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Field evidence of a negative correlation between saturated hydraulic conductivity and soil carbon in a sandy soil

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[1] Soil organic matter (SOM) is generally assumed to be positively correlated with saturated hydraulic conductivity (K_S). However, recent studies of pedotransfer functions suggest a possible negative K_S-SOM relationship that still needs independent verification. Our field K_S study of sandy soils in a semiarid region provides such in situ evidence of a negative K_S-SOM relationship, which is nonlinear and is strongest at the lowest levels of soil carbon (<0.1%). A regression analysis also shows that soil carbon is an important factor for explaining K_S in those soils. The likely reason for the observed negative K_S -SOM relationship is a reduced wettability caused by SOM, which is believed to outweigh the impacts of any increase in K_S caused by soil aggregation. The low SOM content and large particle size of sand may explain the limited effect of SOM on soil aggregation processes in the examined soils.

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1. Introduction

[2] Saturated hydraulic conductivity (K_S) is a critical property affecting water and solute movement in soils. It is often time consuming to measure in situ K_S values, which might vary by several orders of magnitude at field scales. To address the problem of lack of in situ measurements of K_S, pedotransfer functions (PTFs) [see *Wösten et al.*, 2001] have been widely used to estimate K_S and other soil hydraulic parameters for various application purposes such as modeling groundwater recharge [*Wang et al.*, 2009], contaminant transport [*Dann et al.*, 2006], and root water uptake [*Demirkanli et al.*, 2008]. Therefore for the use of PTFs, the impact of the factors controlling K_S, like soil organic matter (SOM), has to be validated.

[3] In general, SOM is assumed to be positively correlated with K_S because SOM can stimulate soil aggregation, which lowers bulk density (ρ_b), increases porosity, and hence elevates K_S [*Rawls et al.*, 2005]. Existing PTFs also show the same positive K_S-SOM relationship [see *Rawls et al.*, 2005, and references therein]. However, by reanalyzing the existing and newly developed PTFs on the basis of the soil databases from the U.S. and Europe, *Nemes et al.* [2005] showed a possible negative K_S-SOM relationship. *Rawls et al.* [2005] also showed that predicted K_S values may be lower for elevated SOM content. The conjecture of *Nemes et al.* [2005] on the negative K_S-SOM relationship is based on regression analysis of existing soil data sets, which still needs independent verification based on field experiments. Here, we present in situ K_S measurements made in the Nebraska Sand Hills (NSH), which indicates a negative K_S-SOM relationship. Our results also reveal that soil carbon is an important factor for explaining K_S in the sandy soils of the NSH.

2. Study Area and Soil Profile Description

[4] This study was performed as a part of the Grassland Destabilization Experiment at the University of Nebraska's Barta Brothers Ranch site (BBRS) in the eastern NSH (Figure 1), which investigates the ecological and geomorphic stability of the NSH from an interdisciplinary perspective and focuses on atmosphere–land surface–groundwater interactions [*Wang et al.*, 2008]. The Nebraska Sand Hills is the largest native grassland–stabilized sand dune area in the Western Hemisphere and an important groundwater recharge source for the High Plains aquifer [*Loope and Swinehart*, 2000]. Mean annual temperature at the site is 8.1°C and mean annual precipitation is 576 mm. About 90% of the landscape at the site is composed by upland dunes and dry interdunal areas covered by native warm-season grasslands, while the remaining 10% consists of wet meadows and wetlands. Holocene dune sands overlie Quaternary and/or Pliocene alluvial sand and silt with low SOM content throughout the NSH.

[5] Ten circular plots, each 120 m in diameter, were constructed, of which five were equipped with two meteorological stations for evaluation of water and energy balances. For each of the five instrumented plots, soil profile descriptions were made at one dune top and two interdunal locations using the methods of *Schoeneberger et al.* [2002]. At dune top locations, A (A1/A2) horizons (e.g., the top layer of soil horizons) extended to an average depth of 11.8 cm (range 6–21 cm) and AC horizons extended to an average depth of 27.8 cm (range 13–55 cm). Soils were classified in the Valentine series, a mixed, mesic Typic

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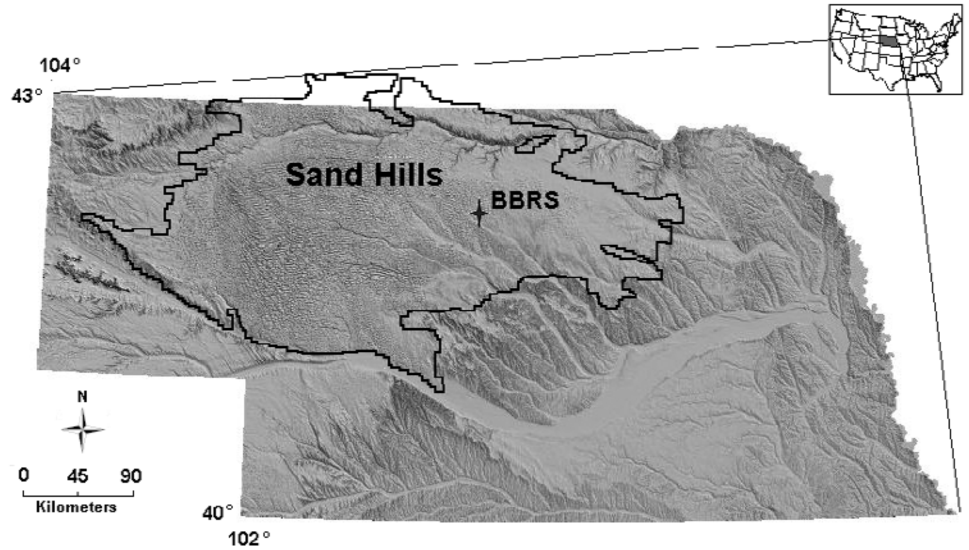

Figure 1. Location of the Barta Brothers Ranch site (BBRS) in the Nebraska Sand Hills. The contoured line indicates the Nebraska Sand Hills.

Ustipsamments that lacks any diagnostic subsurface horizon. At interdunal locations, A horizons extended to an average depth of 22.8 cm (range 6–41 cm) and AC horizons extended to an average depth of 39.1 cm (range 19–59 cm). Soils were classified either as the Valentine series or where A horizons exceeded 25 cm as the Dunday series, a sandy, mixed, mesic Entic Haplustolls with a diagnostic mollic epipedon.

3. Methodology

[6] Eleven in situ K_S profiles, which were located within 3 m from the meteorological stations [*Wang et al.*, 2008], were measured at depths of 20, 50, 100, 150, and 200 cm using a compact constant-head permeameter [*Amoozegar*, 1989a]. The permeameter maintains a constant water head in a borehole and measures the discharge from the borehole into the surrounding vadose zone. The well-validated solution of *Glover* [1953] was used to calculate K_S values [*Amoozegar*, 1989b; *Stephens*, 1996]. This solution is valid when the distance between the groundwater table and the borehole bottom is at least twice as large as the water depth in the borehole [*Stephens*, 1996]. A total of 55 measurements of K_S with three replicates in each borehole were collected from the 11 profiles, of which 10 measurements were excluded from the analysis because of the high groundwater table or evidence of macroscale biological activity leading to macropores. Soil samples taken from depths of 20, 50, 100, 150, and 200 cm were analyzed for particle size distributions. A sieving method was used for assessing sand size particles ($\geq 63\ \mu$m) and a sedimentation procedure was used for assessing clay size particles ($<2\ \mu$m) [*International Organization for Standardization*, 2001] with the rest for silt size particles ($2 \sim 63\ \mu$m). This procedure was repeated three times for each sample, and mean contents of sand, silt, and clay are used in the analysis. Bulk density was measured to 100 cm depth by *Hellerich* [2006] in a related NSH study using the core method [*Sollins et al.*, 1999]. Soil samples were checked with HCl for the presence of carbonates and none were detected. Thus, the reported total soil carbon values, which were measured by high-temperature dry combustion [*Sollins et al.*, 1999], can be assumed to represent soil organic carbon (SOC). The root density distribution was analyzed using 3 m deep soil cores taken from the site, which were washed free of sand over a 1 mm screen and then analyzed using the software Winrhizo (Regent Instruments, Quebec).

4. Results and Discussions

[7] The experimental results averaged by depth (e.g., 20, 50, 100, 150, and 200 cm) are plotted in Figure 2. Typically, K_S increases from ~500 cm/d in the surface layer to ~1300 cm/d at 200 cm depth. The averaged soil carbon content at 20 cm (approximately the A horizon) is 0.42% and quickly drops below 0.1% at depths greater than 100 cm. Soil textures are relatively uniform throughout the soil profiles and sandy soils are prevalent at the site (average 96.28% sand, 3.32% silt, and 0.40% clay). *Hellerich* [2006] showed in a related NSH study that the vertical trend in ρ_b is consistent, and mean ρ_b increases from 1.50 g/cm^3 at 5 cm depth to 1.58 g/cm^3 at 30 cm depth and 1.65 g/cm^3 at 100 cm depth. In the 3 m deep soil cores analyzed for root biomass, 60–70% of the total root mass occurs in the top 20 cm and 85–90% occurs in the top 50 cm, which is consistent with literature reviews on root biomass distribution in native grasslands globally [*Jackson et al.*, 1996].

[8] Figure 2a shows opposite vertical trends in K_S and soil carbon, which indicates a negative relationship between K_S and SOC. However, except for SOC, K_S may be also influenced by soil texture, ρ_b, and root density distribution (RDD), of which texture and ρ_b are the principal components in most PTFs [*Wösten et al.*, 2001]. Therefore, it is necessary to show that this negative K_S-SOC relationship is not just an artifact of correlations between soil carbon and

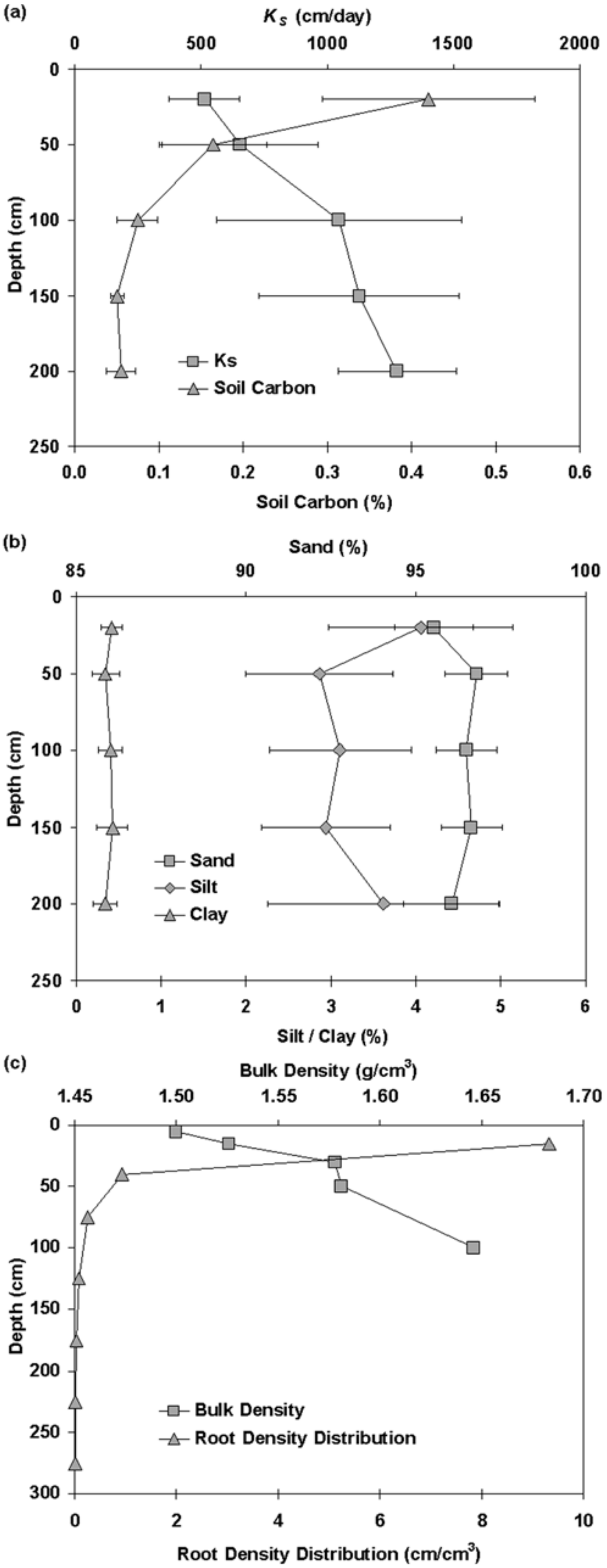

Figure 2. Vertical trends in K_S and its controlling factors (horizontal lines represent standard deviation): (a) K_S and soil carbon; (b) sand, silt, and clay; and (c) bulk density [*Hellerich*, 2006] and root density distribution.

other factors. Although K_S, ρ_b, and RDD were measured at different depths, the increasing trend of ρ_b and the decreasing trend of RDD with depth should otherwise result in reduced K_S at greater depths [*Nemes et al.*, 2005; *Rawls et al.*, 2005]; therefore, the vertical trends in ρ_b and RDD do not explain the elevated K_S at greater depths and can be excluded from the analysis. Besides soil carbon, the relationships of K_S with sand, silt, and clay content are also plotted in Figure 3, as soil texture is the most important component in PTFs. Figure 3 exhibits an inverse relationship between K_S and soil carbon. For the tested soil samples, which averaged 96.28% sand, 3.32% silt, and 0.40% clay, no apparent pattern exists between K_S and clay, while K_S is correlated with sand (positive) and silt (negative) content. The Pearson correlation coefficients are given in Table 1. As expected from Figure 3, soil carbon, sand, and silt contents show significant correlations with K_S; while clay has a very weak correlation with K_S. Soil carbon is also significantly correlated with sand and silt, but not with clay. Therefore, it is necessary to differentiate the impacts of soil carbon, sand, and silt on K_S. The second-order partial correlation coefficients among K_S, soil carbon, sand, and silt are given in Table 2. While holding sand and silt contents constant, a significant negative correlation emerges between K_S and soil carbon contents ($r = -0.407$, $p = 0.0068$), which is much stronger than the partial correlation of K_S with either sand or silt.

[9] Furthermore, this negative relationship between K_S and soil carbon is nonlinear. Interestingly, when the content of soil carbon is above approximately 0.1%, soil carbon does not affect K_S significantly. To linearize the relationship between K_S and soil carbon, K_S was regressed against sand content, the inverse of soil carbon content (denoted as 1/C here), and the interaction of 1/C and sand. The multiple regression model was highly significant ($r^2 = 0.656$). Among the three predictors, 1/C was the most important ($F = 37.73$, $P < 0.0001$), sand was significant but less important ($F = 12.10$, $P = 0.0013$), and their interaction was also significant ($F = 4.799$, $P = 0.0345$). The result indicates that the effect of sand content on K_S depends upon the amount of soil carbon. Compared to topographic position (categorical variable) and depth (either continuous or categorical [see *Wang et al.*, 2008]), 1/C and sand together were more important for predicting K_S and explaining the spatial pattern of increasing K_S with depth. In summary, a negative K_S-SOM relationship is apparent in those semiarid soils, particularly at soil carbon values less than 0.1%.

[10] Soil organic matter has two opposite effects on K_S, either elevating K_S by improving soil aggregation or reducing K_S by inhibiting water flow due to a reduced wettability caused by SOM [*Ellerbrock et al.*, 2005]. The overall effect is the result of these two counteracting processes. As long as the effect of reduced wettability associated with SOM outweighs its effect on soil aggregation, a negative K_S-SOM relationship might occur. Compared to coarser soils, finer soils more easily form granular or blocky soil structures because of the presence of SOM, which could result in larger pore sizes and higher K_S. On the other hand, sandy soils remain largely loose and unaggregated. The positive effect of SOM on K_S is relatively weak, as the SOM-induced soil aggregation process depends on SOM levels

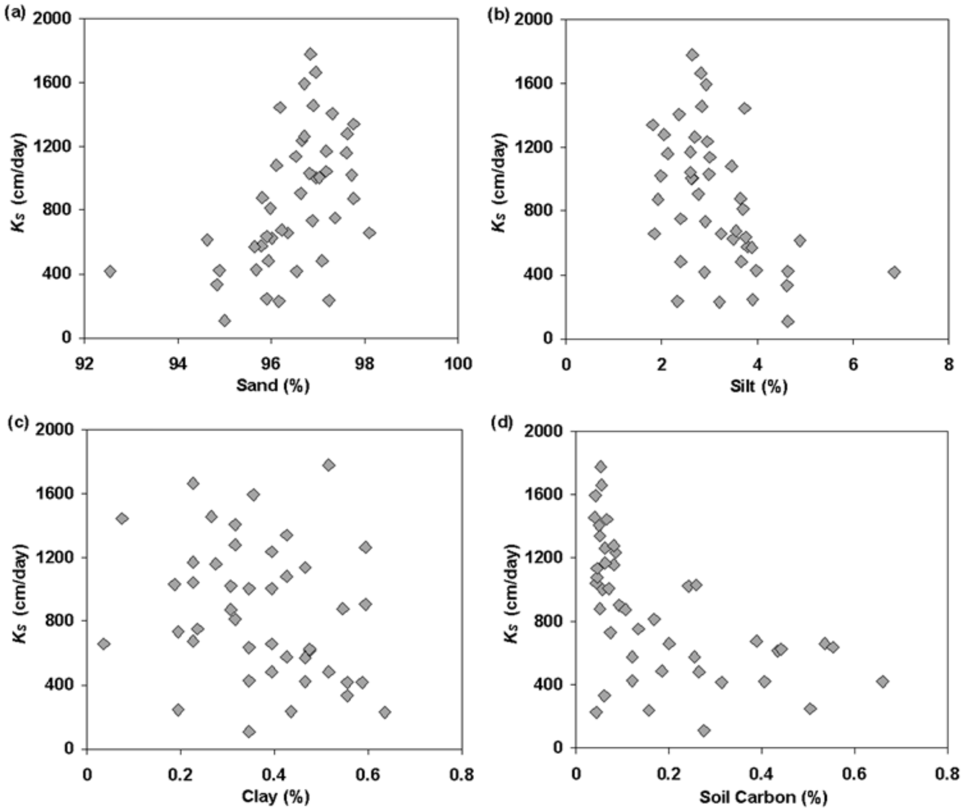

Figure 3. Relationships of K_S with soil texture and soil carbon: (a) sand, (b) silt, (c) clay, and (d) soil carbon.

as well. *Greenland et al.* [1975] and *Haynes and Swift* [1990] showed that there is a critical level of SOM, below which soil aggregates are unstable. *Greenland et al.* [1975] found that at least 2% SOM is necessary to start forming soil aggregates in soils in the United Kingdom. Because of the larger particle sizes, it needs relatively higher critical levels of SOM for coarser soils to initiate aggregation processes, which counteract the effect of the reduced wettability. The low SOC content in the NSH is probably insufficient for the aggregation process. The large soil particle size and low SOC content are likely to cause the negative K_S-SOC relationship found at this site (Figure 3a). Therefore, a negative K_S-SOM relationship is more likely to occur in regions where soil particle sizes are large while SOM contents are low.

[11] In conclusion, soil carbon and sand contents were found to be important for explaining K_S at the study site. Over the range of soil carbon content (0.05–0.7%) and sand content (92.5–98.3%) that are seen in this study and are characteristics of soils in the Nebraska Sand Hills, soil carbon content is more important than sand content in explaining K_S. Thus, we suggest that factors determining SOM are also influential in determining K_S. Besides the large-scale processes that control soil texture (e.g., weathering conditions), the long-term balance of plant productivity and belowground decomposition might be also important for controlling K_S. Finally, the relationship between K_S and soil carbon was found to be nonlinear, and K_S becomes more sensitive to soil carbon at a soil carbon content less than 0.1%. Therefore, a small quantity change in SOM may have large and disproportionate effects on the ecohydrology of sand dune systems in the Nebraska Sand Hills.

Table 1. Pearson's Correlation Coefficients Between Contents of Soil Carbon, Sand, Silt, and Clay[a]

	Soil Carbon	Sand	Silt	Clay
K_S	−0.554***	0.494***	−0.484***	−0.254
Soil carbon		−0.561***	0.581***	0.071
Sand			−0.991***	−0.435**
Silt				0.313

[a] Here *** means significant at the 0.001 probability level, and ** means significant at the 0.01 probability level.

Table 2. Second-Order Partial Correlation Coefficients for K_S, Soil Carbon, Sand, and Silt[a]

	r	*p* Value
WX.YZ	−0.407	0.0068
WY.XZ	0.193	0.2152
WZ.XY	0.152	0.3304
XY.WZ	0.192	0.2173
XZ.WY	0.259	0.0935
YZ.WX	−0.986	<0.0001

[a] W, K_S; X, soil carbon; Y, sand; Z, silt.

[12] **Acknowledgments.** This study was supported by NSF Biocomplexity program grant DEB 387 0322067 (D. Wedin, V. Zlotnik, and T. Wang) and NSF Hydrologic Sciences Program grant EAR-0609982 (V. Zlotnik). We thank P. Schoeneberger and D. Wysocki, both at NRCS-National Soil Survey Center; N. Smith (UNL); and three anonymous reviewers for their comments on the manuscript. The soil database is available from the corresponding author upon request.

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