from the inner cylinder where the measurements are made.

The constant-head method of determining infiltration rates can be used on ring infiltrometers. The constant-head method requires an apparatus that supplies water at a variable flow rate to maintain a constant head.

Sources of error in K_s estimates that occur with ring infiltrometer methods include soil compaction from cylinder installation; short-circuit flow along cylinder walls, and interference from a shallow water table. Because hydraulically active flow paths are spatially variable, increasing the size of the rings increases the chance of capturing a representative elementary area (the smallest area that would yield a representative value of the whole) and decreases the variability in the measurements (Lai and Ren, 2007).

Measurements of K_s based on the well-permeameter are obtained by ponding one or more heads of water on a borehole augered into unsaturated soil. There are several designs for constant head well permeameters including the Amoozemeter (Amoozegar, 1992) and the Guelph permeameter (Reynolds and Elrick, 1983). These two designs utilize different methods of maintaining a constant head of water in boreholes and in measuring how much water is infiltrated into the soil. Procedures for preparing the measurement area, equations, and analysis are the same regardless of the permeameter design that is used. The constant head well permeameter allows the measurements of K_s at different depths within the soil profile that typically are not done with the larger ring infiltrometers because excavating a large pit is required. An appreciable source of error of K_s estimated from the well-permeameter method is associated with smearing or compaction of the measurement zone while auguring the borehole, closing off hydraulically active flow paths.

Factors that affect both K_s derived from laboratory and from field-based methods include water temperature and plugging of soil pores due to migration of silt and clay particles carried by water. Field-based methods generally require fewer samples to get a representative mean of K_s, because field-based methods generally sample a much larger area than a soil core in the laboratory. The different methods of measuring K_s are each valuable depending on how the measurements are intended to be used. For example, field-based methods might be appropriate for obtaining K_s values for modeling runoff in a watershed compared to obtaining K_s values to determine relative differences in flow rates of water through different soil horizons which could be better estimated using laboratory-based methods.

Spatial and Temporal Variation

Saturated hydraulic conductivities of Vertisols are spatially and temporally variable because the aperture of soil cracks changes on shrinking and swelling of clay soil upon drying and wetting. Studies where multiple hydraulic conductivity measurements were made on the same soil have identified variability in K_s associated with macroporosity, which is a function of soil moisture at the time of measurement (Messing and Jarvis, 1993; Lin et al., 1998; Sobieraj et al., 2002; Gupta et al., 2006). Variability in unsaturated hydraulic conductivity of a Vertisol was shown to increase as the soil approached saturation with coefficients of variation (CV) as high as 135% (Gupta et al., 2006). The high CV values were attributed to the influence of macropores.

The effect of antecedent moisture on soil hydraulic conductivity of high-clay soil can be attributed, in large part, to the shrink-swell properties of the soils and their associated changes in macroporosity (Lin et al., 1998). Changes in macroporosity in shrink-swell soils as a function of water content have a greater impact on water flow near or at saturation. As a result infiltration rates near or at saturation have a negative exponential relationship with antecedent soil moisture (Reynolds and Zebchuk, 1996).

Texture appears to play a role in the magnitude which hydraulic conductivity varies as indicated by coefficients of variation found in studies of soils with different textures (Table 1).

Table 1. Comparison of coefficient of variation (CV) of saturated hydraulic conductivity values among different studies with different soil textures.

Study	Soil Texture	CV
Bosch and West, 1998	sand to loamy sand	32%
Bosch and West, 1998	loamy sand	26%
Lin et al., 1998	clay	57%
Gupta et al., 2006	silty clay	136%

Land Use, Vegetation, and Management Effects

Land use through cultivation and alterations of vegetation likely has an impact on soil hydraulic properties. Changes in soil hydraulic conductivity have been associated with changes in bulk density, soil organic carbon, and soil structure but with no definite patterns. Bormann and Klaassen (2008) found surface bulk densities under forest land to be significantly lower than under grassland and cropland for two different soils, but the saturated hydraulic conductivity was highest under the forest for one soil and lowest under the forest for the other soil. The interaction between the two soils show that bulk density cannot be used alone to explain variations in K_s. However, Zhou et al. (2008) found that differences in K_s were consistently related to differences in bulk density between land use and management practices (woodland, cropland, pasture, and urban). Celik (2005) conducted a study of soils under cultivated and uncultivated land use and found that cultivation was associated with increased bulk density, decreased soil organic matter, and decreased hydraulic conductivity.

Under a single land use, soil management such as different cultivation practices, can have a significant impact on the physical properties of the soil. Shukla et al., (2003) compared the effects of different tillage treatments (no-till with and without manure, no-till corn-soybean rotation, conventional tillage, and meadow) on soil hydrological properties. Manure application improved aggregation, decreased bulk density, and increased the hydraulic conductivity of the soil. Conventional tillage treatments had the highest bulk densities and lowest infiltration rates.

Effects of Landscape Position

Soil formation processes result in a systematic change of soil properties across the landscape, described in the concept of a catena (Opp, 1994). Although some studies have been conducted looking at the spatial and temporal variations of soil hydraulic conductivities, few have looked at the variability of K_s across a catena. On a catena, it would be expected that soil organic carbon and clay content, as a result of erosion and transport processes, would be highest in the footslope and lowest in the backslope (Cambardella et al., 2004; Wei et al., 2008). Lower organic carbon and the associated higher bulk density in the backslope would likely result in lower K_s on the backslope than the footslope (Jiang et al., 2007). West et al. (2008) looked at the changes in K_s values at different landscape positions with sandy loam surface textures. While means of K_s were not significantly different among the different landscape positions, significant interactions between sites of similar land use and hill slope positions showed that the upper 1/3 of the hill slope had higher K_s than the lower 1/3 of the hill slope position at some of the sites. To explore the theory that soil properties were linked to landscape position by functional relationships, Sobieraj et al. (2002) measured K_s along a tropical rainforest catena with varying soil types with surface textures of sandy clay loam and sandy loam, respectively. Little difference in K_s was found between different landscape positions, and they speculated that homogeneity of K_s was attributed to the homogenizing effects of bioturbation.

With soil cores removed from a row crop field under no-tillage management, Mohanty and Mousli (2000) investigated whether the relative position on a slope contributed to the variability of soil hydraulic properties in a complex terrain of glacial till with loam surface textures. Within a homogeneous soil, significantly higher values in K_s were found in the lower landscape positions compare to the upper landscape positions. Jiang et al. (2007) investigated the interactions of landscape position (summit, backslope, and footslope) and conservation management practice on soil bulk density, saturated hydraulic conductivity, soil water retention, and pore-size distribution for claypan soils with silt loam surface textures. Contrary to what the other investigators found the bulk densities were found to be higher and K_s values were found to be lower in the footslope than the upper positions. Different land management practices led to varying amounts of erosion and deposition which in turn led to variations in bulk densities and K_s.

Means of Mapping Variability of Soil Properties Across Landscape Positions

One potential way of non-destructively predicting systematic variations in K_s across the landscape is through the use of an instrument that maps apparent soil electrical conductivity (EC_a). The same soil properties affecting EC_a, also affect K_s (McKeague et al., 1982; Jaynes et al., 1995; Rawls et al., 1998; Griffiths et al., 1999; Lin et al., 1999a). Factors that affect soil EC_a include salinity, clay type, clay content, and moisture (McNeil, 1980; Rhoades et al., 1976). Given a well drained soil with uniform salinity, EC_a should respond to clay type and percentage, bulk density, and moisture. It should be possible to delineate general zones of K_s with EC_a (Johnson et al., 2005).

Means of Using Soil Properties to Estimate K_s

A common method for estimating the variations in K_s from variations of soil properties is through the use of a pedotransfer function. Pedotransfer functions are models that use soil properties, such as particle size distribution, bulk density, and organic carbon, properties that are easier to measure or estimate than the soil property of interest (e.g., K_s) (Bouma and van Lanen, 1987). Pedotransfer models are usually developed using regression techniques or neural networks (e.g. Rawls et al., 1991; van Genuchten and Leij, 1992; Leij and van Genuchten, 1999).

ROSETTA is a computer program that has been developed to combine pedotransfer functions from Schaap et al. (1998), Schaap and Leij (1998), and Schaap and Leij (2000). ROSETTA is based on neural network analysis structured with five hierarchal pedotransfer functions to allow the use of limited and/or more extended sets of soil property information as input (Schaap et al., 2001). To estimate soil K_s, ROSETTA uses input as limited as textural class or particle size distribution only, or as intense as particle size distribution, bulk density, water content at -33 kPa water potential, and water content at -1500 kPa water potential.

Pedotransfer functions provide the opportunity to estimate the systematic variability of K_s across a small catena or large watershed. A study was conducted comparing ROSETTA predicted K_s values with actual measured K_s on soils in Peru (Sobieraj et al., 2001). The study area was separated into three different land units based on relief and soil properties, steep lower side slope, an intermediate terrace, and a gentle upper sideslope. The three land units had surface textures ranging from loam to sandy clay loam. ROSETTA estimates of K_s were based on two different models, particle size distribution only and particle size distribution with bulk density. ROSETTA estimates based on particle size distribution alone did not provide accurate estimates of $K_{s.}$ When bulk density was added, ROSETTA provided improved estimates of K_s, but estimates were still under the mean measured values by about 50% for the gentle upper side slope land unit. For steep, lower side slope and intermediate terrace land units, ROSETTA was 50% lower than the measured mean K_s; however, ROSETTA did provide accurate estimates of the variability of K_s.

Objectives/Hypotheses

The goal of this study was to determine the best methods for applying published K_s values for USDA NRCS benchmark soils to site-specific management situations. Four research objectives were chosen to address this goal. The first objective of this study was to determine how K_s varies with landscape positions on three Vertisol catenas of a single soil type. The hypothesis was that within these catenas, with one soil type, K_s would be lowest under the more eroded landscape positions (backslope) and highest under positions that would be receiving deposition of sediments, organic carbon, and water flow and having improved structural macropores (footslope). The second objective of this study was to determine if a soil EC_a map could be used to determine where systematic variations in K_s might occur. The hypothesis was that the EC_a maps could' be used to predict variations in K_s. The third objective of this study was to determine which soil properties were most highly correlated with variations in K_s across the three catenas. The hypothesis was that, through the use of multiple regression analysis, K_s will be associated with soil properties, like soil organic carbon and clay content, that are associated with soil aggregation and macroporosity. The fourth objective of this study was to evaluate whether ROSETTA could be used to estimate the variability of K_s across a small catena or large watershed. Based on the results of Sobieraj et al. (2001), the hypothesis was that ROSETTA may provide reasonable estimates of the variability in K_s across a large watershed.

CHAPTER III

MATERIALS AND METHODS

Site Selection

The study was conducted on three catenas at the United States Department of Agriculture – Agricultural Research Service Grassland Soil and Water Research Laboratory near Riesel, TX at coordinates 31°28'14.10"N and 96°53'1.39"W (Harmel et al., 2007). The catenas were in separate fields under different land uses: native prairie, conventional-tillage row crop, and improved pasture. The soils in the catenas have homogeneous texture. The native prairie field (coded SW12 in the watershed) is 8.6 ha and has remained untilled, ungrazed, and under native vegetation (predominantly bluestem grasses) since 1948. The conventional tillage field (coded Y8) is 8.4 ha and has been under a corn (*Zea mays* L.)-winter wheat (*Triticum aestivum* L.) rotation since 1949. The improved pasture field (coded Y2) is 7.3 ha and has been under rotational grazing on Coastal Bermudagrass (*Cynodon dactylon* L.) vegetation since 1949. The soils in these fields are mapped as Houston Black clay (fine, smectitic, thermic Udic Haplusterts) and Heiden clay (fine, smectitic, thermic Udic Haplusterts). These upland soils formed in clayey residuum weathered from clayey shale parent material of the Eagle Ford Shale and Taylor Marl formations. These two soils are mapped across 980,234 hectares of Texas (National Soil Information System (NASIS)) and are listed as benchmark soils (www.tx.nrcs.usda.gov/soil/index.html).

Mapping and Point Selection

In an attempt to select measurement points that represented the most variability in hydraulic conductivity within each catena, maps of soil EC_a (Fig. 1) and topography (Fig. 2) were created. The data for the maps were generated from an EM38DD landscape survey sensor (Geonics, Mississauga, Ontario, Canada) and a Trimble R7/R8 dual frequency GPS (Trimble, Sunnyvale, CA) on 10-m transects. The Trimble GPS was mounted to an all-terrain vehicle and the EM38DD was mounted to a sled pulled by that vehicle. The data were logged at 1 Hz with simultaneous GPS coordinates while traveling at a rate of approximately 5 m s^{-1}. Three zones in the field were identified based upon fuzzy k-means separation of EC_a readings from the vertical dipole of the EM38DD using the statistical software package R (R Development Core Team, 2004).

Distinct landscape positions can be found in the three catenas with slopes ranging from 4 to 6% on the backslope. Changes in elevation of 14 m across the improved pasture and native prairie catenas, and 9 m across the conventional tillage catena were measured. In the improved pasture catena, EC_a values in the three EC_a zones ranged from 33 to 139 mS m^{-1} with EC_a Zone 1 found in the more eroded backslope position, EC_a Zone 2 predominantly found in the summit position, and EC_a Zone 3 predominantly found in the footslope position. In the native prairie, catena EC_a values in the three EC_a zones ranged from 10 to 175 mS m^{-1} with EC_a Zone 1 found in the summit and the upper backslope positions and EC_a Zones 2 and 3 predominantly found in the backslope and the footslope positions. In the conventional tillage catena, EC_a values in the three EC_a zones ranged from 63 to 189 mS m^{-1} with EC_a Zone 1 predominantly found in the

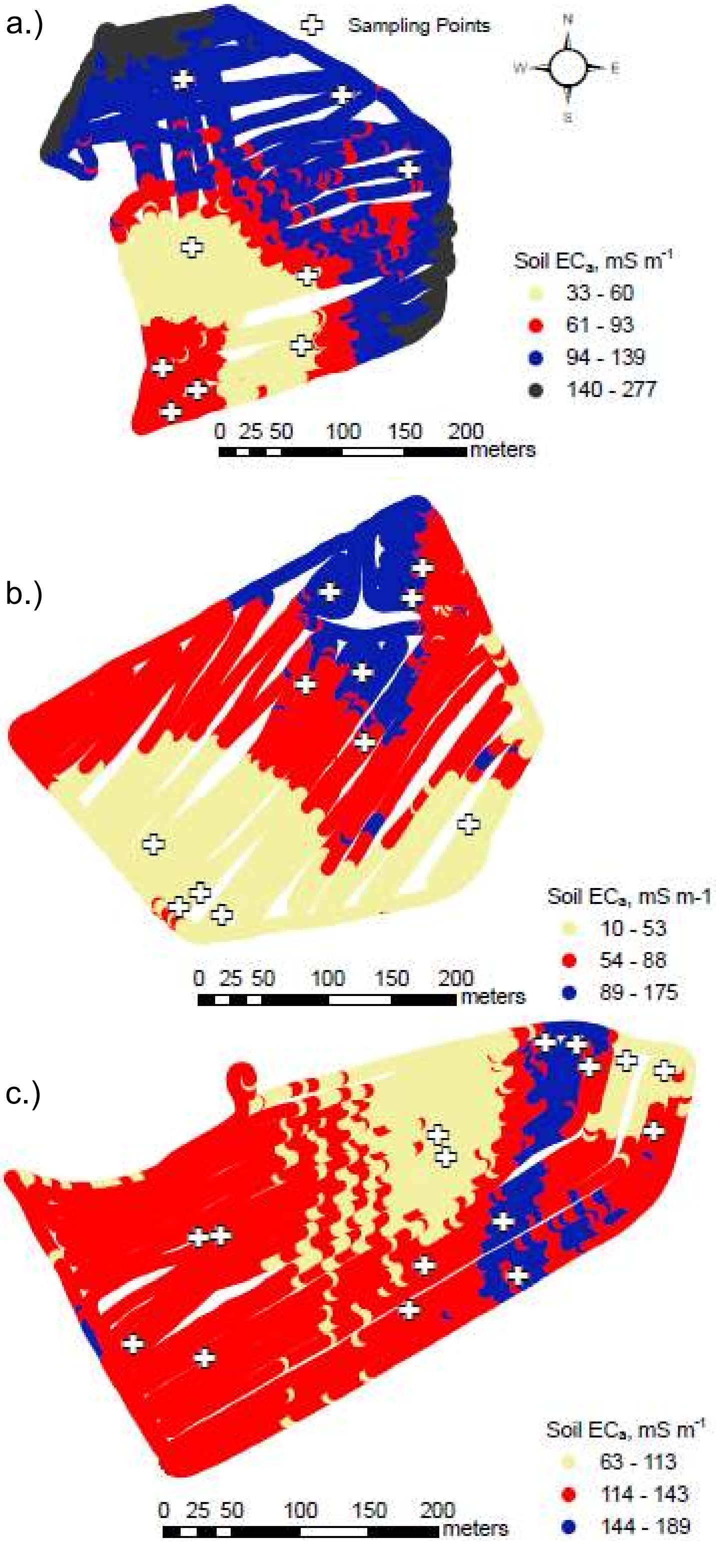

Figure 1: Soil apparent electrical conductivity (EC_a) maps and measurements points of the a.) improved pasture, b.) native prairie, and c.) conventional tillage catenas.

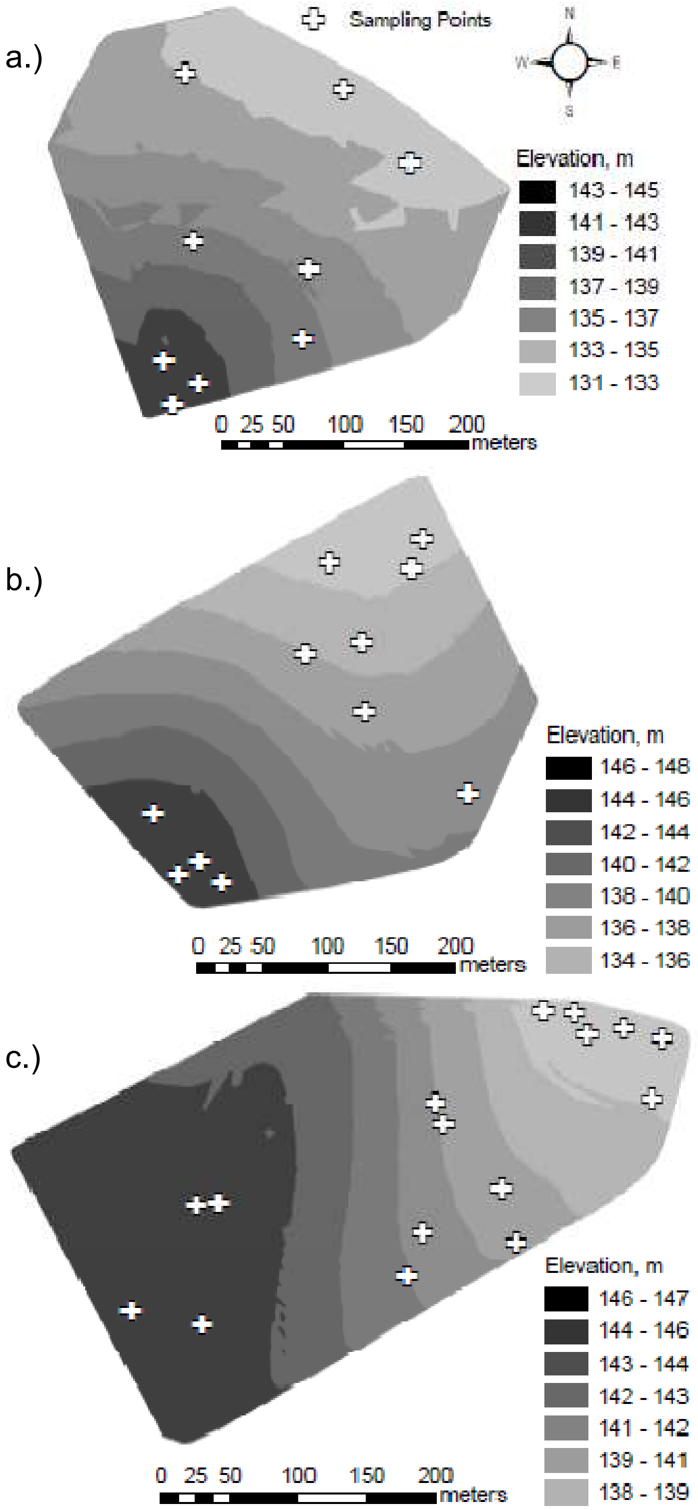

Figure 2: Elevation maps and measurements points of the a.) improved pasture, b.) native prairie, and c.) conventional tillage catenas.

backslope and lower portions of the footslope positions, EC_a Zone 2 found in all three positions, and EC_a zone 3 found in a strip running through the backslope and footslope positions. Typically, EC_a values were higher in areas were deposition of sediments were likely to have occurred resulting in deeper soils and lower in areas were higher amounts of erosion would be expected resulting in a more shallow soil.

Using the topographical maps, zones for summit, backslope, and footslope positions were delineated. Locations within each EC_a zone and landscape position were randomly selected as sites for measurements of soil hydraulic conductivities. At each of these randomly selected sites, three measurements of infiltration rates were made. In total, 102 individual measurements were conducted across the three catenas. In the conventional tillage catena, 48 measurements were conducted from November 2008 through February 2009. In the native prairie catena, 27 measurements were conducted from February through April 2009. In the improved pasture catena, 27 measurements were conducted from April through June 2009. The spring of 2008, prior to taking the hydraulic conductivity measurements, was a fairly wet leading into a dry summer (Fig. 3a). During the fall of 2008, when the measurements where first conducted, sparse rainfall events occurred and surface cracks in the soil were closed. Winter and spring of 2009, more rainfall events, especially between the months of April through May, resulted in wet conditions leading, once again, into a dry summer (Fig. 3b).

Saturated Hydraulic Conductivity Measurements

Measurements of saturated hydraulic conductivity were conducted using a constant-head, double-ring infiltrometer apparatus. Three replicate measurements were

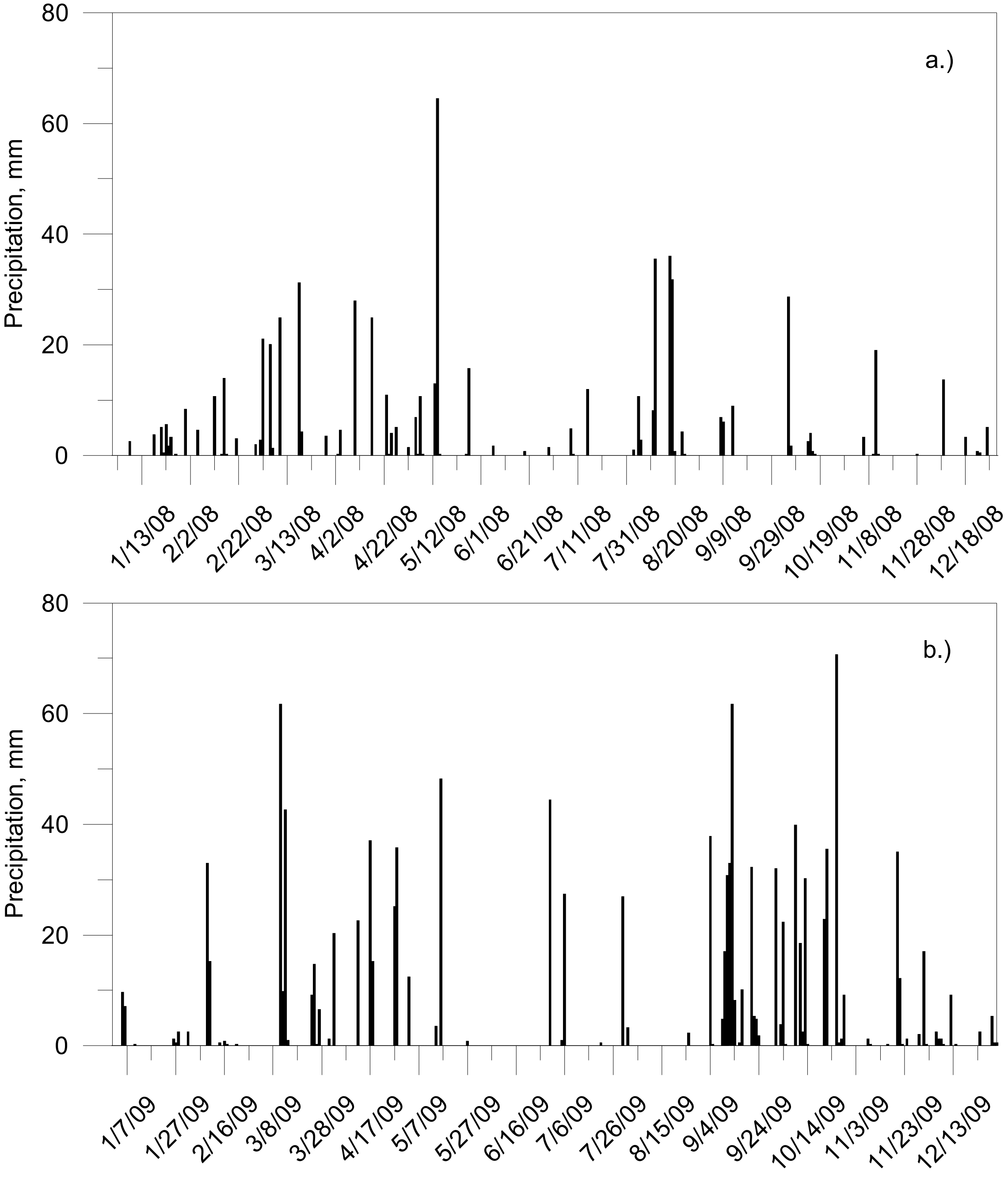

Figure 3. Daily precipitation for Riesel, TX in a.) 2008 and b.) 2009.

made simultaneously at each measurement site using three stainless-steel, double-ring infiltrometers (Geotest, Evanston, IL). The infiltrometers consisted of a 60-cm outer ring diameter and a 30-cm inner ring diameter. Each infiltration measurement was carefully conducted following a standard procedure. The rings were driven into the soil to a depth of 5 cm (*d*). A constant head of 5 cm of water (*H*) was maintained in both rings based on methods from Reynolds et al. (2002b) using water supplied from reservoirs and float valves. When working on slopes, the 5 cm water level was set mid-slope within the rings (Bodhinayake et al., 2004). The water reservoirs for the inner rings contained temperature compensated (-40 to 85 ˚C working range) pressure transducers (model PX 309/319, Omega Engineering, Stanford, CT) to determine the depth of water in the reservoir and the rate of infiltration. The pressure transducers were connected to a HOBO Energy Logger Pro data logger (Onset Computer Corporation, Bourne, MA), and each pressure transducer was individually calibrated to a specific reservoir. The infiltration rate was measured until apparent steady state infiltration was reached, typically within 120 minutes. Steady state was determined when the infiltration rate was steady ($\pm$ 0.2 cm h^{-1}) at least 20 minutes.

Saturated hydraulic conductivity (K_s) was calculated using the following equation (Reynolds et al., 2002b):

$$K_s = \frac{q_s}{[H/(C_1 d + C_2 a)] + \{1/[\alpha * (C_1 d + C_2 a)]\} + 1}, \qquad [5]$$

where q_s is the measured quasi-steady state infiltration rate (cm h^{-1}), *a* is the inside cylinder radius (cm), $C_1 = 0.316\pi$ and $C_2 = 0.184\pi$ are dimensionless quasi-empirical constants, and $\alpha = 0.12$ is soil macroscopic capillary length (cm^{-1}), which is based on soil texture and structure categories (Reynolds et al., 2002). At the time of the measurements, soil temperature and water temperature were recorded using a digital soil thermometer. Samples of the surface 15 cm of the soil, were collected next to the measurement sites, to document antecedent soil moisture conditions and bulk density. The samples were collected using a 7.6-cm diameter by 15.2-cm tall core sampler (AMS Incorporated, American Falls, ID) within 30-cm distance of the infiltrometer. The soil samples were stored in a cooler for transport to a laboratory where they were weighed moist, oven-dried at 105 ˚C and weighed dry. Weights were used to calculate bulk density and antecedent soil water content.

Soil Sampling and Analysis

Upon completion of the infiltration measurements, cores were taken vertically to a depth of approximately 200 cm using a NRCS truck mounted probe at each measurement site. A 6.35-cm diameter probe was used to collect the samples to 120-cm depth, a 3.81-cm diameter probe was used from 120-cm to the 200-cm depth. In the field, the cores were dissected by soil horizon. The soil samples of the top 2 horizons were air-dried and ground to pass through a 2 mm sieve. Particle size distribution was measured using the pipette method for clay (Steele and Bradfield, 1934; Kilmer and Alexander, 1949), wet sieving method for sand, and silt was determined by the difference.

Measurements of soil carbon content were performed on fine-ground sub samples. Soil inorganic carbon content was measured using the modified pressure-calcimeter method (Sherrod et al., 2002) and total carbon content was measured using the dry combustion method (Soil Survey Staff, 1972; Nelson and Sommers, 1982). Organic carbon content was calculated as the difference between total carbon and inorganic carbon contents.

Soil water retention was measured on samples that were collected from the three catenas at each landscape position. Intact soil cores were collected from the surface 15 cm using a 7.6-cm diameter by 15.2-cm tall core sampler with plastic sleeve inserts. The tops and bottoms 3.8 cm of the 15.2 cm cores were removed leaving 7.6-cm diameter by 7.6-cm tall core samples. The intact cores were stored at 4˚C until the water retention measurements were made. The undisturbed soil samples were allowed to reach room temperature then saturated from the bottom using 0.005 M $CaSO_4$ water solution. After saturation, the samples were weighed, and then placed on a pressure plate extractor (Dane and Hopmans, 2002) at a water potential of -10 kPa, allowed to equilibrate and then weighed. The samples were then equilibrated at -33, and -100 kPa and weighed after each equilibration. After equilibration at -100 kPa, the samples were oven dried at 105 ˚C to determine water contents. Volumetric water content of a sample was determined from the mass of water lost, the density of water, and the volume of the sample when collected from the field.

ROSETTA Modeling

The computer program ROSETTA (Schaap et al., 2001) was used to estimate variations in K_s based on particle size distribution, bulk density, and water content at -33 kPa water potential. Estimates of K_s were based on models using particle size distribution only; using particles size distribution and bulk density; and using particle size distribution, bulk density, and water content at -33 kPa water potential. The estimated K_s values based on each of the three models were compared with the measured K_s values to determine which model best estimated the variability of K_s across each catena.

Statistical Analysis

Variance in the mean logarithmic-transformed values of K_s was compared to variance in landscape position and EC_a using ANOVA in the SAS statistical software (SAS 2002). All statistical analyses were conducted using log-transformed values of K_s (Messing and Jarvis, 1993; Lin et al., 1998; Sobieraj et al., 2002; Gupta et al., 2006). Statistical analysis of differences between means of log-transformed K_s at the different landscape positions and EC_a zones were analyzed using Fishers protected LSD (SAS 2002). Multiple linear regression, using the R statistical software package, was performed to identify the soil properties that best describe the measured variability in K_s. In addition to the soil properties measured, two indicator variables were added to the multiple regression analysis to account for the three catenas (Chatterjee and Hadi, 2006). Backward elimination was used, and each variable with the highest p-value was eliminated, one at a time, until the only remaining variables were significant at a p-value of less than 0.05.

CHAPTER IV

RESULTS AND DISCUSSION

Variation of Soil Properties Across the Landscape

Soil properties varied across the catenas as a result of both pedogenic processes and land management practices. Means of soil properties from each catena were tested for differences. However, when differences between catenas were significant, those differences could not be attributed to land use because land use was not replicated in the experimental design. Land use should not affect soil texture of a whole catena, but texture can vary with landscape position because of erosion and deposition. Clay content of the soil surface was not significantly different across landscape positions (Table 2). Clay content of the soil surface was found to be significantly lower in the native prairie catena than in the improved pasture and conventional tillage catenas (p-value < 0.01).

Soil properties that are frequently modified with change in land use and management include, soil organic carbon, water retention, and bulk density. Soil organic carbon was significantly different between all three catenas (p-value < 0.05). The native prairie catena contained the highest soil organic carbon content with a mean of 2.9% (Fig. 4a). The average soil organic carbon content in the improved pasture catena was 2.1%. The conventional tillage catena had the lowest soil organic carbon content with an average of 1.4%. The observed differences in soil organic carbon between the catenas under different land uses are consistent with difference in soil

Table 2. Surface horizon clay percentages for the different landscape positions within each catena.

Catena	Position	Clay (%)	
		$\overline{X}$	s†
Improved pasture	Summit	43.9Aa	2.0
	Backslope	39.6Ab	2.4
	Footslope	43.5Aa	1.2
Native prairie	Summit	36.6Ba	3.9
	Backslope	37.3Ba	2.9
	Footslope	38.1Ba	3.6
Conventional tillage	Summit	49.7Aa	1.2
	Backslope	46.4Ab	2.9
	Footslope	47.1Ab	4.4

†s, sample standard deviation; $\overline{X}$, arithmetic mean of clay content.
A, B indicates significant differences between the catenas; a,b indicate significant differences across the different landscape positions within each catena.

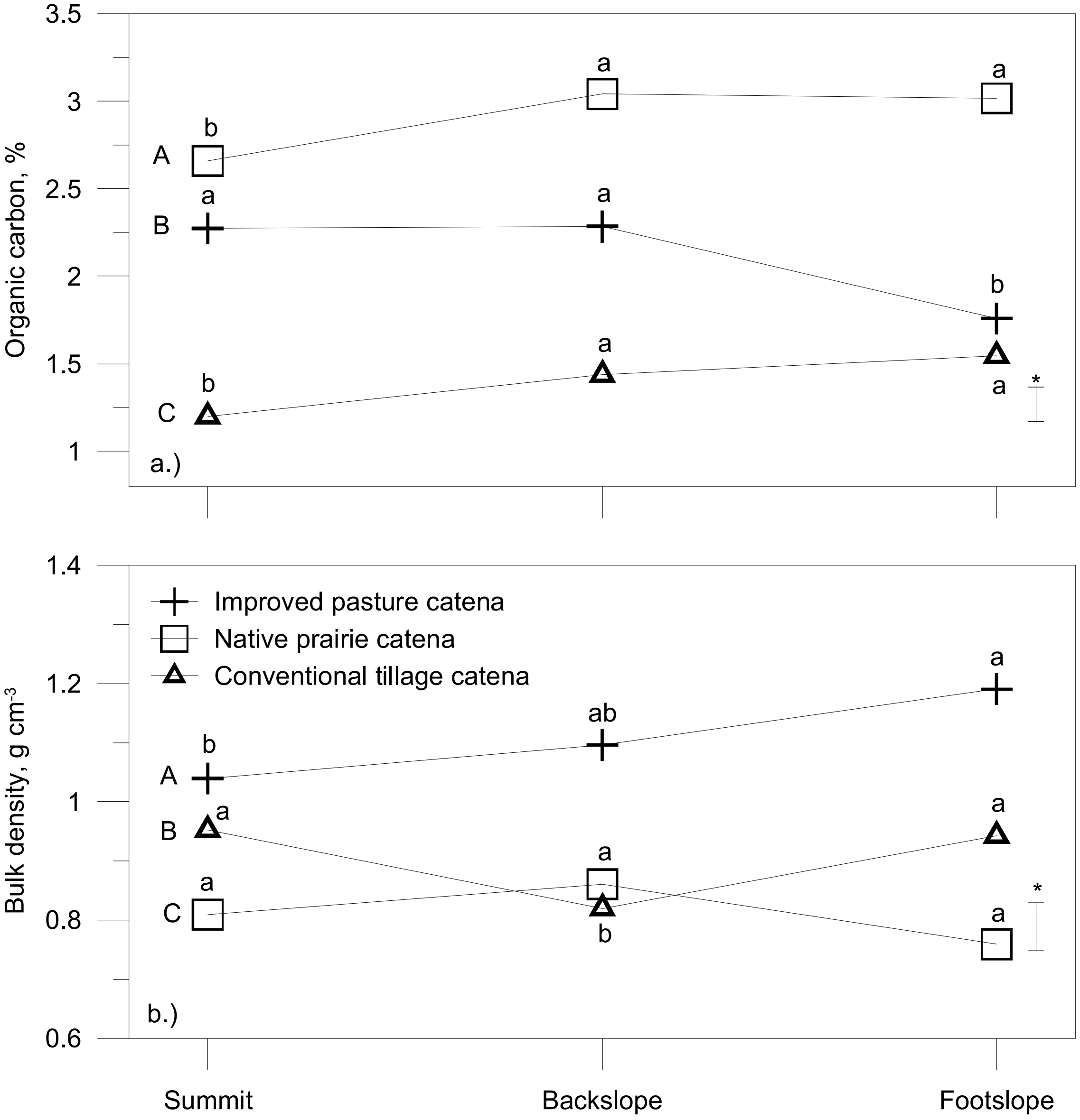

Figure 4. Mean a.) soil organic carbon and b.) bulk density across the different landscape positions within each catena. *, LSD bar. A, B, C indicated significant differences among land uses; a, b indicate significant differences among the different landscape positions.

organic carbon as a function of land use found in other studies (Brye et al., 2002; Brye and Pirani, 2005; Potter, 2006; Wei et al., 2008).

Bulk density of the soil at the surface was also significantly different between the three catenas (p-value < 0.05) (Fig. 4b). The water contents varied between the catenas at the time of measurements because the measurements spanned from fall of 2008 to late spring 2009. Bulk density varied with water content, and because these are shrink-swell soils, some of the differences in bulk density are attributed to water contents at the time of the measurements. The native prairie catena has not been grazed or plowed since 1948 and had the lowest bulk density, but it was also the wettest and had the highest organic matter, which may account for these lower densities–bulk density decreases as water content at the time of obtaining the cores increases. Bulk density was not significantly different across landscape positions within the native prairie catena. Bulk density was highest in the improved pasture catena, but the water content was also the lowest. Bulk density was significantly higher in the footslope position of the improved pasture catena, but the water content was lowest in the footslope. In the conventional tillage catena, bulk density was significantly lower in the backslope, but the backslope also had the highest water content. Landscape position did not consistently correlate with changes in bulk density. Soil in the conventional tillage catena had lower water content at -33 kPa water potential than the improved pasture and native prairie catenas (Fig. 5). The lower water content in the conventional tillage catena at higher water potentials is possibly attributed to the destruction of water stable aggregates from the

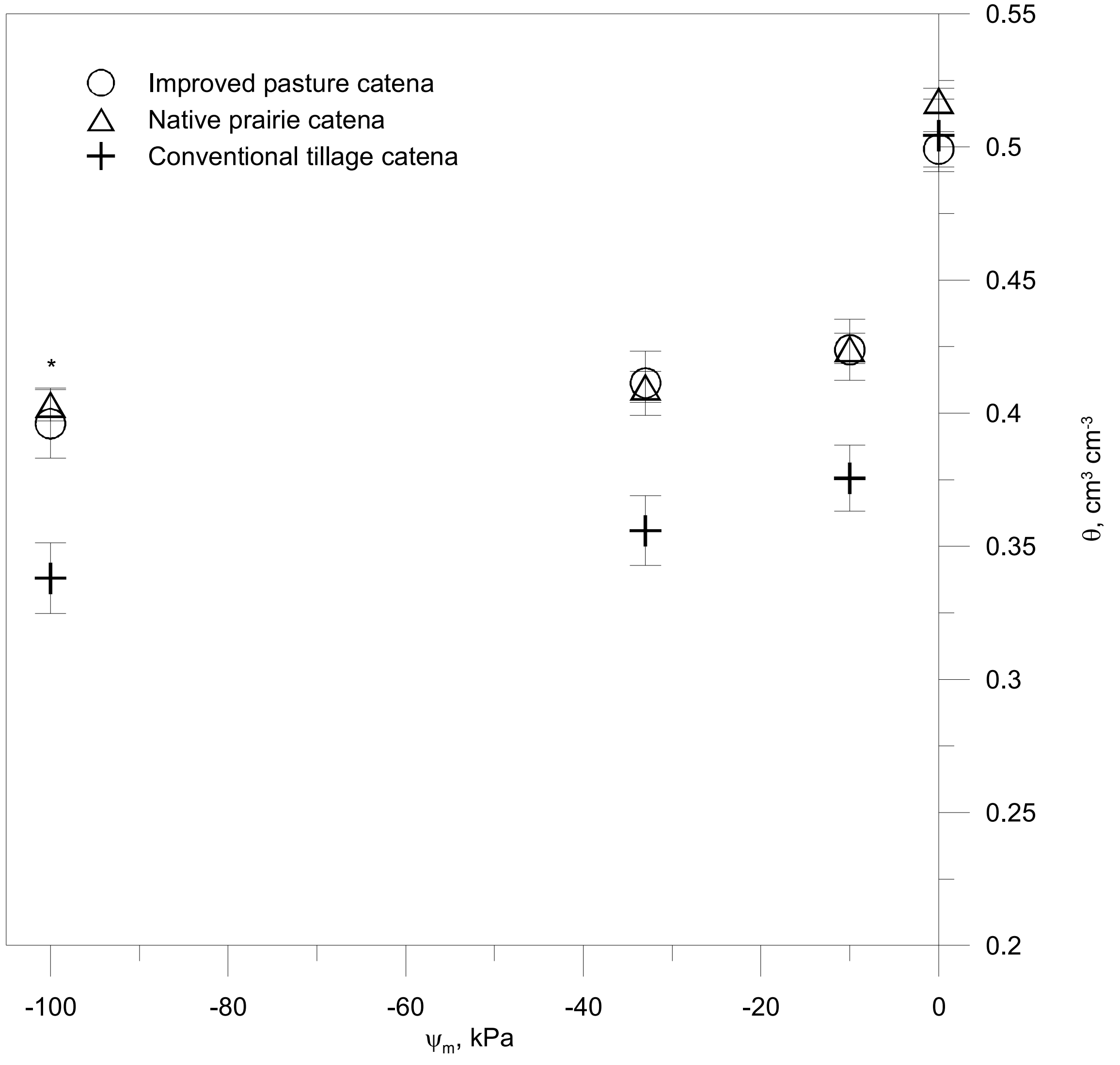

Figure 5. Average volumetric water contents (θ) at different water potentials (ψ_m) for the three catenas. Bars indicate standard error.

plowing which would typically hold more water at higher potentials (Chang and Lindwall, 1990; Mapa, 1995).

Variation of K_s Across the Landscape

The measured K_s values across the three catenas were found to range from 0.16 to 34.72 cm h^{-1} (Table 3). The high variability of K_s can be attributed to the spatial variability of macropores, especially in high clay content soils where K_s is highly influenced by macropore flow (Messing and Jarvis, 1993; Lin et al., 1998; Sobieraj et al., 2002; Gupta et al., 2006). Across all three land uses, K_s was skewed right and non-normally distributed, as expected (Fig. 6). When the K_s values were log-transformed the data were normally distributed (Fig. 7). Of the 102 K_s measurements, 60 measurements were conducted on the Houston Black soil series and 42 measurements were conducted on the Heiden soil series. The overall geometric means of K_s on the Houston Black and Heiden soil series, 4.4 and 3.9 cm h^{-1}, respectively, were not significantly different ($\alpha = 0.05$). The overall mean of K_s was 4.1 cm h^{-1}, but the three catenas had different means. The mean of K_s in the improved pasture catena was 1.7 cm h^{-1}. The mean of K_s in the native prairie catena was 2.4 cm h^{-1}. The mean of K_s in the conventional tillage catena was 9.2 cm h^{-1}. The amount of measurements needed to be statistically confident that the sample mean is within a certain percentage of the population mean can be estimated based on the measured means and standard deviations of the collected data (Fig. 8). For example, based on Fig. 8, for a sample set to be within 10% of the population mean with 90% statistical confidence 18 measurements are required. To have 80% statistical

Table 3. Measured K_s values within each EC_a zone of the different landscape positions within each catena.

Catena	Position	EC_a zone	n	$\overline{X}_g$ K_s (s)	Max	Min	CV†
				--------------cm h^{-1}--------------			
Native prairie	Summit	Low	3	3.01 (2.11)	9.60	1.12	0.70
	Backslope	Low	3	2.25 (3.03)	7.92	0.98	1.35
	Backslope	Medium	3	11.51 (2.15)	21.05	3.26	0.23
	Backslope	High	3	2.61 (2.67)	7.87	1.20	1.02
	Footslope	Medium	3	2.18 (1.78)	4.98	1.15	0.81
	Footslope	High	6	0.51 (3.03)	1.44	0.16	5.89
Improved pasture	Summit	Medium	9	1.94 (3.07)	12.86	0.61	1.23
	Backslope	Low	9	2.69 (1.96)	7.56	0.79	0.66
	Footslope	High	9	0.88 (2.50)	4.86	0.20	2.10
Conventional tillage	Summit	Medium	12	6.69 (1.61)	18.53	2.91	0.24
	Backslope	Low	6	8.17 (2.09)	26.08	3.99	0.26
	Backslope	Medium	6	7.96 (2.23)	20.07	1.51	0.28
	Backslope	High	6	7.47 (1.55)	14.24	3.47	0.21
	Footslope	Low	6	17.10 (1.32)	21.21	9.44	0.08
	Footslope	Medium	6	15.98 (1.72)	34.72	6.81	0.11
	Footslope	High	6	9.24 (1.56)	18.43	4.50	0.17

†CV, coefficient of variance; s, sample standard deviation; $\overline{X}_g$ K_s, geometric mean of saturated hydraulic conductivity; n, number of measurements.

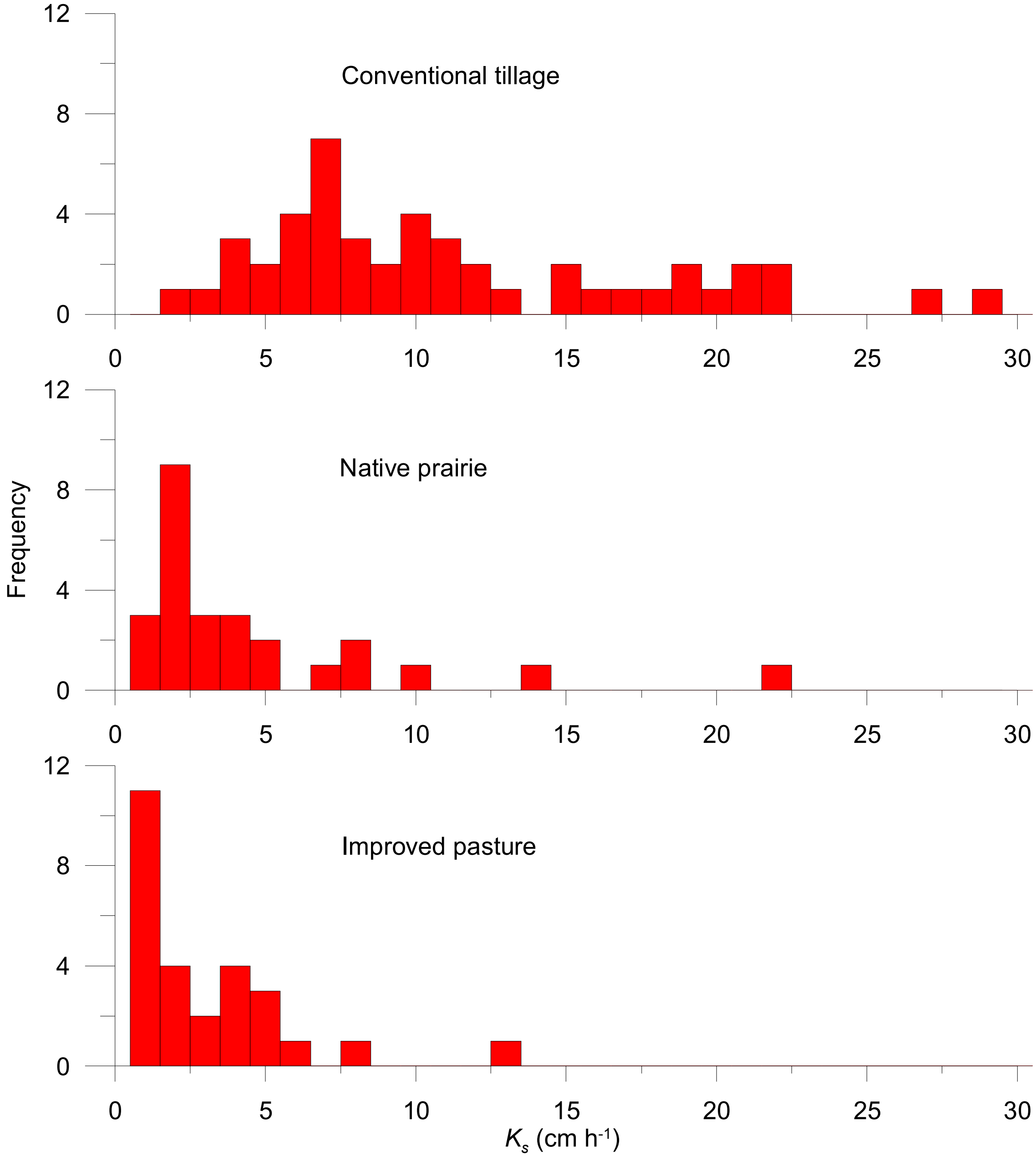

Figure 6. Histograms of untransformed K_s data across the improved pasture, native prairie, and conventional tillage catenas. A skewed right distribution of K_s is shown requiring K_s to be transformed for statistical analysis.

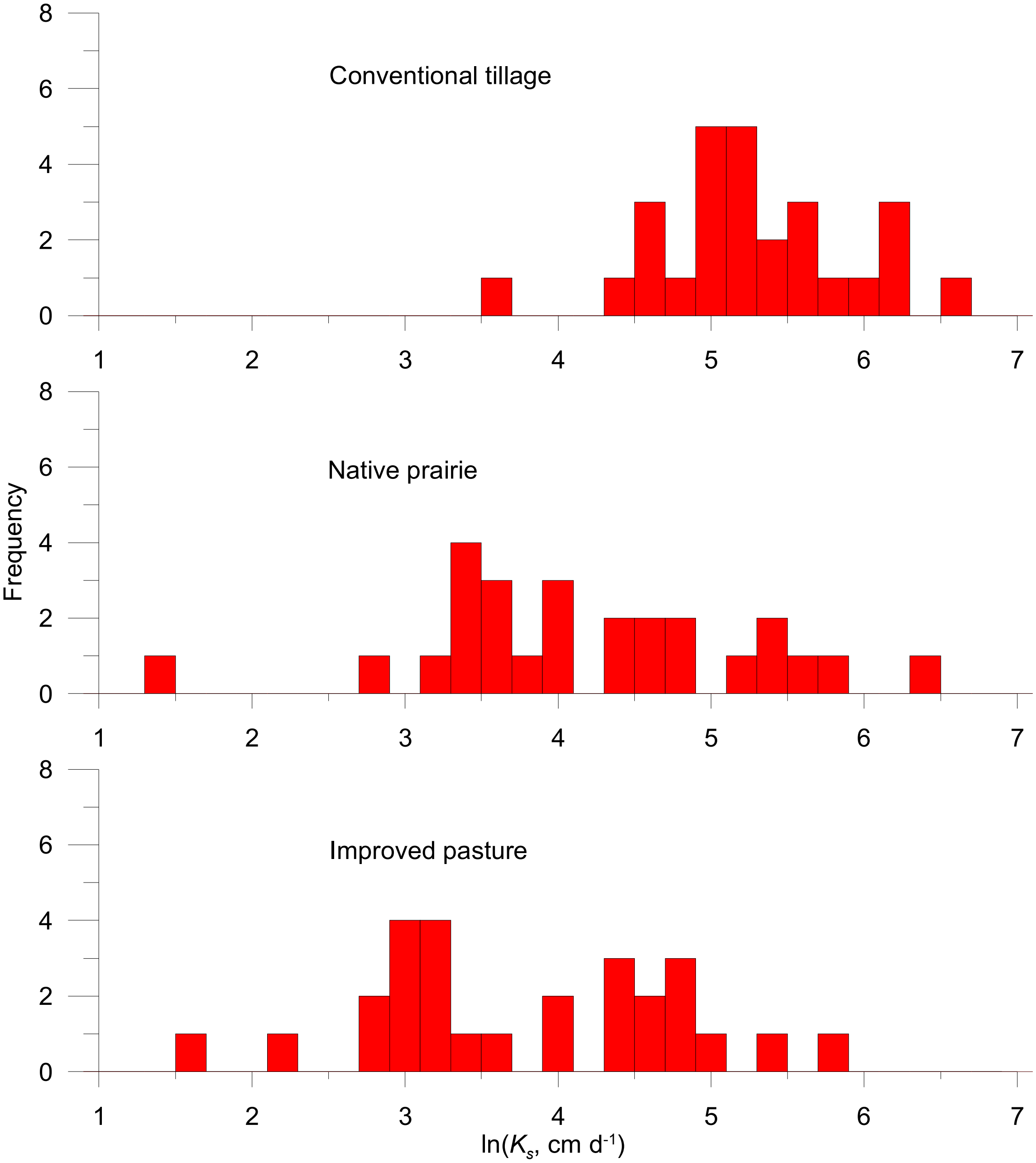

Figure 7. Histograms of log-transformed K_s across the improved pasture, native prairie, and conventional tillage catenas.

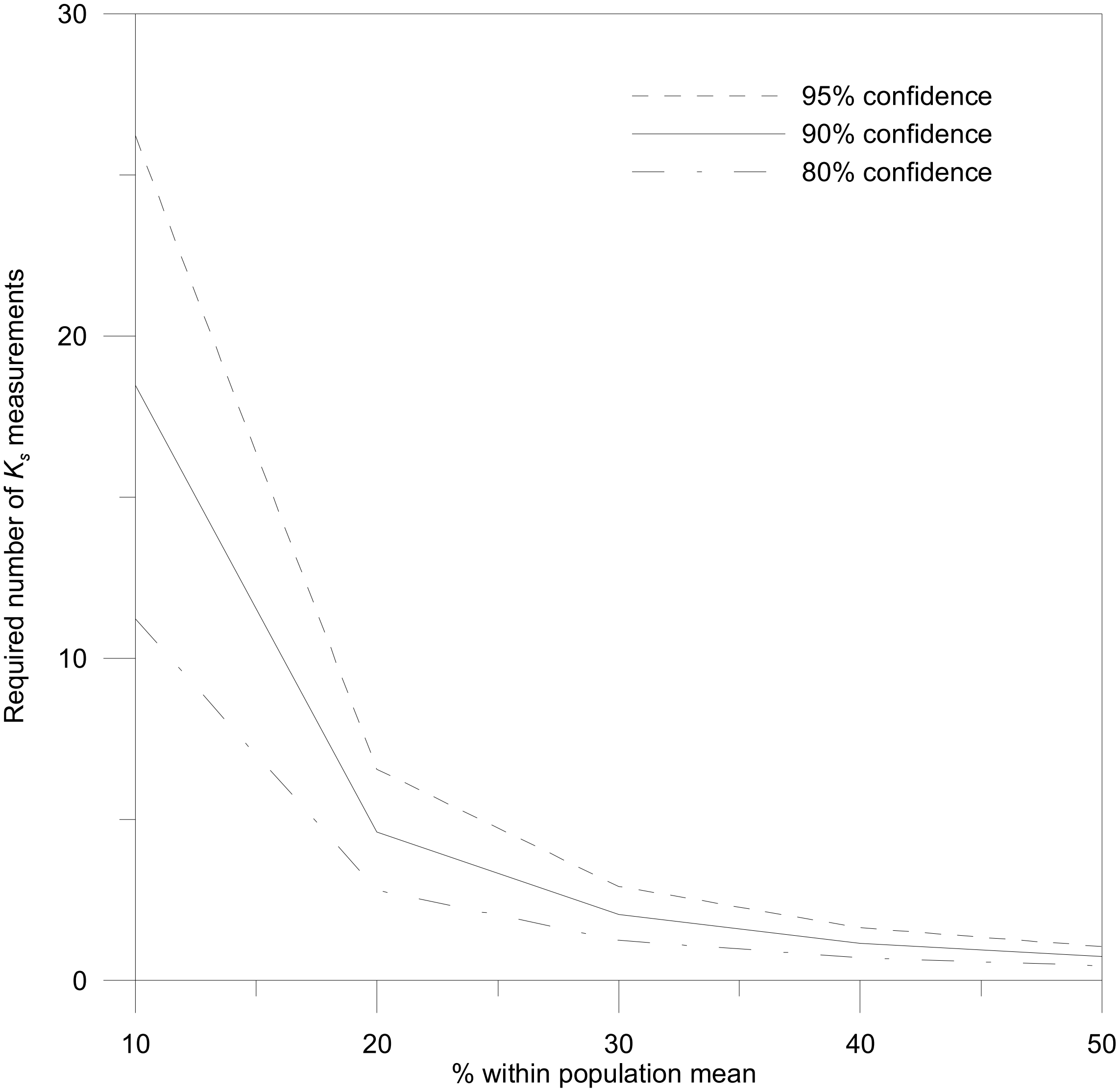

Figure 8. The required number of K_s measurements to fall within a certain percentage of the population mean at 95, 90, and 80% statistical confidence based on the measured means and standard deviations in this study.

confidence that the sample set is within 10% of the population mean 12 measurements are required.

When K_s values were compared across landscape position, statistically there were no significant differences between landscape positions (Table 4). There was however a significant block effect across the three catenas. When K_s values were compared across the different landscape positions within each individual catena, K_s values at the different landscape position were significantly different, but did not follow a consistent trend (Fig. 9). In the improved pasture and native prairie catenas, the mean K_s were significantly lower in the footslope position than the backslope position. A different trend was found in the conventional tillage catena, with the footslope position having the higher mean of K_s than the backslope and summit positions. The variation in K_s across the different landscape positions can partially be attributed to variations in clay content, bulk density, and soil organic carbon among the different landscape positions. Similar results showing a variation of K_s with landscape position have been found in catenas of other soils (West et al., 2008). The finding of a higher K_s value in the backslope position of the improved pasture and native prairie catenas is contradictory to results in Jiang et al. (2007). However, the soils in this study are deep clay soils, whereas the soils in the study by Jiang et al. (2007) were in the clay pan region of Missouri where the subsoil is known to have a significantly lower hydraulic conductivity in the more eroded positions due to the shallow claypan. Erosion on a Vertisol catena, would lead to exposure of similar textured subsoil likely to have similar hydraulic properties, where as exposure of

Table 4. Analysis of variance table of log-transformed K_s across the different landscape positions blocked by land use.

Source	DF	Sum of Squares	Mean Square	F-value	Pr (> F)
Model	4	61.48	15.37	20.13	<0.0001
Error	96	73.29	0.76		
Total	100	134.77			
Block (land use)	2	59.47	29.74	38.95	<0.0001
Landscape position	2	1.32	0.66	0.87	0.4232

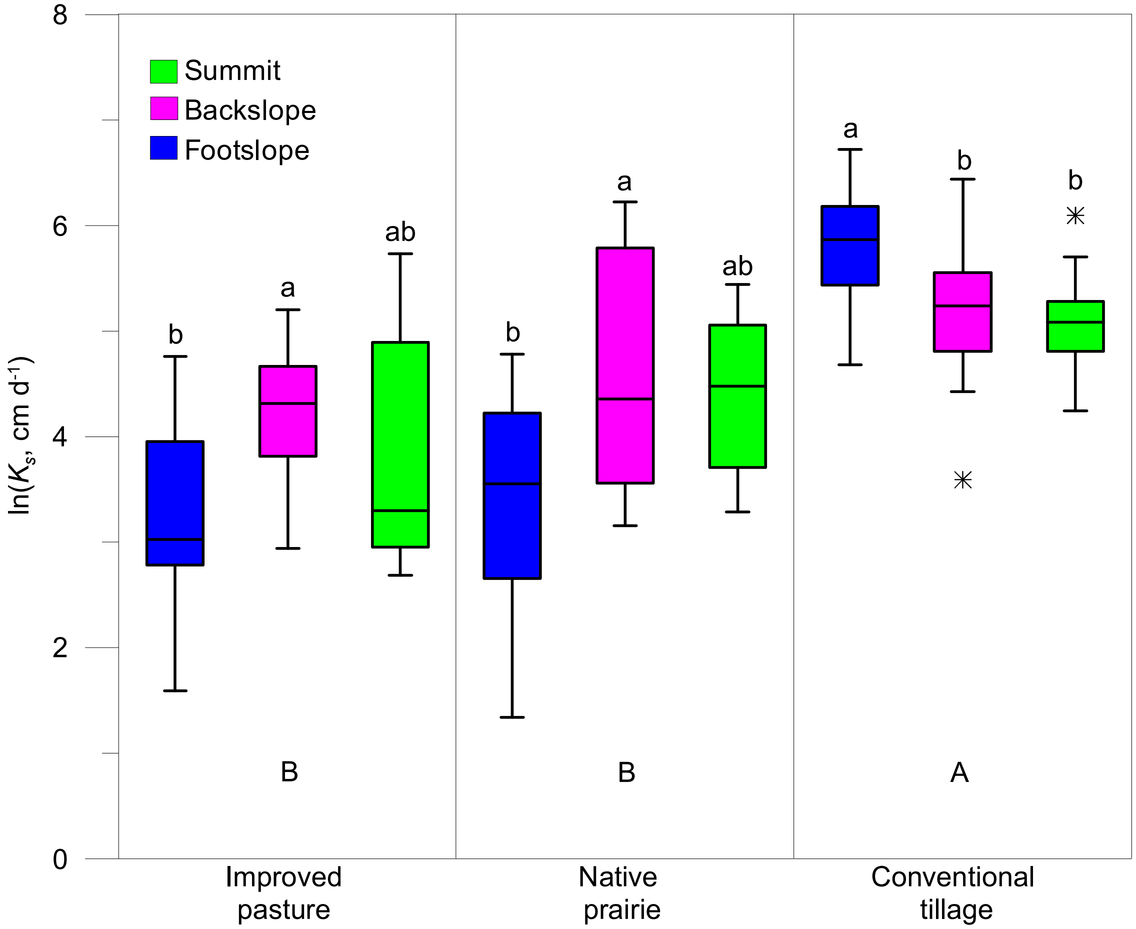

Figure 9. Boxplot of log-transformed K_s separated by landscape position within each catena. A, B indicated significant differences among land uses; a, b indicate significant differences among the different landscape positions within each catena.

subsoil in a clay pan soil would lead exposure of soil with appreciably lower hydraulic conductivity.

Finding a lone soil property that can be used to explain variations in K_s over landscape position and land use is unlikely, even under relatively uniform soils like the Vertisols in this study. Some of the different soil properties that are known to influence K_s include bulk density, organic carbon, and particle size distribution (Mapa, 1995; Baldock and Nelson, 2000) which was also the case in this study. There was a slight trend with landscape position showing that higher bulk densities were associated with lower K_s values (Fig. 4b and Fig. 9). Soil organic carbon can have a large influence on soil hydraulic properties because of its influence on the size, shape, and stability of soil aggregates (Mapa, 1995; Baldock and Nelson, 2000; Wagner et al., 2007). Variations in soil organic carbon across landscape positions shared similar trends to the variation in K_s changes across the landscape positions within each land use (Fig. 4a and Fig. 9).

Variation of K_s Between EC_a Zones

Within the catena under improved pasture, K_s were significantly lower in EC_a Zone 3 (highest value EC_a zone) compared to Zones 1 (lowest value EC_a zone) and 2 (Fig. 10) (p-value < 0.05), but overall, the means of K_s did not vary significantly between different EC_a zones. The lower K_s in EC_a Zone 3 is possibly due to the significantly higher bulk density in EC_a Zone 3 than in Zones 1 and 2 (Fig. 11). One of the reasons that EC_a zones may not have been correlated with variations of K_s may be attributed to the fact that EC_a changes in these catenas responded more to depth to parent material (Fig. 12) than the soil properties that influence water flow in the soil. The EC_a

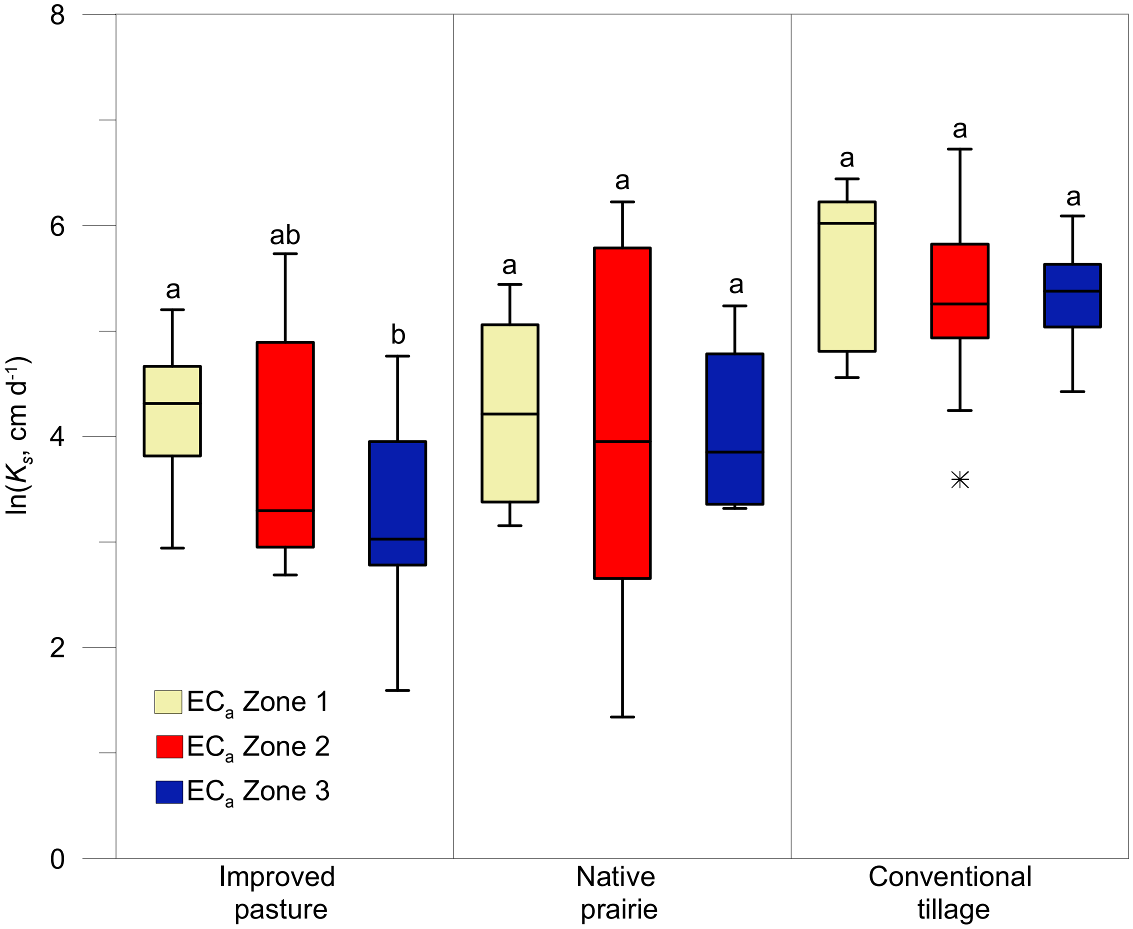

Figure 10. Boxplot of log-transformed K_s separated by EC$_a$ zone within each catena. a, b indicate significant differences between the different EC$_a$ zones.

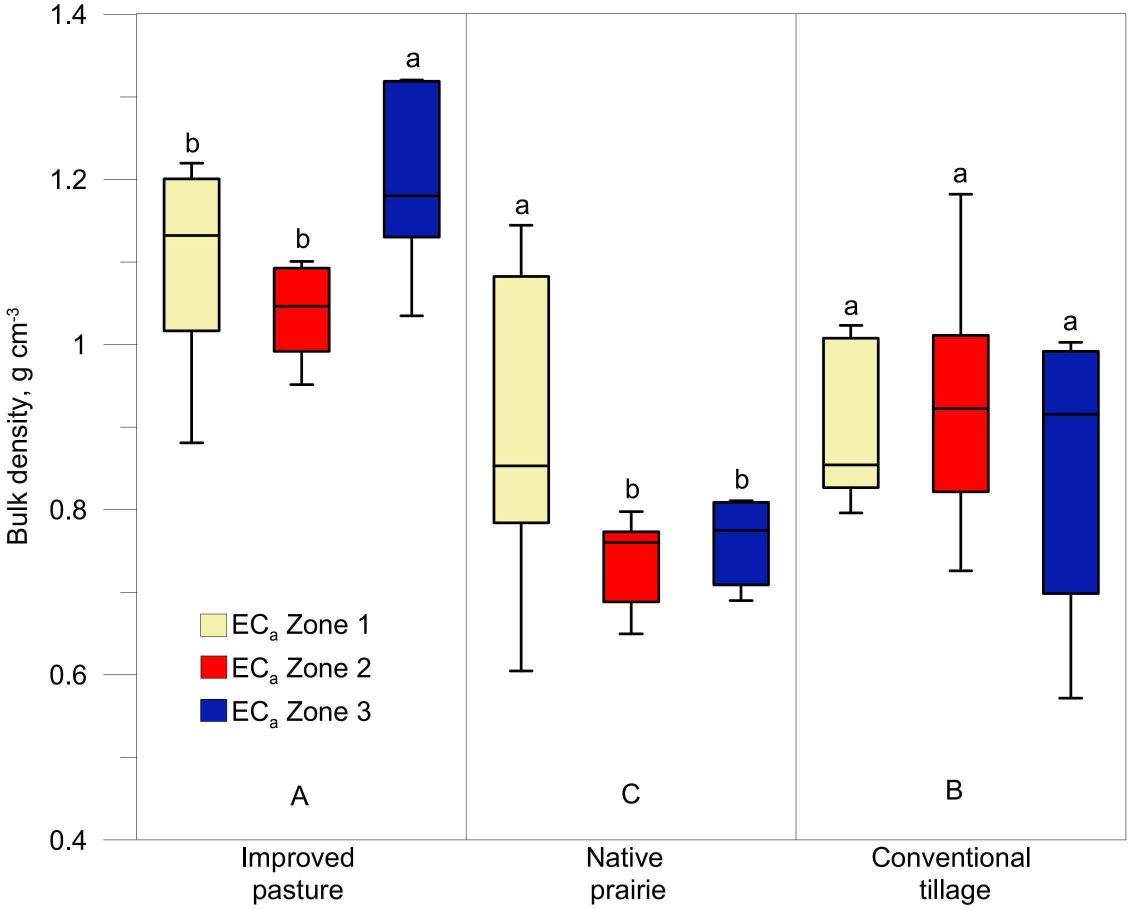

Figure 11. Boxplot of bulk density (ρ_b) separated by EC_a zone within each catena. A, B, C indicated significant differences between land uses; a, b indicate significant differences between the different EC_a zones.

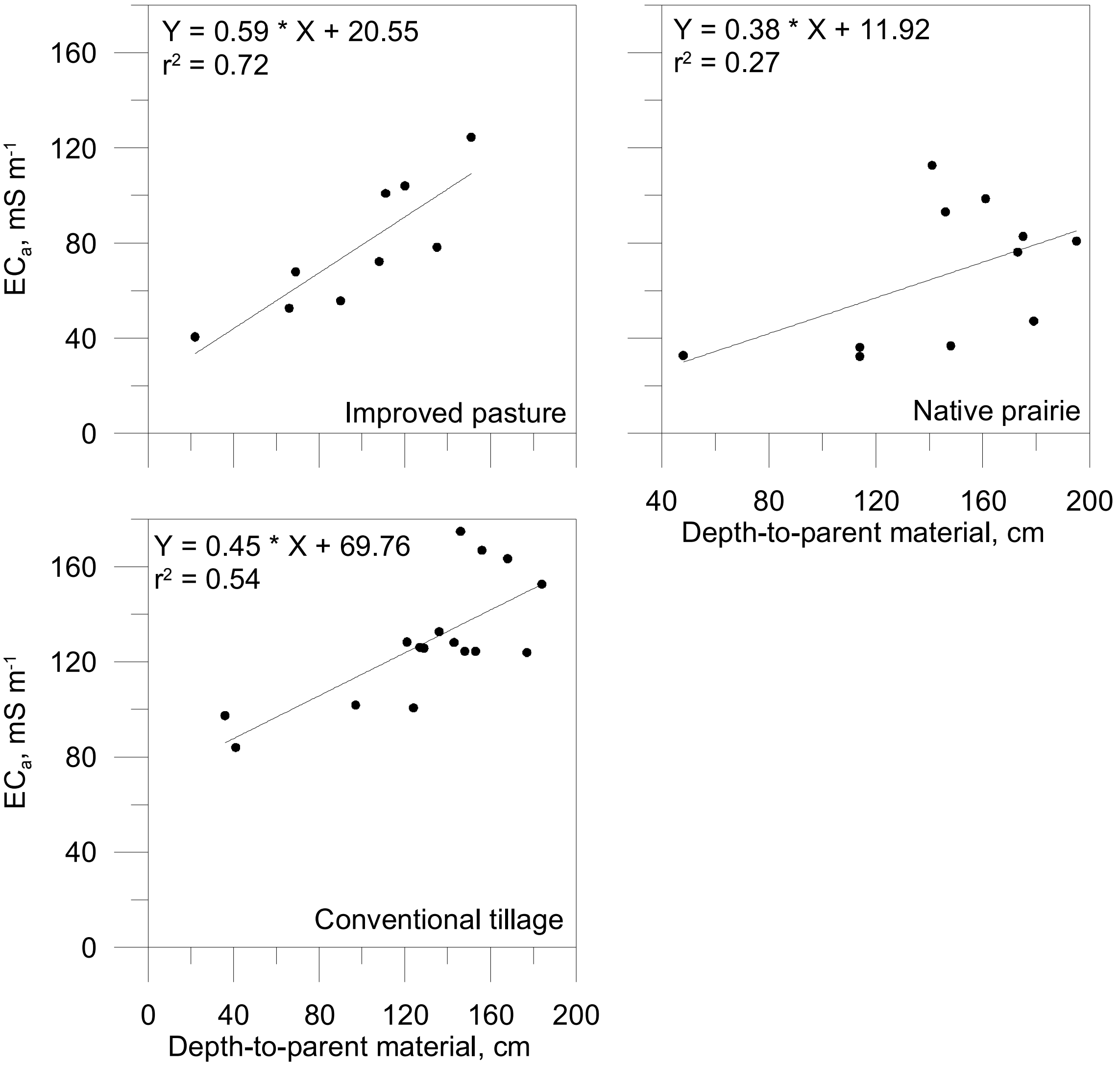

Figure 12. Values of EC_a plotted with field measurements of depth-to-parent material for the improved pasture, native prairie, and conventional tillage catenas.

measurements cannot be compared for all three catenas together because the EC_a measurements were taken on different days while the soils were at different water contents.

Multivariate Analysis

To assess what variations in soil properties were most correlated with variations in K_s, clay content, EC_a value, bulk density, antecedent water content, soil organic carbon, and indicator variables for the improved pasture and native prairie catenas were used in multiple linear regression analysis. The best fit model included clay content, soil organic carbon, bulk density, water content and the catena indicator variables (Table 5). Increases in clay content and soil organic carbon were positively correlated with increases in K_s (Fig. 13a and Fig. 14). Increases in clay and soil organic carbon content are known to increase wet aggregate stability, which helps preserve flow paths for water (Mapa, 1995; Baldock and Nelson, 2000; Wagner et al., 2007). Bulk density and antecedent water content are negatively correlated with K_s (Fig. 13b and Fig. 13c). The decrease in K_s with decrease in bulk density and antecedent water content is possibly attributed to the shrink-swell characteristics of these soils and the decrease in macropores as the soil swells reducing flow paths for water (Reynolds and Zebchuk, 1996; Lin et al., 1998).

When the indicators variables for the individual catenas are removed from the model, the adjusted-r^2 value reduced to 0.42, meaning that separating the catenas explains 17% of the variability in K_s that cannot be explained the other measured soil properties. Removing the catena parameters from the model also results in soil organic

Table 5. The best model to explain K_s using multiple regression with backward elimination.

Input Variable	Estimate	p-value	r^2	Adjusted-r^2
Indicator for improved pasture	-1.87	1.42e-08		0.59
Indicator for native prairie	-1.48	0.007657		
Clay content	0.08	0.000102	0.15	
Soil organic carbon	1.05	0.000162	0.14	
Bulk density	-2.84	0.000803	0.11	
Antecedent water content	-7.29	0.003105	0.03	

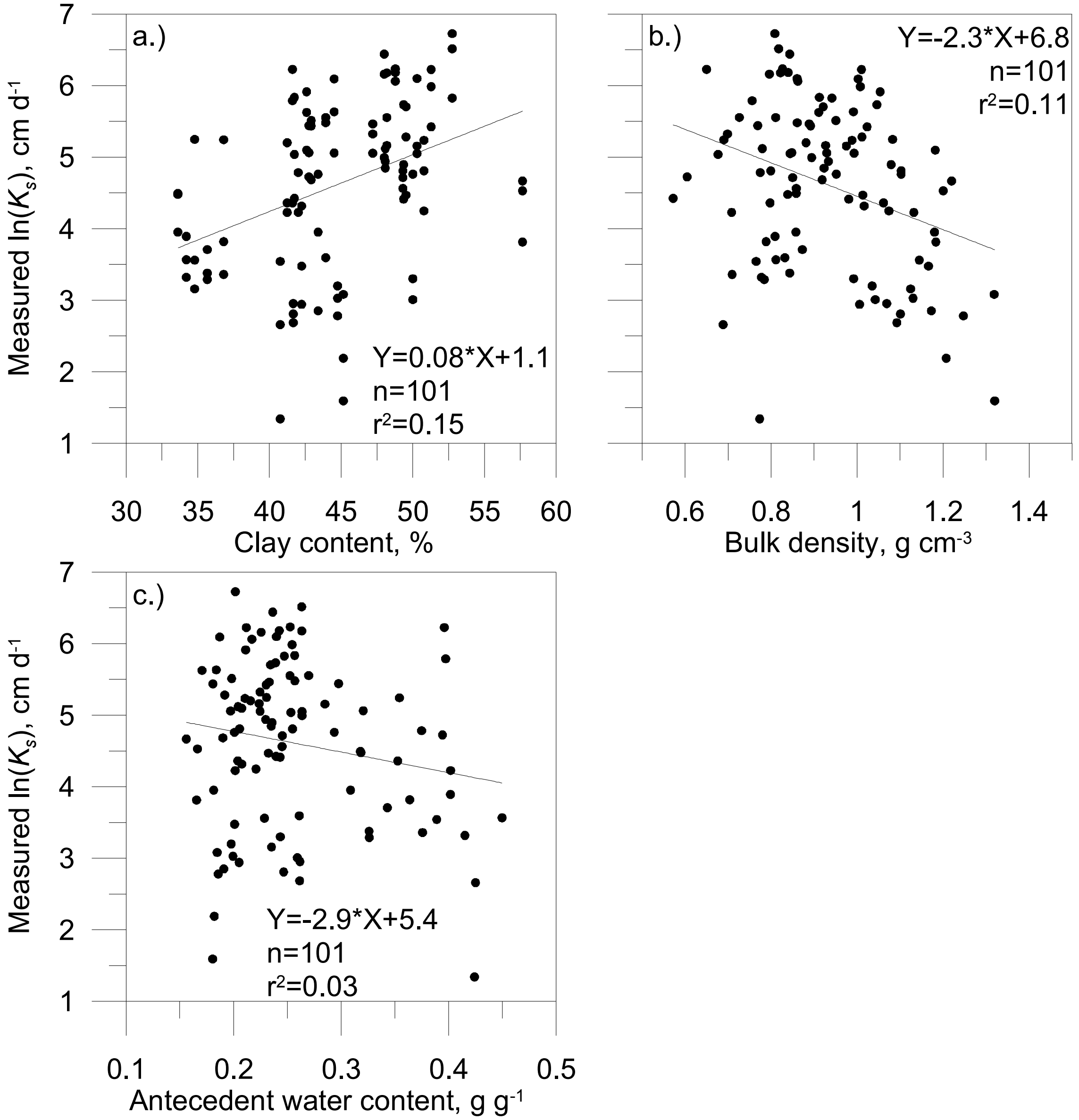

Figure 13. Soil a.) clay content, b.) bulk density, and c.) antecedent water content plotted with ln(K_s) from all catenas and landscape positions.

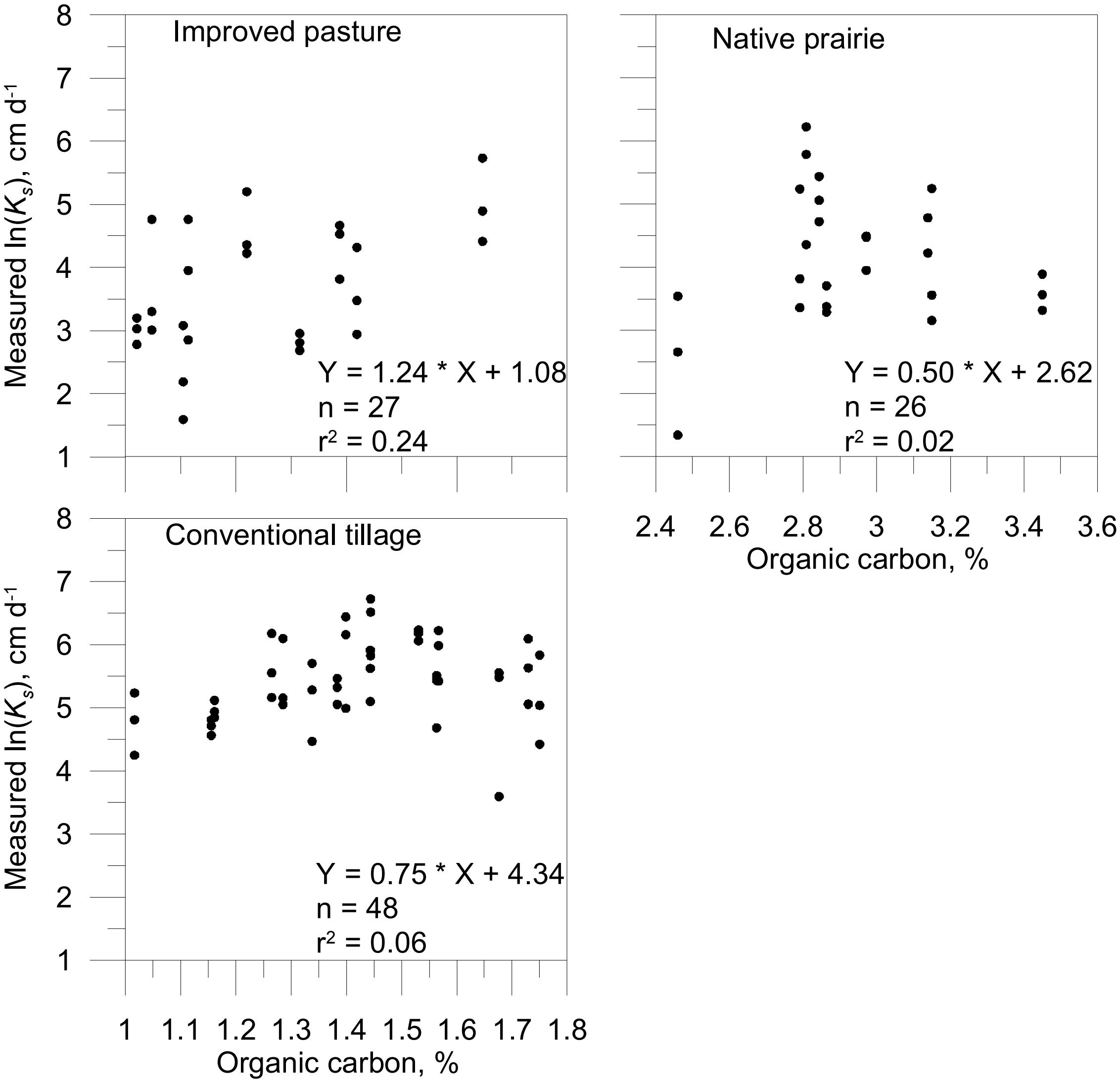

Figure 14. Soil organic carbon plotted with ln(K_s) from all catenas and landscape positions.

carbon becoming a non-significant (p-value 0.47) predictor for K_s. The catena-specific relationship between organic carbon and K_s is weak at best and likely catena-specific because organic carbon is so much higher in the native prairie.

Vertisols shrink and swell with changes in water content, so there is an inherent relationship between bulk density and soil water content (Fig. 15). To remove some of the effect of shrinkage and swelling from using bulk density as a predictor, a new macroporosity variable was defined as the portion of a soil's total porosity remaining after subtracting an estimate of the volume fraction of immobile water. The maximum soil bulk density $\rho_{b,max}$ at the antecedent gravimetric water content (g g^{-1}), w, can be calculated as:

$$\rho_{b,max} = \frac{1}{\left(w + \frac{1}{\rho_s}\right)} \qquad [6]$$

where ρ_s is the particle density. The volume fraction of immobile water or intraaggregate water can be calculated using $\rho_{b,max}$ by using the following equation:

$$f_{im} = \left(1 - \frac{\rho_{b,max}}{\rho_s}\right). \qquad [7]$$

Because a plot of $\rho_{b,max}$ vs w present a form of a soil shrinkage curve, subtracting the volume fraction of immobile water, f_{im}, from total soil porosity, f_t:

$$f_t = \left(1 - \frac{\rho_b}{\rho_s}\right), \qquad [8]$$

should remove some effect of the shrink-swell behavior of the soil. An estimate of the macroporosity f_m created by the shrinking of the soil might be:

$$f_m = f_t - f_{im} = \left(1 - \frac{\rho_b}{\rho_s}\right) - \left(1 - \frac{\rho_{b,max}}{\rho_s}\right). \qquad [9]$$

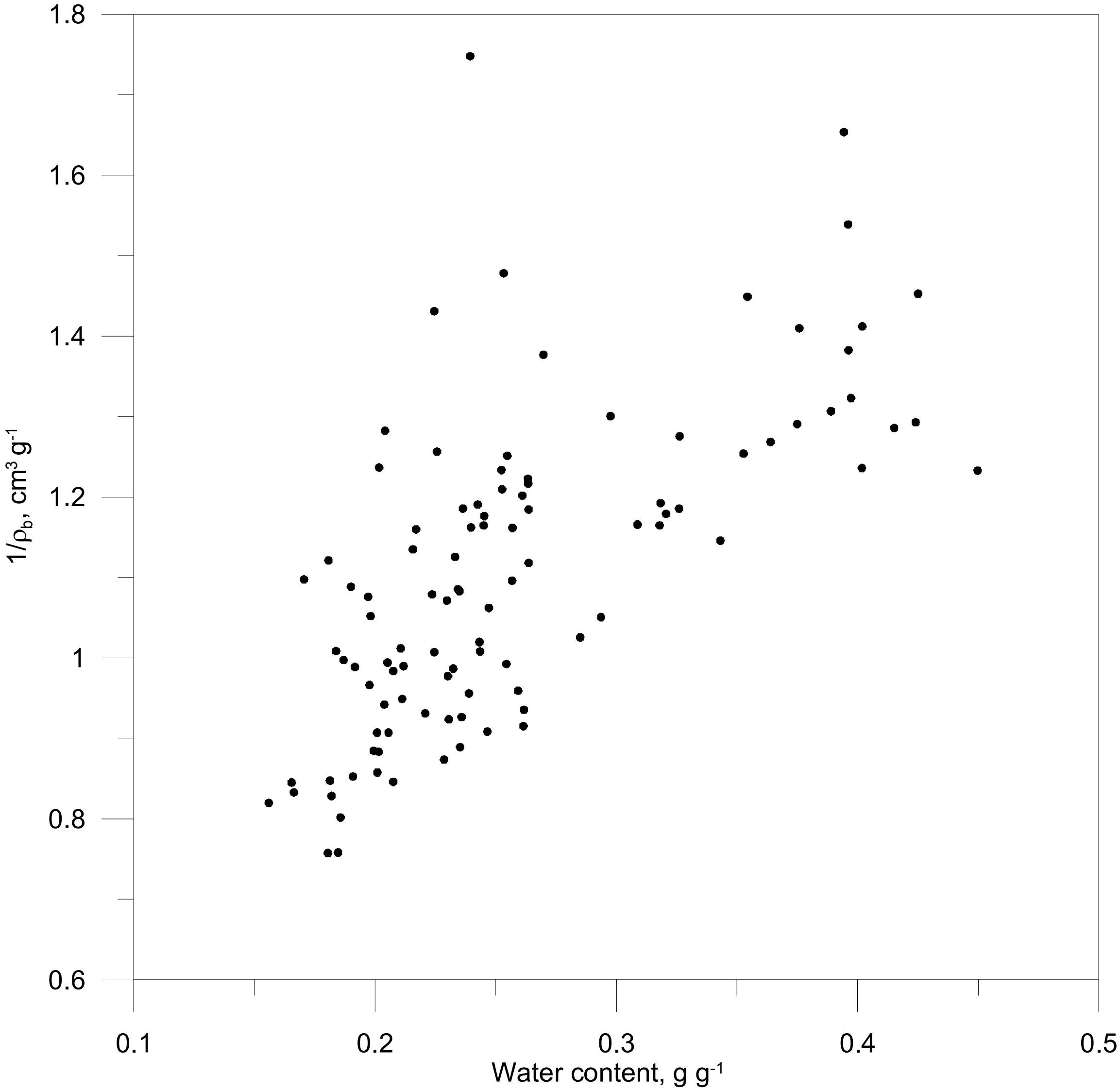

Figure 15. Inverse bulk density plotted with antecedent water content from all catenas and landscape positions.

This macroporosity estimate removes some of the variation of bulk density with water content. The relationship between $\rho_{b,max}$ and water content and ρ_b is shown in Fig. 16. Also shown (Fig. 15) is the relationship between typical field bulk density and water content and typical maximum bulk density and water content when the shrink-swell properties of the soil, based on the Coefficient of Linear Extensibility (COLE), is considered. Macroporosity f_m, of dry soil would be better estimated as the difference between these latter two curves. However, our soils were never dry enough to consider the complexity of the additional theory needed to account for macroporosity in dry soils. When this macroporosity values is used to replace bulk density and antecedent water content in the multiple regression model, the adjusted-r^2 value is only reduced to 0.58 from 0.59. Macroporosity in these shrink-swell soils has a strong positive relationship with variations in K_s (Fig. 17). Estimated macroporosity is able to account for the changes in bulk density due to changes in water content as well as showing that macroporosity has a strong influence on variations of K_s. Notably, this is the highest single correlation between any of the measured soil properties and K_s.

ROSETTA Modeling

ROSETTA estimates of K_s were based on three different pedotransfer functions, namely, particle size distribution alone (sand, silt, and clay, or SSC); particle size distribution with bulk density (SSC-BD); and particle size distribution with bulk density and volumetric water content at -33 kPa water potential (SSC-BD-θ_{-33}). All three pedotransfer functions provided appreciably different estimates of the means and variances in K_s. ROSETTA estimates of K_s are compared to the mean and coefficient of

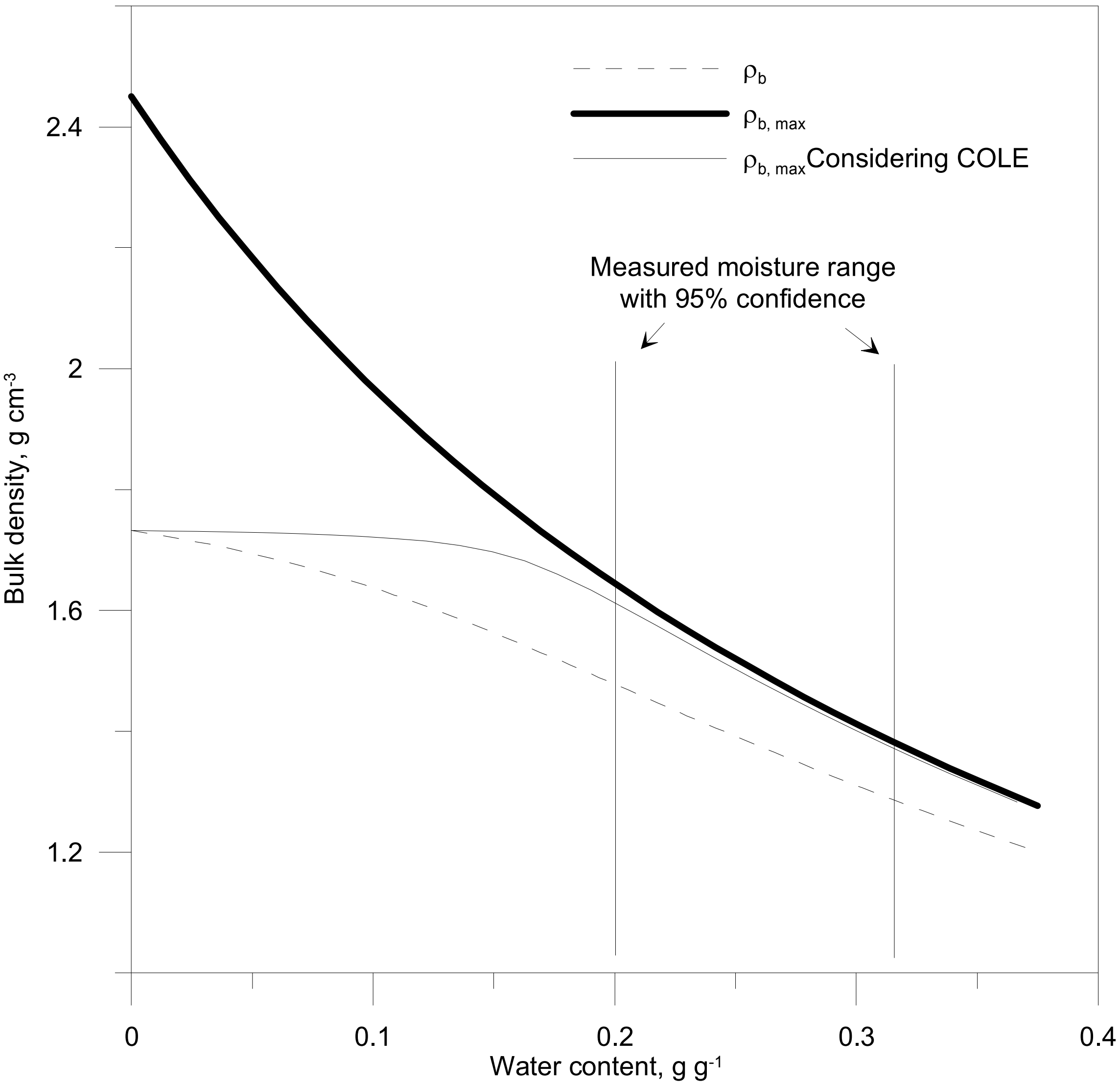

Figure 16. Typical maximum soil bulk density ($\rho_{b,max}$) and a typical field bulk density (ρ_b) found in the three catenas at different gravimetric water contents.

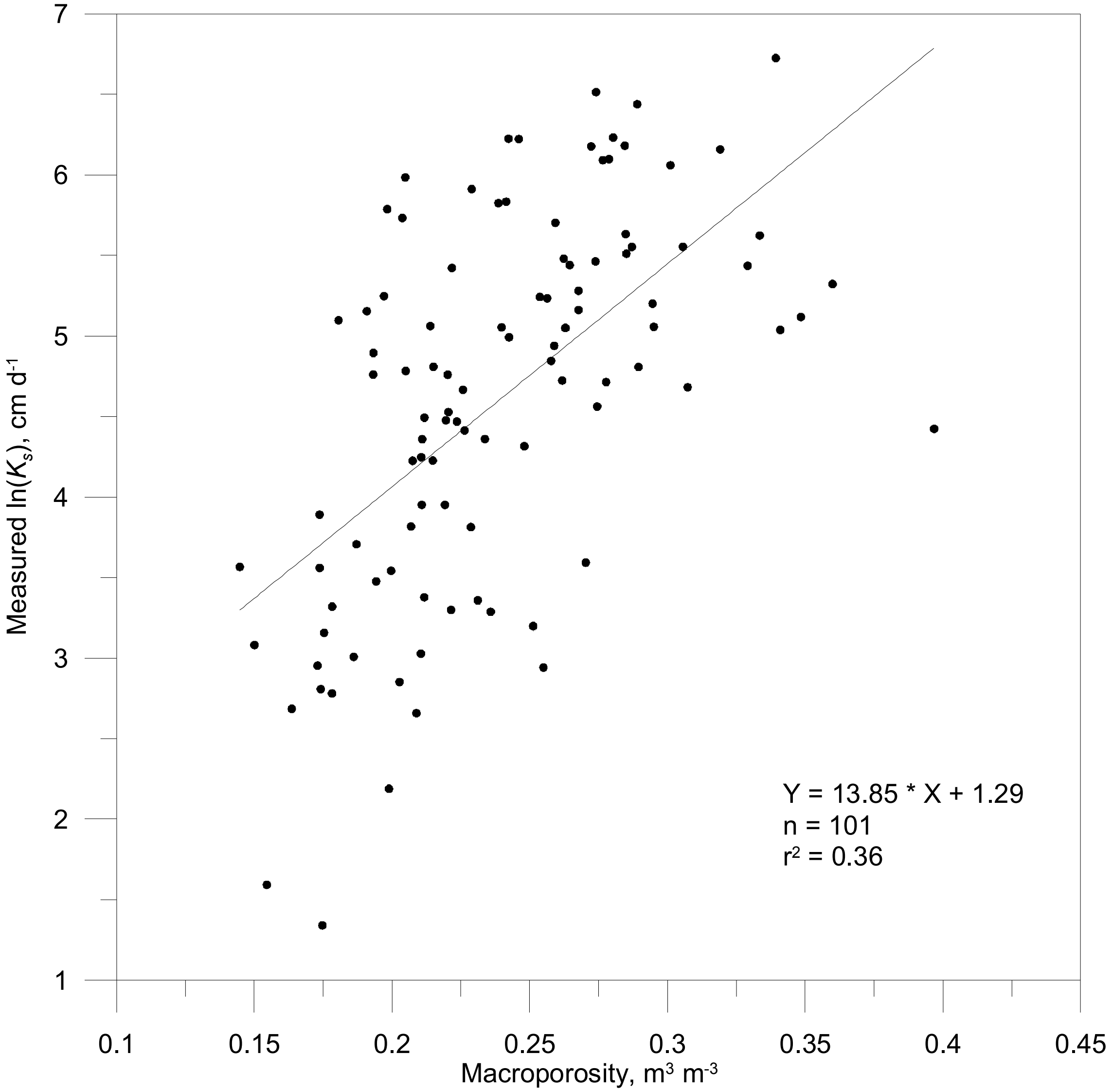

Figure 17. Soil macroporosity plotted with ln(K_s) from all catenas and landscape positions.

variability of the measured K_s values. Depending on the inputs used to estimate K_s, ROSETTA provided reasonable estimates of the overall mean and variance of K_s. When ROSETTA used SSC only to estimate K_s, the estimates were 59% below the measured values (Table 6). When ROSETTA used SSC-BD to estimate measured values of K_s, the estimates more closely matched the measured values. The SSC-BD estimates of mean K_s were only 2% higher than the measured mean of all K_s values. However ROSSETTA estimates of K_s using SSC-BD were compared with the mean K_s within each catena, the predicted means of K_s were 5% higher, 29% higher, and 10% lower than the measured means in the improved pasture, native prairie, and conventional tillage catenas, respectively. The SSC-BD-θ_{33} estimates of K_s produced similar results to the SSC-BD estimates with slightly improved estimates of the overall mean of K_s. The variability of K_s within the SSC, SSC-BD, and the SSC-BD-θ_{-33} estimates were 28%, 64%, and 64% of the measured variability, respectively.

Depending on the inputs used to estimate K_s, ROSETTA also provided reasonably accurate estimates of the mean and variance of K_s across landscape positions within each catena. ROSETTA estimates of K_s using SSC did not produce near the variations in K_s that were observed in the actual measurements (Fig. 18). ROSETTA estimates of K_s using SSC-BD more closely estimated variations of K_s across the different landscape positions within each catena (Fig. 19). The variations of K_s across the different positions were underestimated in the native prairie catena. The SSC-BD model estimated similar spatial trends of K_s across the different landscape positions to that of the measured in the improved pasture catena. ROSSETTA estimates of K_s using

Table 6. Comparison of measured and ROSETTA predicted means and variances of K_s across the three catenas. ROSETTA estimates of K_s are based on particle size distribution alone (SSC), particle size distribution with bulk density (SSC-BD), and particle size distribution, bulk density, and water content at -33 kPa water potential (SSC-BD-θ_{33}).

Catena	Model	ln(K_s, cm d^{-1})		
		$\overline{X}$†	s	CV
Overall	Measured	4.6	1.2	0.25
	SSC	2.7	0.2	0.07
	SSC-BD	4.7	0.8	0.16
	SSC-BD-θ_{-33}	4.6	0.8	0.16
Improved pasture	Measured	3.7	1.0	0.27
	SSC	2.6	0.1	0.03
	SSC-BD	3.9	0.6	0.16
	SSC-BD-θ_{-33}	3.9	0.6	0.16
Native prairie	Measured	4.1	1.1	0.26
	SSC	2.5	0.1	0.02
	SSC-BD	5.3	0.5	0.10
	SSC-BD-θ_{-33}	5.3	0.6	0.11
Conventional tillage	Measured	5.4	0.7	0.12
	SSC	2.8	0.2	0.07
	SSC-BD	4.9	0.5	0.10
	SSC-BD-θ_{-33}	4.7	0.5	0.11

†$\overline{X}$, arithmetic mean of ln(K_s); s, sample standard deviation; CV, coefficient of variance.

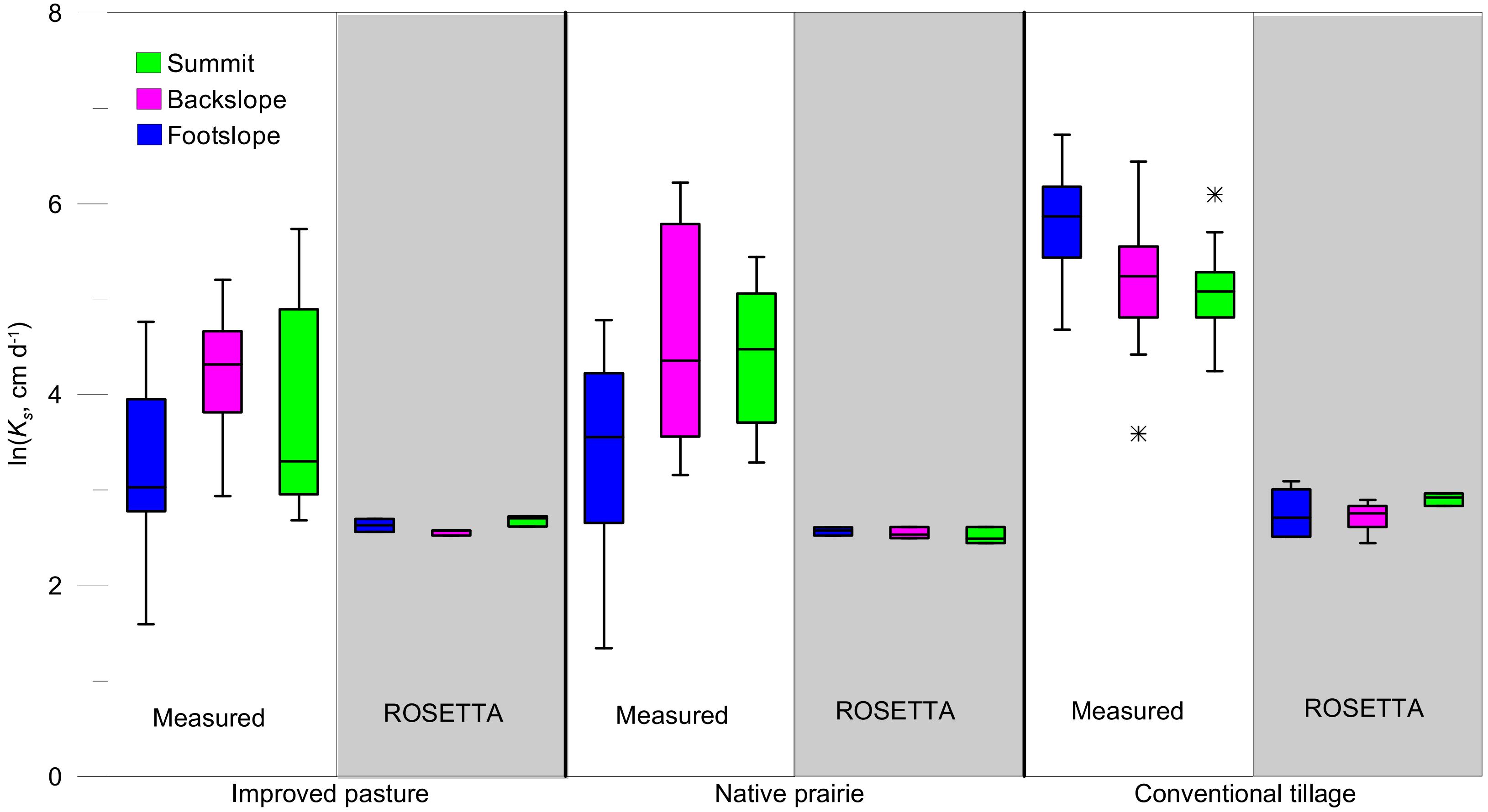

Figure 18. Boxplots of ROSETTA estimates of log-transformed K_s, based on particle size distribution alone, compared with the measured estimates of K_s separated by landscape position within each catena.

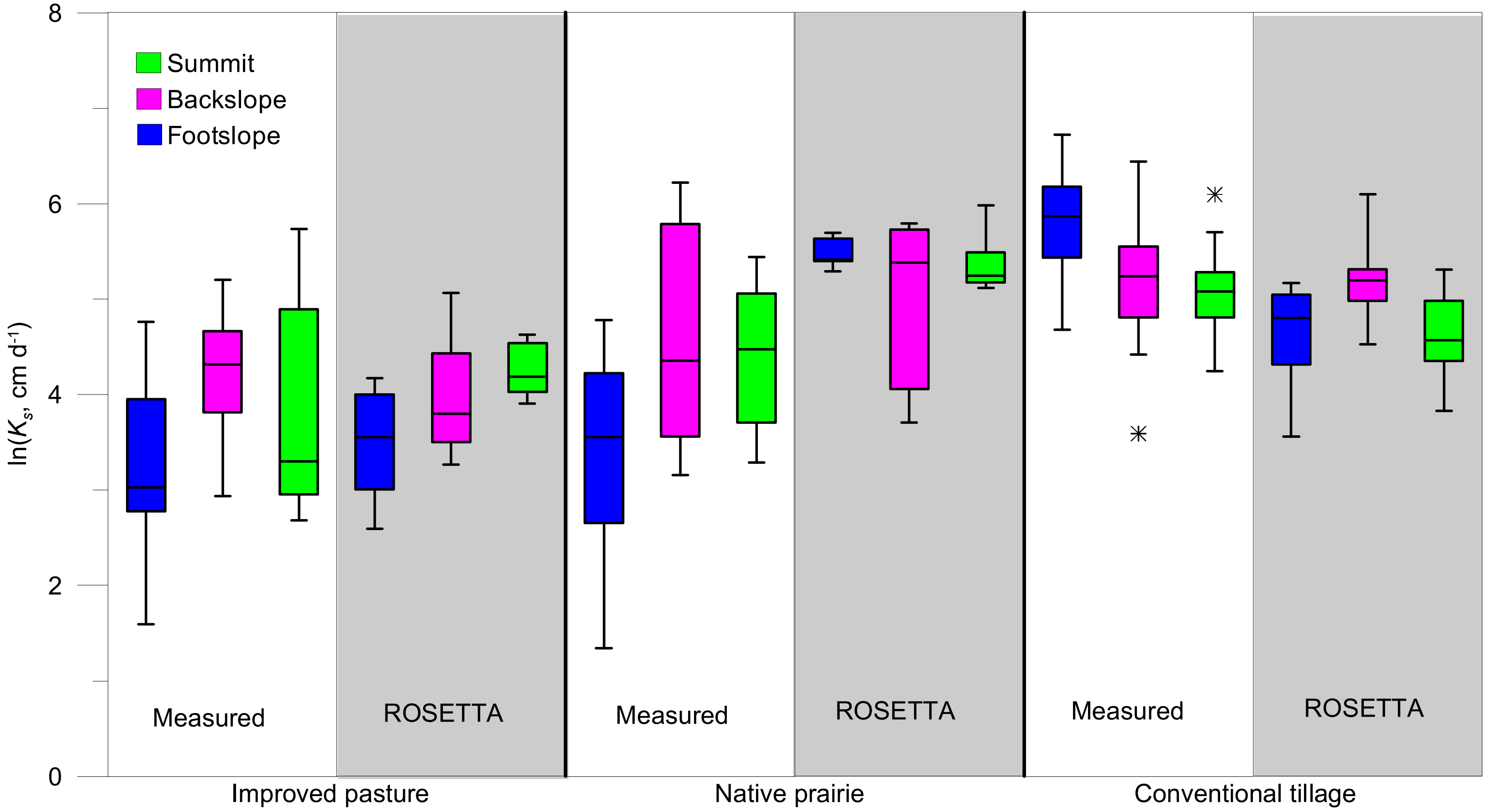

Figure 19. Boxplots of ROSETTA estimates of log-transformed K_s, based on particle size distribution with bulk density, compared with the measured estimates of K_s separated by landscape position within each catena.

SSC-BD-θ_{33} produced essentially the same results as SSC-BD with slightly improved estimates of the variation of K_s within the landscape positions (Fig. 20).

ROSETTA estimates of K_s using SSC-BD-θ_{33} were able to predict overall K_s with a Root Mean Square Error (RMSE) of 184.9 cm d^{-1} or 7.7 cm h^{-1} and a coefficient of determination (r^2) of 0.28 (Fig. 21). Within each individual catena, ROSETTA estimates more closely matched the measured data in the improved pasture catena when compared to the native prairie and conventional tillage catenas (Fig. 22). In the improved pasture catena, K_s were estimated with an RMSE of 60.2 cm d^{-1} and an r^2 value of 0.50. In the native prairie catena, K_s were estimated with an RMSE of 171.9 cm d^{-1} and an r^2 value of 0.09. In the conventional tillage catena, K_s were estimated with an RMSE of 232.1 cm d^{-1} and an r^2 value of 0.16.

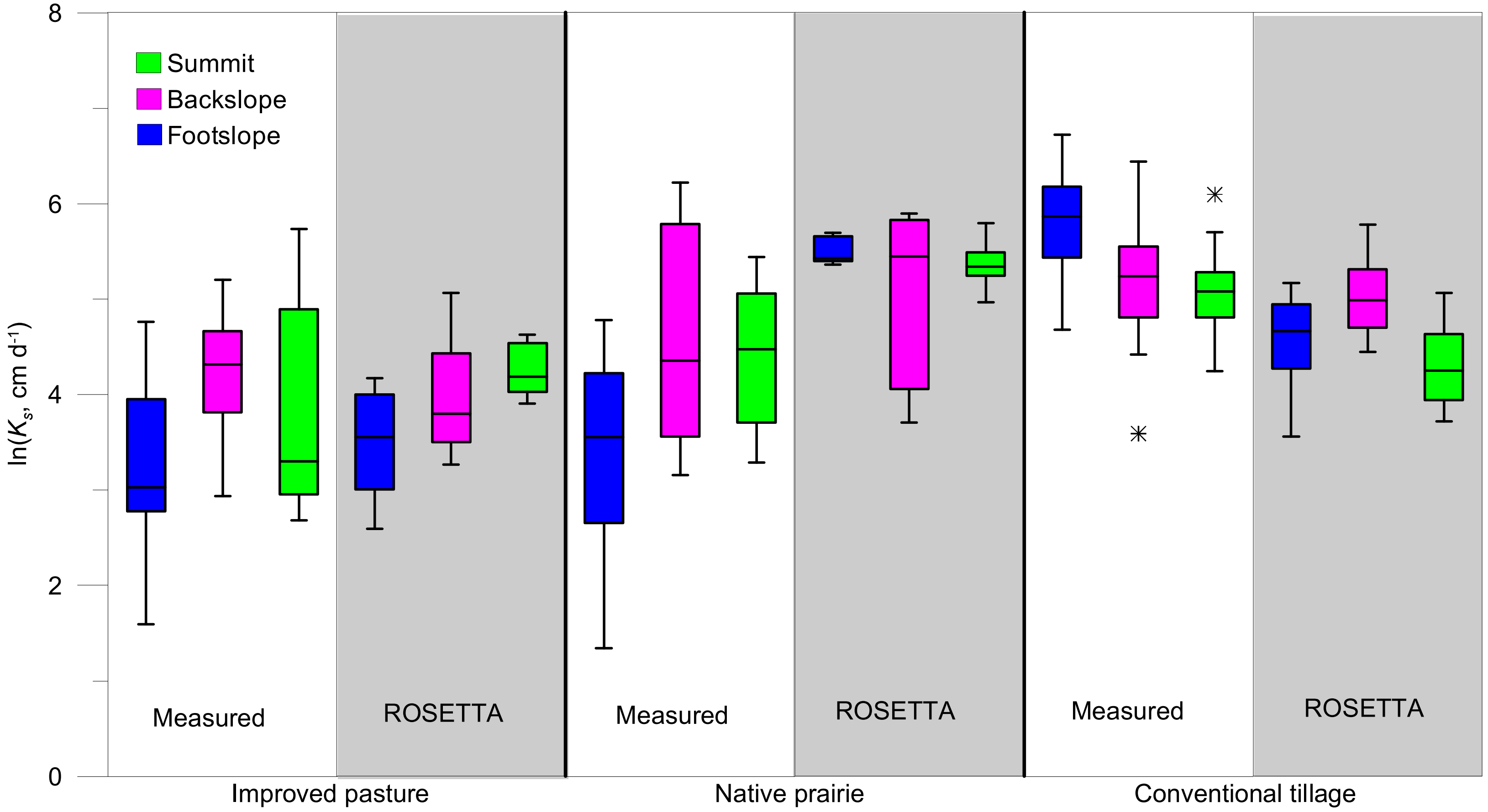

Figure 20. Boxplots of ROSETTA estimates of log-transformed K_s, based on particle size distribution with bulk density and water content at -33 kPa water potential, compared with the measured estimates of K_s separated by landscape position within each catena.

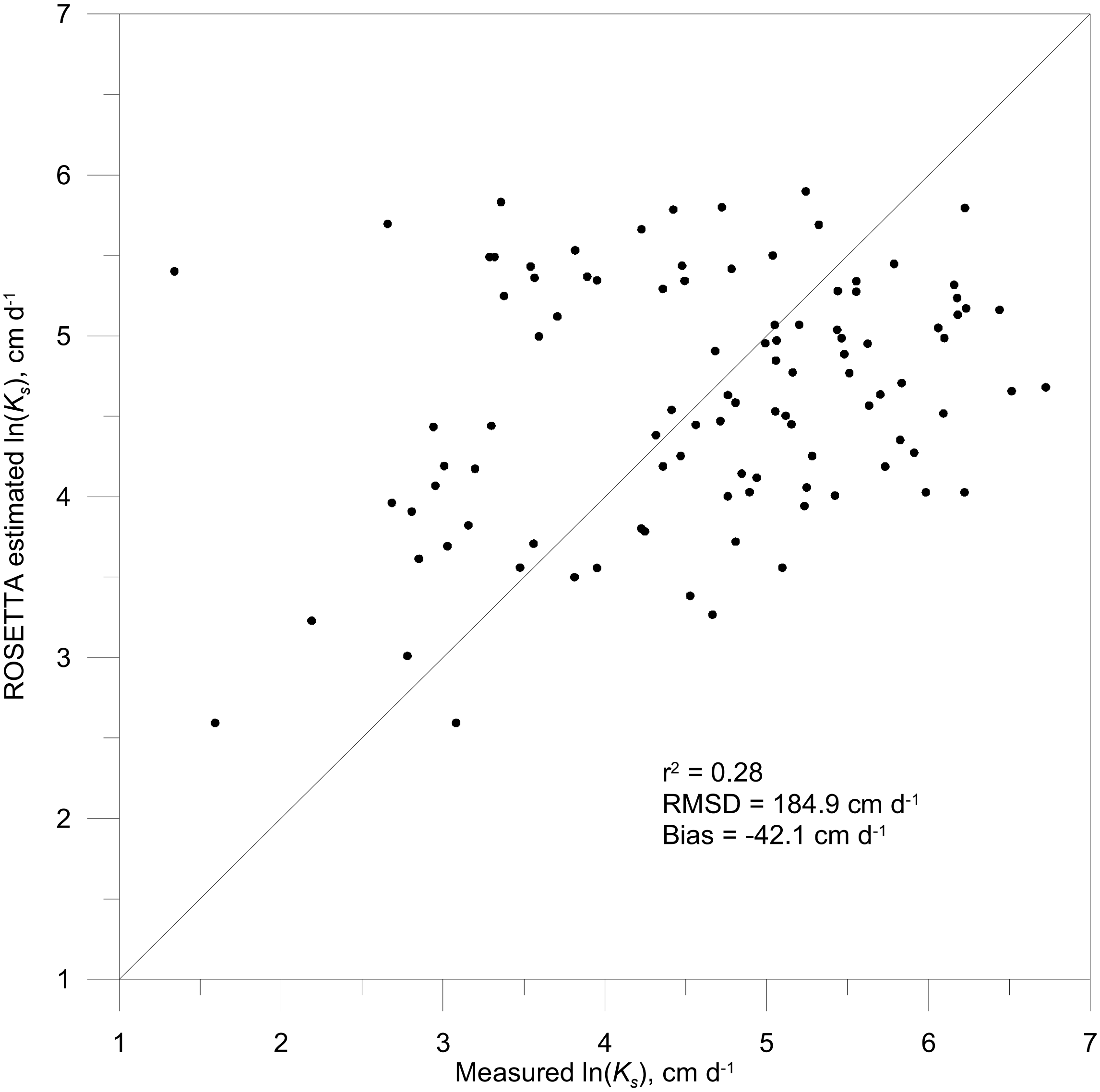

Figure 21. ROSETTA estimates of $\ln(K_s)$ plotted with the measured $\ln(K_s)$ values with a one-to-one line.

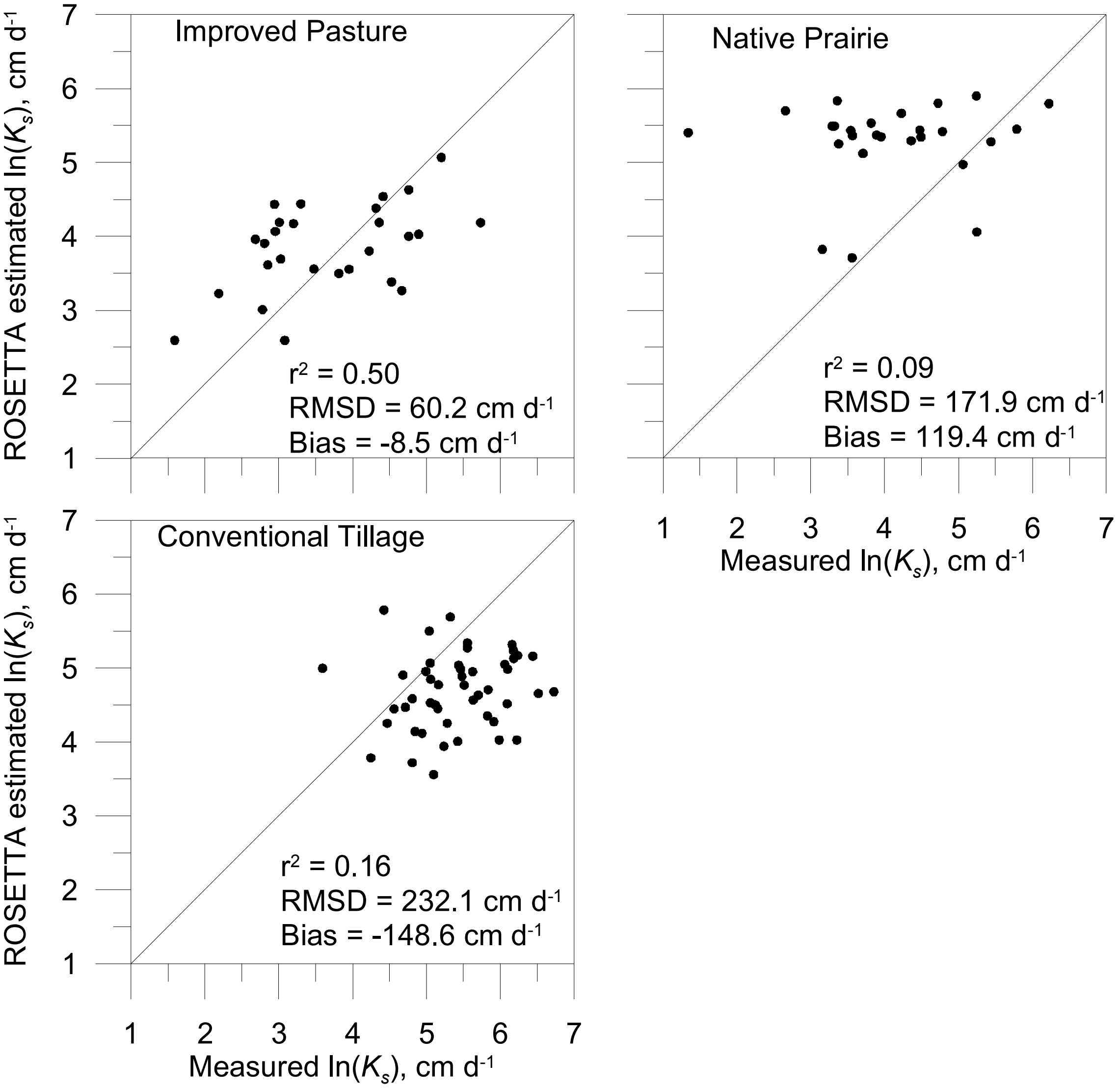

Figure 22. ROSETTA estimates of ln(K_s) plotted with the measured ln(K_s) values with a one-to-one line for each individual catena.

CHAPTER V

CONCLUSIONS

Variations in saturated hydraulic conductivity across three Houston Black/Heiden Clay catenas were influenced by variations in clay content, soil organic carbon, bulk density, and land use. Contrary to our hypothesis, when K_s means by landscape positions were compared, no significant differences were found, but there was a significant blocking (catena) effect. When K_s values were compared across the different landscape positions within each individual catena, K_s means were significantly different by landscape position.

The soil properties that were significantly correlated with variations in K_s were, as hypothesized clay content and soil organic carbon along with bulk density, antecedent water content and indicator variables that adjust the intercept are used to account for the differences under the individual catenas. Replacing bulk density and antecedent water content in the multivariate model with a macroporosity parameter explained the same amount of the variation in K_s. Contrary to our hypothesis, though soil bulk EC_a responds to soil moisture, clay content, and soil organic carbon, no correlation between EC_a and K_s was found; perhaps these relationships were confounded by the shallow depth to parent material across the landscape. ROSETTA, as hypothesized, was able to predict the variation in K_s and did a better job than expected at predicting the mean K_s for the whole data set, but did not do so well if K_s of individual catenas was considered. ROSETTA estimates of K_s using particle size distribution alone did not provide enough information for ROSETTA to provide accurate estimates of K_s. When bulk density was added to particle size distribution, estimates of the mean and the variance of K_s were matched better with the measured means and variance. Adding water content at -33 kPa water potential only slightly improved estimates of the mean and variance of K_s. Based on the extra sample collection and laboratory time to measure water content at -33 kPa water potential, particle size distribution and bulk density data provide a sufficient model for obtaining estimates of K_s. Particle size distribution and bulk density did not provide enough information to estimate the variations of K_s across the landscape positions that were observed. The fact that estimates in K_s from ROSETTA were closer to the measured values in some of the catenas may indicate that there are subsoil features that are affecting K_s that we are unable to measure with our sampling techniques and include in the ROSETTA model. Based on ROSETTA performance on 3 Vertisol Catenas, ROSETTA can be used with measurements of particle size distribution and bulk density to provide reasonable estimates of the mean and variance of K_s at scales that include multiple catenas.

When NRCS measures K_s on Benchmark soils and especially high clay soils, it is recommended that particle size distribution, soil organic carbon, bulk density, and antecedent water content data be collected with these measurements. Based on the means and standard deviations found in this study, it is also recommended that the NRCS collect 18 to 20 measurements to have 90% confidence that they are within 10% of the population mean. Further research is needed to quantify how K_s will vary across other soil types and land uses. Because land use was not replicated in this study, the effects of land use could not be adequately concluded. Continuation of these measurements with land use replicated is suggested to better quantify the effects of land use on K_s in a Vertisol.

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APPENDIX A

LINEAR MODEL RESULTS FROM MULTIPLE REGRESSION ANALYSIS IN R

```
> > lm1<-lm(lnkfs ~ X4 + X5 + clay + soil organic carbon (O.C.) + bulk density +
antecedent water content (w), data=dat)
> summary(lm1)

Call: lm(formula = lnkfs ~ Improved pasture indicator variable (X4) + Native prairie
indicator variable (X5) + Clay + soil organic carbon (O.C.) + bulk density + antecedent
water content (w), data = dat)

Residuals:
Min           1Q            Median        3Q            Max
-2.09001      -0.47001       -0.04623     0.50750       1.81905

Coefficients:
              Estimate      Std. Error     t value      Pr(>|t|)
(Intercept)    4.35014      1.52257       2.857         0.005263 **
X4            -1.87357      0 0.30164      -6.211       1.42e-08 ***
X5            -1.48162      0.54361       -2.726        0.007657 **
clay           0.07972      0.01964       4.060         0.000102 ***
O.C.           1.05340      0.26800       3.931         0.000162 ***
bulk density  -2.83998       0.81984      -3.464        0.000803 ***
w             -7.28880       2.40109      -3.036        0.003105 **
---
Signif. codes:  0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1 ‘ ’ 1

Residual standard error: 0.7456 on 94 degrees of freedom
  (1 observation deleted due to missingness)
Multiple R-squared: 0.6122,     Adjusted R-squared: 0.5875
F-statistic: 24.73 on 6 and 94 DF,  p-value: < 2.2e-16

> lm2<-lm(lnkfs ~ clay + soil organic carbon (O.C.) + bulk density + antecedent water
content (w), data=dat)
> summary(lm2)

Call: lm(formula = clay + soil organic carbon (O.C.) + bulk density + antecedent water
content (w), data = dat)
```

```
Residuals:
Min           1Q            Median        3Q            Max
-2.39652      -0.58833      0.07028       0.59815       1.75951

Coefficients:
              Estimate       Std. Error   t value       Pr(>|t|)
(Intercept)   8.75747       1.58519       5.525         2.82e-07 ***
clay          0.07072        0.02160      3.274         0.001477 **
O.C.          0.15146       0.20983       0.722         0.472142
bulk density  -5.57604      0.82261       -6.778        9.83e-10 ***
w             -9.38846      2.36538       -3.969        0.000139 ***
---
Signif. codes:  0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1 ‘ ’ 1

Residual standard error: 0.8814 on 96 degrees of freedom
  (1 observation deleted due to missingness)
Multiple R-squared: 0.4466,     Adjusted R-squared: 0.4235
F-statistic: 19.37 on 4 and 96 DF,  p-value: 1.041e-11

> lm3<-lm(lnkfs ~ X4 + X5 + clay + soil organic carbon (O.C.) + macroporosity,
data=dat)
> summary(lm3)

Call:
lm(formula = lnkfs ~ Improved pasture indicator variable (X4) + Native prairie indicator
variable (X5) + clay + soil organic carbon (O.C.) + macroporosity, data = dat)

Residuals:
Min           1Q            Median        3Q            Max
-2.25951      -0.44682      -0.06254      0.55464       1.74974

Coefficients:
           Estimate             Std. Error     t value      Pr(>|t|)
(Intercept)   -1.53722      1.21436       -1.266        0.208657
X4            -1.90426      0.29541       -6.446        4.74e-09 ***
X5            -1.72626      0.48838       -3.535        0.000633 ***
clay          0.07647       0.01961       3.900         0.000180 ***
O.C.          1.05235       0.26995       3.898         0.000180 ***
macroporosity 6.63100       2.00985       3.299         0.001366 **
---
Signif. codes:  0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1 ‘ ’ 1

Residual standard error: 0.7508 on 95 degrees of freedom
  (1 observation deleted due to missingness)
```

```
Multiple R-squared: 0.6027,     Adjusted R-squared: 0.5818
F-statistic: 28.82 on 5 and 95 DF,  p-value: < 2.2e-16
```

APPENDIX B

SOIL PROPERTIES WITH RESPECTIVE SATURATED HYDRAULIC CONDUCTIVITIES

ln(K_s) (cm d^{-1})	Bulk density (g cm^{-3})	Clay %	Sand %	Silt %	Organic carbon %	Soil temperature (˚C)
3.3	0.99	50.0	10.3	39.7	1.70	29.1
3.0	1.04	50.0	10.3	39.7	1.70	29.1
4.8	0.95	50.0	10.3	39.7	1.70	29.1
2.7	1.09	41.7	13.5	44.8	2.23	25.4
2.8	1.10	41.7	13.5	44.8	2.23	25.4
3.0	1.07	41.7	13.5	44.8	2.23	25.4
4.4	0.98	49.4	10.8	39.9	2.89	26.1
4.9	1.08	49.4	10.8	39.9	2.89	26.1
5.7	1.05	49.4	10.8	39.9	2.89	26.1
4.7	1.22	57.7	18.7	23.6	2.38	28.9
3.8	1.18	57.7	18.7	23.6	2.38	28.9
4.5	1.20	57.7	18.7	23.6	2.38	28.9
4.3	1.02	42.2	17.2	40.6	2.44	23.3
3.5	1.17	42.2	17.2	40.6	2.44	23.3
2.9	1.01	42.2	17.2	40.6	2.44	23.3
5.2	0.88	41.2	18.2	40.6	2.04	27.7
4.4	1.06	41.2	18.2	40.6	2.04	27.7
4.2	1.13	41.2	18.2	40.6	2.04	27.7
3.0	1.13	44.8	10.1	45.1	1.64	34.9
3.2	1.04	44.8	10.1	45.1	1.64	34.9
2.8	1.25	44.8	10.1	45.1	1.64	34.9
1.6	1.32	45.2	10.3	44.6	1.81	27.8
2.2	1.21	45.2	10.3	44.6	1.81	27.8
3.1	1.32	45.2	10.3	44.6	1.81	27.8
4.0	1.18	43.4	19.5	37.1	1.83	29.3
2.9	1.17	43.4	19.5	37.1	1.83	29.3
4.8	1.10	43.4	19.5	37.1	1.83	29.3
4.5	0.86	33.6	24.1	42.3	2.97	19.3
4.0	0.86	33.6	24.1	42.3	2.97	19.3
4.5	0.84	33.6	24.1	42.3	2.97	19.3
5.4	0.77	42.8	17.0	40.2	2.84	19.2

Appendix B cont.

$\ln(K_s)$ (cm d^{-1})	Bulk density (g cm^{-3})	Clay %	Sand %	Silt %	Organic carbon %	Soil temperature (˚C)
5.1	0.85	42.8	17.0	40.2	2.84	19.2
4.7	0.60	42.8	17.0	40.2	2.84	19.2
3.3	0.78	35.7	25.6	38.7	2.86	23.6
3.4	0.84	35.7	25.6	38.7	2.86	23.6
3.7	0.87	35.7	25.6	38.7	2.86	23.6
3.8	0.79	36.8	16.8	46.3	2.79	8.2
3.4	0.71	36.8	16.8	46.3	2.79	8.2
5.2	0.69	36.8	16.8	46.3	2.79	8.2
6.2	0.65	41.6	12.6	45.8	2.81	10.9
5.8	0.76	41.6	12.6	45.8	2.81	10.9
4.4	0.80	41.6	12.6	45.8	2.81	10.9
3.2	1.12	34.8	21.6	43.6	3.15	26.9
3.6	1.14	34.8	21.6	43.6	3.15	26.9
5.2	1.08	34.8	21.6	43.6	3.15	26.9
3.9	0.81	34.2	15.7	50.1	3.45	15.3
3.6	0.81	34.2	15.7	50.1	3.45	15.3
3.3	0.78	34.2	15.7	50.1	3.45	15.3
4.8	0.77	42.0	14.3	43.7	3.14	18.4
4.2	0.71	42.0	14.3	43.7	3.14	18.4
----	0.72	42.0	14.3	43.7	3.14	18.4
1.3	0.77	40.8	13.5	45.8	2.46	21.9
2.7	0.69	40.8	13.5	45.8	2.46	21.9
3.5	0.77	40.8	13.5	45.8	2.46	21.9
4.8	0.92	48.1	9.9	42.0	1.16	17.7
5.1	0.78	48.1	9.9	42.0	1.16	17.7
4.9	0.93	48.1	9.9	42.0	1.16	17.7
5.7	0.92	49.5	12.3	38.1	1.34	14.7
4.5	1.01	49.5	12.3	38.1	1.34	14.7
5.3	1.01	49.5	12.3	38.1	1.34	14.7
4.8	1.10	50.8	9.9	39.3	1.02	12.3
4.2	1.07	50.8	9.9	39.3	1.02	12.3
5.2	0.99	50.8	9.9	39.3	1.02	12.3
5.2	0.98	50.3	10.1	39.6	1.29	7.6
5.0	0.84	50.3	10.1	39.6	1.29	7.6
6.1	0.86	50.3	10.1	39.6	1.29	7.6
4.8	0.80	49.3	13.2	37.5	1.16	8.6
4.7	0.85	49.3	13.2	37.5	1.16	8.6

Appendix B cont.

$\ln(K_s)$ (cm d^{-1})	Bulk density (g cm^{-3})	Clay %	Sand %	Silt %	Organic carbon %	Soil temperature (˚C)
4.6	0.86	49.3	13.2	37.5	1.16	8.6
6.4	0.84	48.0	14.7	37.3	1.40	6.3
6.2	0.80	48.0	14.7	37.3	1.40	6.3
5.0	0.89	48.0	14.7	37.3	1.40	6.3
6.2	0.82	48.2	14.4	37.4	1.26	10.1
5.6	0.81	48.2	14.4	37.4	1.26	10.1
5.2	0.93	48.2	14.4	37.4	1.26	10.1
5.5	0.86	43.9	18.4	37.7	1.68	7.3
3.6	0.83	43.9	18.4	37.7	1.68	7.3
5.6	0.73	43.9	18.4	37.7	1.68	7.3
5.8	0.91	41.7	21.6	36.6	1.75	12.7
5.0	0.68	41.7	21.6	36.6	1.75	12.7
4.4	0.57	41.7	21.6	36.6	1.75	12.7
5.1	0.99	47.2	17.3	35.5	1.38	8.8
5.5	0.89	47.2	17.3	35.5	1.38	8.8
5.3	0.70	47.2	17.3	35.5	1.38	8.8
6.2	1.01	51.3	11.6	37.1	1.57	14.7
6.0	1.01	51.3	11.6	37.1	1.57	14.7
5.4	1.02	51.3	11.6	37.1	1.57	14.7
6.2	0.83	48.8	12.9	38.3	1.53	14.2
6.1	0.86	48.8	12.9	38.3	1.53	14.2
6.2	0.84	48.8	12.9	38.3	1.53	14.2
6.5	0.82	52.8	10.6	36.7	1.44	11.0
6.7	0.81	52.8	10.6	36.7	1.44	11.0
5.8	0.94	52.8	10.6	36.7	1.44	11.0
5.9	1.05	42.6	20.4	37.0	1.44	15.4
5.6	0.91	42.6	20.4	37.0	1.44	15.4
5.1	1.18	42.6	20.4	37.0	1.44	15.4
5.1	0.93	44.5	19.6	35.9	1.73	14.1
6.1	1.00	44.5	19.6	35.9	1.73	14.1
5.6	0.99	44.5	19.6	35.9	1.73	14.1
5.5	0.95	42.9	20.4	36.7	1.56	13.9
4.7	0.92	42.9	20.4	36.7	1.56	13.9
5.4	0.89	42.9	20.4	36.7	1.56	13.9

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