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

Tiejun Wang,1,2 David Wedin,3 and Vitaly A. Zlotnik1

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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.


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 Wosten 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 ($\rho_b$), 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 of 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
Ustipsammments 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 (2–63 $\mu m$). 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 $\sim 500$ cm/d in the surface layer to $\sim 1300$ 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 $r_b$ is consistent, and mean $r_b$ 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, $r_b$, and root density distribution (RDD), of which texture and $r_b$ 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
other factors. Although $K_S$, $\rho_s$, and RDD were measured at different depths, the increasing trend of $\rho_s$ 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 $\rho_s$ 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.

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%.

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 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.
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.

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.

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

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**Table 1.** Pearson’s Correlation Coefficients Between Contents of Soil Carbon, Sand, Silt, and Clay

<table>
<thead>
<tr>
<th></th>
<th>Soil Carbon</th>
<th>Sand</th>
<th>Silt</th>
<th>Clay</th>
</tr>
</thead>
<tbody>
<tr>
<td>$K_S$</td>
<td>$-0.554^{***}$</td>
<td>0.494***</td>
<td>$-0.484^{***}$</td>
<td>$-0.254$</td>
</tr>
<tr>
<td>Soil carbon</td>
<td>$-0.561^{***}$</td>
<td>0.581***</td>
<td>0.071</td>
<td></td>
</tr>
<tr>
<td>Sand</td>
<td>$-0.991^{***}$</td>
<td>$-0.435^{**}$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Silt</td>
<td></td>
<td></td>
<td>0.313</td>
<td></td>
</tr>
</tbody>
</table>

$^{*}$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

<table>
<thead>
<tr>
<th></th>
<th>$r$</th>
<th>$p$ Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>WX.YZ</td>
<td>$-0.407$</td>
<td>0.0068</td>
</tr>
<tr>
<td>WY.XZ</td>
<td>0.193</td>
<td>0.2152</td>
</tr>
<tr>
<td>WZ.XY</td>
<td>0.152</td>
<td>0.3304</td>
</tr>
<tr>
<td>XY.WZ</td>
<td>0.192</td>
<td>0.2173</td>
</tr>
<tr>
<td>XZ.WY</td>
<td>0.259</td>
<td>0.0935</td>
</tr>
<tr>
<td>YZ.WX</td>
<td>$-0.986$</td>
<td>&lt;0.0001</td>
</tr>
</tbody>
</table>

$^*$W, $K_S$: X, soil carbon; Y, sand; Z, silt.
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References

T. Wang and D. Wedin, School of Natural Resources, University of Nebraska at Lincoln, 3310 Holdrege Street, Lincoln, NE 68583-0961, USA (twang3@unl.edu; dwdedin1@unl.edu); V. A. Zlotnik, Department of Geosciences, University of Nebraska at Lincoln, 214 Bessey Hall, Lincoln, NE 68588-0340, USA. (vzlotnik1@unl.edu)