Strength and Permeability of Cultivated Histosols Characterized by Differing Degrees of Decomposition

Jacynthe Dessureault-Rompré,* Laura Thériault, Cédrick-Victoir Guedessou, and Jean Caron

Cultivated organic soils (Histosols) are an important part of the agricultural economy in Canada. However, problems of degradation and compaction affect this particular type of soil. The objective of this study was to characterize the soil penetration resistance and the saturated hydraulic conductivity ($k_{sat}$) in cultivated organic soils that differed in their degree of decomposition. Three fields in the plain of Montreal, in southwestern Quebec, were selected to provide a gradient of degrees of decomposition. Site 1 was classified as a Limnic Fibrisol, Site 2 was classified as a Terric Mesic Humisol, and Site 3 was classified as a Terric Humisol. At each site, penetration resistance and $k_{sat}$ were measured directly in the field. Penetration resistance, particularly at the 25-cm depth and deeper, was found to increase with increasing soil degradation. An inverse relationship was observed for $k_{sat}$ in the compact layer. The results presented in this study indicate that penetration resistance and $k_{sat}$ are both linked to the degree of soil decomposition. However, the relationship between both parameters is complex, and both parameters are to be measured to achieve a more accurate characterization of organic soils. Further work could assess the depth of the compact layer, as well as the degree of decomposition of organic soils at different spatial scales using penetration resistance. In Histosols, accurately mapping $k_{sat}$ would help in designing field drainage systems, as this soil property is difficult to predict from other parameters.

Core Ideas

- Cultivated organic soils (Histosols) are highly productive but very sensitive to degradation and compaction.
- Penetration resistance and saturated hydraulic conductivity are two important parameters related to the degree of decomposition of Histosols.
- Penetration resistance could be used to assess the depth of the compact layer, as well as the degree of decomposition, of Histosols.

Abbreviations: LM.F, Limnic Fibrisol; $k_{sat}$, saturated hydraulic conductivity; TH, Terric Humisol; TMH, Terric Mesic Humisol.

Worldwide, organic soils (Soil Classification Working Group, 1998), or Histosols (Soil Survey Staff, 1999), cover a land area between 325 and 375 million ha, most of which is located in the boreal, subarctic, and low arctic regions of the northern hemisphere. Most Histosols occur in temperate lowlands and cool mountain areas; only one-tenth of all Histosols are found in the tropics. Although extensive areas of Histosols can be found in the United States, Canada, and Western Europe, Canada has the largest total area (Armstrong and Castle, 1999). Histosols can be very productive under intensive cropping or horticulture systems; however, they must be carefully managed (Driessen and Deckers, 2001).

Cultivated organic soils in Canada represent an important part of the agricultural economy. In the plain of Montreal in southwestern Quebec, close to 12,000 ha of land is covered in deep organic soils (Grenon et al., 1999). These lands supply fruits and vegetables to Montreal and the northeastern United States (Grenon et al., 1999). Although cultivated organic soils are highly productive, they are also sensitive to degradation and compaction (Lucas, 1982; Kroetsch et al., 2011).

In organic soils, cultivation significantly affects the soil-forming processes (Johnson et al., 1995) and can thus substantially influence its properties (Kroetsch et al., 2011). To be suitable for agricultural purposes, organic soils must first be drained. Drainage initiates an irreversible sequence (Fig. 1) of morphological and structural transformations, including enrichment in humic substances and changes in the mineral composition and microbial population of the soil (Ilnicki and Zeitz, 2003). The degradation process after drainage leads first to soil consolidation and subsidence, and then repeated shrinkage and swelling.
However, in Histosols, pedotransfer functions to estimate soils water and soil porosity, as well (Brandyk et al., 2002). Water retention and hydraulic conductivity depend on the degree of decomposition and the botanical origin of the peat. Particle size and shape also strongly affect hydraulic conductivity (Nkongolo and Caron, 1999) and gas diffusivity (Caron and Rivière, 2001; Caron et al., 2005). Peat decomposition markedly influences plant available water and soil porosity, as well (Brandýk et al., 2002).

The typical evolution of organic soils has a significant effect on soil strength and permeability. The impact on drainage depends on the permeability of the soil, as well as the presence and location of compacted horizons. An efficient drainage design requires detailed information on the spatial variability of hydraulic conductivity (Gallichand et al., 1991, 1992). Such information is often missing in Histosol soil surveys or is simply outdated because of their evolution (Millette et al., 1982). Because hydraulic conductivity is difficult and time consuming to measure, it is sometimes predicted using bulk density in mineral soils (Assouline, 2006). However, in Histosols, pedotransfer functions to estimate soils properties such as hydraulic conductivity are missing. Hallem et al. (2015) found poor correlation of $k_{sat}$ with other soil properties (bulk density, porosity, particle density, and organic matter content). Penetration resistance takes much less time and expertise to measure and can also help to locate the depth of compacted layers for further characterization but has so far not been used for such a purpose. Developing relationship between hydraulic conductivity and penetration resistance could therefore be helpful in the survey of organic soils. The objective of this study was to characterize soil penetration resistance and $k_{sat}$ in cultivated organic soils of differing degrees of decomposition and investigate the potential relationship between these parameters.

**Materials and Methods**

In 2015, three fields were selected in the plain of Montreal in southwestern Quebec. The fields were chosen to provide a gradient in the degree of decomposition among the soils (Fig. 1). The degree of decomposition is the basis for differentiating Great Groups of peat in Canada and Suborders in the American soil classification system. Both systems include the approximately equivalent Fibrisols (Fibrists), Mesisols (Hemists), and Humisols (Saprists) (Anderson and Smith, 2011). In both classification systems, this sequence of Great Groups or Suborders represents an increase in the degree of decomposition of organic soil or Histosols. Because of the difficulties in finding a precise equivalent in the classification below, being the subgroup in the Canadian soil classification system and the Great Group in the USDA Soil Taxonomy, this study used the Canadian soil classification system to describe the site used for the experiment. The description of the profiles is provided in Fig. 1. Site 1 was classified as a Limnic Fibrisol (L.M.F) (Soil Classification Working Group, 1998). The L.M.F profile had a thin humified surface layer over a thin mesic layer and a more dominant middle tier of undecomposed fibric organic material (Fig. 1). The bottom tier was composed of coprogenous earth (sedimentary peat), diatomaceous earth, or marl. Site 2 was classified as a Terric Humisol (TMH) (Soil Classification Working Group, 1998). The profile presented a significant quantity of visible fibric mixed with humic material (mesic material) and had a characteristic compact layer located at a depth of ~25 cm in the soil profile. Site 3 was classified as a Terric Humisol (TH) (Soil Classification Working Group, 1998). This soil was particularly degraded, composed of a layer of ~40 cm of humified and compact soil over a clay bottom tier (Fig. 1).

At each site, penetration resistance profiles were established by taking measurements at nine points per site using an Eijkelkamp digital penetrometer. Saturated hydraulic conductivity was measured directly in the field using a modified Guelph infiltrometer (Elrick et al., 1987). Measurements were taken at 18 points at the soil surface (0–10 cm) and in the compact layer (25 and 35 cm, by removing soils from above) for the L.M.F and TMH sites, and at 12 points per depth layer for the TH site. Each site measured ~0.25 to 0.5 ha. Soil water content was also measured at the same location as the penetration resistance. Although good relationships between soil water content and penetration resistance have been
found in mineral soils (Vaz et al., 2011), we did not find significant relationship in the Histosol between these two properties, even with more extensive data sets (unpublished data).

Differences in the degree of decomposition (LM.F, THM, and TH) were evaluated using ANOVA, followed by Tukey’s post-hoc honestly significant difference test (SYSTAT 13.0; Systat Software).

Results and Discussion

The penetration resistance profiles corresponding to the three degrees of decomposition clearly differed (Fig. 2), with penetration resistance increasing with the level of degradation (LM.F < THM < TH). In addition, a compact layer clearly developed along the degradation gradient, with a peak between the 30- and 40-cm depth (Fig. 2a). Moreover, the profiles differed significantly in each 10-cm layer of depth, except between 21 and 30 cm (Fig. 2b, Table 1). The penetration resistance was higher in LM.F than in THM in the surface layers (0–20 cm) but was higher in the THM soil in the deeper soil layers. The TH showed the highest penetration resistance in each layer of depth.

Drainage and drying increase the bulk density and volume of the solid phase in the upper layer of organic soils (Ilnicki and Zeitz, 2003). The compaction that occurs in cultivated organic soils as decomposition progresses has two causes. The first is natural and occurs as the solid particles of the soil settle under their own weight (Caron et al., 2015). The second is the migration of fine particles from the surface humic layer to the underlying layers due to drainage and the percolation of rainfall and irrigation water. Because of the inherent composition of the organic soil profile, characterized by layers of fibric material at different stages of decomposition, the migrating particles are stopped when they reach a less decomposed layer, accumulating at that point (Fig. 1). This is part of the natural evolution of cultivated organic soils. An additional source of compaction is the passage of farm machinery and cultivation practices that contribute to the formation of a compact layer (Alakukku, 1996, 2008; Hamza and Anderson, 2005). Penetration resistance is therefore a very useful tool to detect and characterize the development and evolution of compact layers in cultivated organic soils and determine their degree of decomposition.

Field $k_{sat}$, which describes the movement of water through saturated soil, was measured at the soil surface (0–10 cm) and in the compact layer (25–35 cm) at the three sites (Fig. 3a and 3b). At the soil surface, $k_{sat}$ was significantly higher in LM.F and TH than the TMH (Table 2, Fig. 3a). Although $k_{sat}$ at the surface tended to be lower in the TH as compared with the LM.F, the difference was not statistically significant. In the compact layer, $k_{sat}$ increased systematically with the degree of decomposition, from LM.F to THM to TH, with a statistically significant difference between LM.F and TH (Table 2, Fig. 3a).

These results clearly illustrate that the movement of water through a saturated organic soil changes with the degree of decomposition. Our findings are consistent with findings of other studies (Boelter, 1969; Millette et al., 1982; Kechavarzi et al., 2010). The changes observed in the deeper soil layer were more important than those in the surface layer. The surface layers

### Table 1. Analysis of variance of the penetration resistance at each layer of depth studied in organic soils at different degrees of decomposition.

<table>
<thead>
<tr>
<th>Depth (cm)</th>
<th>Type III sum of squares</th>
<th>Numerator df</th>
<th>Denominator df</th>
<th>Mean squares</th>
<th>F-ratio</th>
<th>p-value</th>
</tr>
</thead>
<tbody>
<tr>
<td>0–10</td>
<td>0.436</td>
<td>2</td>
<td>24</td>
<td>0.218</td>
<td>38.00</td>
<td>&lt;0.001</td>
</tr>
<tr>
<td>11–20</td>
<td>0.690</td>
<td>2</td>
<td>24</td>
<td>0.345</td>
<td>4.261</td>
<td>0.026</td>
</tr>
<tr>
<td>21–30</td>
<td>0.962</td>
<td>2</td>
<td>24</td>
<td>0.481</td>
<td>3.035</td>
<td>0.067</td>
</tr>
<tr>
<td>31–40</td>
<td>8.087</td>
<td>2</td>
<td>24</td>
<td>4.043</td>
<td>49.01</td>
<td>&lt;0.001</td>
</tr>
<tr>
<td>41–50</td>
<td>7.256</td>
<td>2</td>
<td>24</td>
<td>3.628</td>
<td>16.53</td>
<td>&lt;0.001</td>
</tr>
<tr>
<td>51–60</td>
<td>1.233</td>
<td>2</td>
<td>24</td>
<td>0.611</td>
<td>23.84</td>
<td>&lt;0.001</td>
</tr>
<tr>
<td>61–70</td>
<td>1.454</td>
<td>2</td>
<td>24</td>
<td>0.727</td>
<td>28.76</td>
<td>&lt;0.001</td>
</tr>
<tr>
<td>71–80</td>
<td>1.816</td>
<td>2</td>
<td>24</td>
<td>0.908</td>
<td>22.44</td>
<td>&lt;0.001</td>
</tr>
</tbody>
</table>
of cultivated organic soils of different pedological classes are more similar in terms of their degree of decomposition, made up of well-decomposed humic material, compared with deeper soil layers. The differences observed for both penetration resistance and $k_{sat}$ in the surface layer at the different sites are therefore more likely due to agricultural and soil management practices, which may have differed among sites. Below the surface layer, close to the compact layer and below, the pedological description of our sites revealed contrasting degrees of decomposition (Fig. 1). Therefore, the degree of decomposition may have influenced the changes observed in penetration resistance and $k_{sat}$. The LM.F is composed of successive layers of undecomposed fibric material (Fig. 4) that, due to their shape and permeability, play an important regulatory role in restricting vertical water movement, probably similar to the effect of bark (Nkongolo and Caron, 1999) and other large organic fragments (Caron et al., 2005) in growing media (Fig. 4). This explains the very low $k_{sat}$ observed in the compact zone of the LM.F. As described by Brandyk et al. (2002), peat layers are commonly anisotropic, and hydraulic conductivity is therefore different in the vertical and horizontal directions. Chason and Siegel (1986) reported horizontal hydraulic conductivity that was twice the magnitude of vertical hydraulic conductivity, due essentially to an accumulation of dead

Table 2. Analysis of variance of field saturated hydraulic conductivity in the surface and compact layers of the organic soils at different degrees of decomposition.

<table>
<thead>
<tr>
<th>Depth</th>
<th>Type III sum of squares</th>
<th>Numerator df</th>
<th>Denominator df</th>
<th>Mean squares</th>
<th>F-ratio</th>
<th>p-value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Surface</td>
<td>2.158</td>
<td>2</td>
<td>45</td>
<td>1.079</td>
<td>6.935</td>
<td>0.002</td>
</tr>
<tr>
<td>Compact layer</td>
<td>3.072</td>
<td>2</td>
<td>45</td>
<td>1.536</td>
<td>4.161</td>
<td>0.022</td>
</tr>
</tbody>
</table>

Fig. 3. Field saturated hydraulic conductivity measured as a function of the degree of decomposition of the organic soil in (a) the surface layer and (b) the compact layer. Different letters for each soil type indicates a significant difference between soils using Tukey's post-hoc honestly significant difference test. LM.F, Limnic Fibrisol; TH, Terric Humisol; TMH, Terric Mesic Humisol.

Fig. 4. View of undecomposed fibric material in organic soils.

Fig. 5. The relationship between saturated hydraulic conductivity and soil penetration resistance in (a) the surface layer and (b) the compact layer. LM.F, Limnic Fibrisol; TH, Terric Humisol; TMH, Terric Mesic Humisol.
Sphagnum plants and the consequent formation of horizontal planar pathways for water flow. Our results indicate that penetration resistance and \( k_{\text{sat}} \) are both linked to the degree of soil decomposition, which was identified by pedological classification. However, although the penetration resistance of the soils increases systematically with the degree of decomposition, the relationship between hydraulic conductivity and the degree of decomposition is not as straightforward, since hydraulic conductivity is sensitive to the presence of undecomposed fibrillar material, and the size, shape, and orientation of the particles must be considered. Consequently, a higher soil strength measured with a penetrometer in a cultivated organic soil does not necessarily indicate a less permeable soil. The relationship between penetration resistance and \( k_{\text{sat}} \) is thus dependent on the degree of decomposition of the organic soil (Fig. 5), particularly in the compact layer (Fig. 5b). Pedotransfer function may be of interest to develop in order to reduce efforts needed to estimate \( k_{\text{sat}} \). However, functions used to predict soil properties in mineral soil are not directly applicable on Histosols due to the nature of this particular soil made of fibrillar material, as opposed to the granular and structural nature of mineral soils. Further investigation of the complex relationship between penetration resistance and \( k_{\text{sat}} \) is currently being performed to evaluate if penetration resistance could be used to assess the hydraulic properties and profile evolution of organic soils, but this study suggests that an in-depth understanding of the mechanism controlling flow processes related to soil mechanical properties is required in fibrillar soils (Caron and Nkongolo, 2004).

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References


