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After the conversion of natural peatland in this study into agricultural land began 50 yr ago, the organic topsoil became compacted and developed drainage issues, which may soon reduce crop yield.

Long-Term Effects of Peatland Cultivation on Soil Physical and Hydraulic Properties: Case Study in Canada

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Organic soils are an excellent substrate for commercial lettuce (*Lactuca sativa* L.) farming; however, drainage accelerates oxidation of the surface layer and reduces the water holding capacity, which is often lethal for crops that are sensitive to water stress. In this case study, we analyzed 942 peat samples from a large cultivated peatland complex (18.7 km^2) in southern Quebec, Canada, and demonstrated from spatial and temporal patterns that agriculture resulted in a compacted layer below the root zone. We grouped the samples based on the year in which the corresponding fields were created on the previously undisturbed peatland (cutoff years 1970, 1980, 1990, and 2000) and discovered that bulk density has continued to increase, partly due to the overburden pressure, while organic matter has continued to decline since the fields were reclaimed and drained in phases between 1955 and 2006. Saturated hydraulic conductivity (K_s) in the upper 20 cm was remarkably lower on fields older than 10 yr (p = 0.0973 for Wilcoxon rank test), with more samples having a $K_s < 2.0 \times 10^{-3}$ yr. Soil water available capacity (SWAC) was between approximately 5 and 33 cm on fields reclaimed after 2000, while samples from fields reclaimed before 2000 had a lower SWAC between 2 and 23 cm (groups discernable at p = 0.0203). It is possible, however, that the greatest rate of change in K_s and SWAC occurred within even a year of reclamation. The results of this study call for active measures to reduce organic soil degradation such as reducing tillage and on-field traffic or following a crop rotation scheme.

Abbreviations: MAE, mean absolute error; SWAC, soil water available capacity.

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Organic peat soils have a large water holding capacity of 80 to 90% (v/v) at saturation (Boelter, 1964), which makes them an excellent natural substrate for commercial lettuce farming and production of other vegetables such as onion (*Allium cepa* L.), carrot (*Daucus carota* L.), celery (*Apium graveolens* L.), and leek (*Allium porrum* L.). Despite their high porosity, allowing a large water holding capacity, these soils have many small dead-end pores that almost never drain. It is estimated that active water-conducting pores account for only 0.01% of the total soil volume (Carey et al., 2007). Bloemen (1983) attempted to derive hydraulic conductivity and capillary rise in organic soils from their physical properties but found that both varied greatly from one location to another. In addition, the water retention characteristics of organic soils display a high degree of hysteresis as a result of a wetting inhibition caused by hydrophobicity in combination with preferential infiltration (Schwärzel et al., 2006).

Studies have suggested that organic soils are very sensitive to the effects of agriculture and water management. Gesch et al. (2007) demonstrated that deep tillage to a depth of 300 mm leads to higher oxidation and subsidence rates, thereby altering the organic soil structure. The higher degree of decomposition in cultivated organic soils vs. natural undisturbed peatlands leads to a faster decline in organic content, increase of bulk density, and loss of structural pores (Kechavarzi et al., 2010). High axle load traffic has been observed to reduce the macroporosity of the organic soil by 37 to 70% between depths of 0.4 and 0.55 m and to reduce saturated hydraulic conductivity by 60 to 98% after as little as four passes (Alakukku, 1996).

Water management studies on organic soils have shown that the oxidation is accelerated by excessive drainage, which in turn also increases the rate of biodegradation, reduces the water storage capacity and hydraulic conductivity (Schlotzhauer and Price, 1999), and in some cases causes the organic soil to subside more than a centimeter per year (Shih et al., 1998). Vegetables such as lettuce are very sensitive to water stress during the growth stage when water demand is high and can quickly develop physiological disorders (tip burn) resulting in yield loss (Périard et al., 2012). Understanding the effects of peatland cultivation on soil physical and hydraulic properties is essential for optimizing water management on organic soils, yet there is no quantitative knowledge of the large-scale effects.

The objective of this study was to determine how decades of lettuce and vegetable farming have affected soil physical and hydraulic properties on a large peatland complex in southern Quebec, Canada. To this end, we first tested the correlation between the physical and hydraulic characteristics of the organic soils in this area and next derived the spatial patterns for each of these characteristics. We then evaluated the long-term effects (40 yr) of commercial lettuce and vegetable farming on the soil physical and hydraulic properties resulting from a transformation of the organic material and the link with a compacted layer below the surface.

Materials and Methods

The Montérégie Cultivated Peatland Complex in Canada

We conducted a study on five lettuce and vegetable farms in the Montérégie peatland complex in Canada near the Quebec–New York border (45°10′ N, 73°31′ W; Fig. 1) between 2008 and 2012. This area is Canada's largest producer of romaine lettuce and mesclun, which is a blend of assorted young lettuce and spinach (*Spinacia oleracea* L.) leaves. Other vegetables such as onion, carrot, celery, and leek were also produced during this period. The 18.7 km^2 of cultivated peatland are concentrated into four districts spread out over an area of roughly 22 by 12 km. Each district is mostly flat, with an elevation between 50 and 65 m, and actively drained with hydraulic pumps.

The organic soil was classified as a Histosol (Soil Survey Staff, 1999) with, at the surface, an Ohp layer disturbed by agriculture. The Oh layer extends to a depth of 20 to 29 cm, and with von Post scale 7 and higher (von Post and Granlund, 1926; Parent and Caron, 1993), this layer is generally in an advanced stage of decomposition. The Oh layer continues to a depth of approximately 37 cm, but below a depth of 29 cm the humic layer is compacted, causing a perched water table during and following moderate rainfall (Lafond et al., 2014). A fibric (Of, von Post scale 2–4) to moderately decomposed layer (Om, von Post scale 4–6) is found beneath the compacted layer up to a depth of 120 cm and locally as deep as 250 cm.

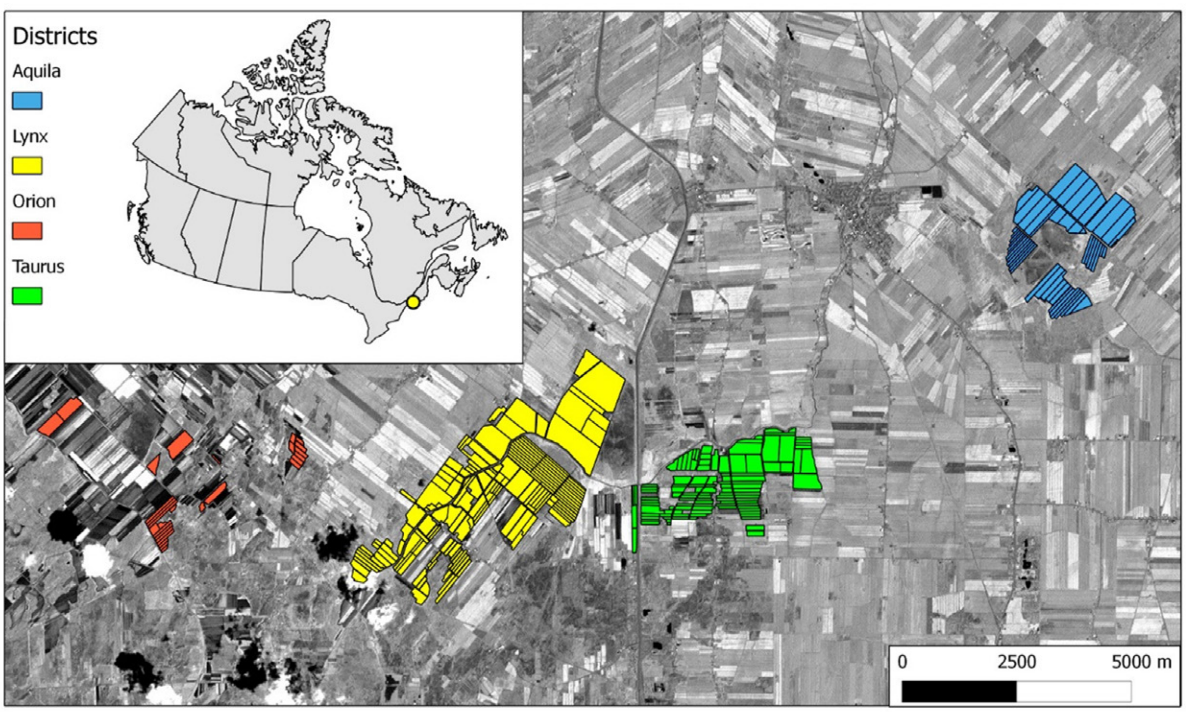

Fig. 1. Location of the Montérégie peatland complex and the four cultivated districts projected onto a panchromatic areal image: Aquila (3.8 km^2), Lynx (9.6 km^2), Orion (the fragmented area on the far left with 1.2 km^2 of peatland), and Taurus (4.1 km^2).

Experiments

A total of 942 peat samples were collected at depths of 5, 20, 35, and 50 cm, using cylinders with a height of 5.5 cm, an internal diameter of 8.2 cm, and a cutting edge, by pushing the cylinders into the soil by hand according to the method described by Grossman and Reinsch (2002). Bulk density, particle density, porosity, and organic matter content were measured in the laboratory for samples taken at all four depths, while the saturated hydraulic conductivity and water retention curves were determined in that order for additional samples taken from the same locations at depths of 20 and 35 cm, which was within the Oh (surface) layer. We used a metal rod to probe the thickness of the organic soil layer and determine the depth of the compacted layer in each profile. The soil water available capacity for lettuce was calculated with a two-layer formula adapted for lettuce farming.

Bulk Density, Particle Density, Organic Content, and Porosity

The samples were oven dried at 70°C for a period of 24 to 48 h and measured with a digital caliper to determine the amount of shrinkage, after which the bulk density, ρ_b (g cm^{-3}), was calculated as the ratio of dry soil mass to the total volume of soil including the pore volume. Organic matter content was determined by heating samples to 375°C for 1 h and subsequently keeping the temperature at 550°C for 16 h until the sample weight stabilized (loss on ignition; Andrejko et al., 1983). The particle density (ρ_p, g cm^{-3}) was estimated based on the ash content according to the method described by Paquet et al. (1993), assuming a particle density of 1.55 g cm^{-3} for organic matter and 2.65 g cm^{-3} for the mineral fraction (Verdonck et al., 1978):

$$\rho_p = \frac{1+F}{\left(F/1.55\right)+\left(1/2.65\right)} \quad [1]$$

where F is the ratio of organic content to ash content. Finally, the total porosity, n, was calculated as one minus the ratio of measured bulk density to particle density.

Saturated Hydraulic Conductivity

Saturated hydraulic conductivity (K_s) was measured for samples taken at depths of 20 and 35 cm at the same locations and using the same type of cylinders as for the samples on which we analyzed the physical properties. Samples were trimmed flush with the cylinders at both ends, and the bottom end of each cylinder was covered with a nylon cloth. Next, the samples were placed on a grill inside a tank and saturated during a 1-d period from the top down by means of dripping until the water outside the cylinder reached just below its upper edge. Once saturated, the cylinders were placed inside another tank, again on a grill, where we determined K_s with the constant-head soil core method (Elrick et al., 1981; Reynolds, 1993). This was done by keeping the samples completely submerged and maintaining a constant water level above the samples using a Marriotte reservoir. Saturated hydraulic conductivity was calculated using the steady-state outflow from the Marriotte reservoir and the hydraulic gradient over the height of the sample.

Soil Water Available Capacity for Lettuce

The soil water available capacity (SWAC, cm) was determined using a formula adapted for romaine lettuce cultivated on organic soils, accounting for a maximum rooting depth of 100 cm (Plamondon et al., 2011) or the total depth of the organic soil, whichever was shallower. The organic soil had a characteristic two-layer profile divided by a thin compacted layer, therefore SWAC was calculated as the sum of SWAC in the surface layer (Oh layer) and the bottom layer (Of or Om) for each profile (calculations by Lafond et al., 2015):

$$\mathrm{SWAC} = \int_{z_0}^{z_1} \left(\theta_{fc} - \theta_{wp}\right)_{SU} dz + \int_{z_1}^{z_2 \le 100} \left(\theta_{fc} - \theta_{wp}\right)_{BO} dz \quad [2]$$

where z_0 indicates the soil surface level (cm), z_1 is the depth of the surface layer (cm), z_2 is the depth of the organic soil (cm) up to a maximum depth of 100 cm, θ_{fc} is the volumetric water content at field capacity (cm^3 cm^{-3}), θ_{wp} is the volumetric water content at the wilting point (cm^3 cm^{-3}), SU indicates the surface layer, and BO indicates the bottom layer.

The field capacity and wilting point are generally understood to correspond with matric potentials of approximately −330 cm (−33 kPa) and −15,300 cm (−1.5 MPa), respectively; however, these values are extremely low for organic soils and would represent lethal water stress for lettuce. Based on an earlier study on the same soils in this study area (Périard et al., 2012), we assumed a field capacity of −50 cm (−5 kPa) for the surface (Oh) layer, a field capacity of −25 cm (−2.5 kPa) for the bottom layer (Of/Om), and a wilting point of −300 cm (−30 kPa) for both layers and determined the corresponding water content for samples taken at depths of 20 (surface layer) and 35 cm (bottom layer) with a multistep outflow experiment using Tempe pressure cells (results described by Hallema et al., 2015). These were the same samples for which we previously determined K_s. Note that, given its high sensitivity to water stress, the temporary and permanent wilting points for lettuce are nearly indistinguishable.

In the specific case where K_s of the surface layer was $<10^{-4}$ cm s^{-1}, indicating the presence of a very densely compacted layer, lettuce roots were unable to penetrate into the bottom layer and SWAC was determined only for the readily available water in the surface layer (Lafond et al., 2015):

$$\mathrm{SWAC} = \int_{z_0}^{z_1} \left(\theta_{fc} - \theta_{wp}\right)_{SU} dz_1 \quad [3]$$

Analyses

Although great care was taken in determining the physical and hydraulic characteristics of the organic soil, several researchers have pointed out the difficulty of obtaining undisturbed peat samples (Hillis and Brawner, 1961; Hardy, 1965). Extraction (smear), transportation, and handling (shaking) can cause sample disturbance that translates into extreme parameter values that cause bias in subsequent analyses. Because we had no means of discriminating between presentative and false outliers, we chose to retain only the values within the 2.5 to 97.5 percentile ranges of each parameter.

Correlation Analysis

We performed a correlation analysis of the physical properties (bulk density and organic matter content), profile characteristics (total thickness of the organic soil and depth of the compacted layer), and hydraulic properties (K_s and SWAC for lettuce). The year of reclamation and drainage, although a characteristic of the entire field rather than of an individual soil sample, was also included in the correlation analysis. This characteristic is further explored below.

Spatial Interpolation

The soil sample data were divided into four districts based on geographical location, Aquila, Lynx, Orion, and Taurus (Fig. 1), and interpolated using a maximum likelihood fitting of thin plate spline surfaces (Duchon, 1976; Wahba, 1990) (see Appendix for details).

The performance of the thin plate spline model was evaluated by means of a leave-one-out cross-validation. This involved using a single observation from the original soil variable as validation data and the other observations as the training data for predicting its value. This procedure was repeated for all n samples of the soil variable, after which the mean absolute error (MAE) was calculated as

$$\mathrm{MAE}=\frac{1}{n}\sum_{i=1}^{n}\left|e_i\right| \quad [4]$$

where e is the residual value after fitting.

Wilcoxon Rank Test on Organic Soil Properties Grouped by Year of Reclamation

Farm records provided an accurate record of the year in which each field in the study area was reclaimed and drained for the purpose of commercial farming and furthermore confirmed that the area originally consisted of natural undisturbed peatlands with mixed hardwood forest. The data set therefore allowed us to estimate to what degree the physical and hydraulic characteristics of the organic soils had changed since reclamation.

A survey among three out of five farmers covering approximately 70% of the Aquila, Lynx, and Taurus districts showed that most fields were reclaimed between 1960 and 1970, with the earliest fields dating back to 1955 and the most recent fields to 2006. To determine whether the organic soil had significantly different characteristics on fields reclaimed after 2000 vs. before 2000, we divided each sample characteristic into two groups based on the year in which the corresponding field was reclaimed and subsequently tested for statistical difference between these groups.

This was done using the Wilcoxon rank test, which is a nonparametric test on the combined order in which the values of two groups of samples are ranked. This ensures that the outcome of the comparative test is not affected by the skewness of the value distribution of each group. The number of samples being on the low side for this type of analysis, we maximized the number of samples per group by successively pushing back the threshold year to allow a comparison of the properties of fields reclaimed before vs. after 1990, before vs. after 1980, and before vs. after 1970 (as mentioned above, we started with 2000).

Results and Discussion

Correlation Analysis

Table 1 gives a statistical summary of the different physical and hydraulic properties of 942 peat samples. Using this table in combination with the corresponding univariate distributions and bivariate scatter plots provided in Fig. 2 and the correlation matrix

Table 1. Statistical summary of physical and hydraulic properties of peat: bulk density (ρ_b), particle density (ρ_p), porosity (n), organic matter content (f_o), thickness of the organic soil layer (D_o), depth of the compacted layer (z_{cl}), saturated hydraulic conductivity (K_s), soil water available capacity (SWAC) for lettuce, and year of reclamation (Reclam. yr).

Statistic	ρ_b	ρ_p	n	f_o	D_o	z_{cl}	K_s	SWAC	Reclam. yr
	g cm^{-3}		cm cm^{-3}		cm		cm s^{-1}	cm	
Observations, no.	886	661	877	878	220	222	233	207	102 fields
Mean	0.263	1.669	0.845	0.830	134.2	33.6	4.13×10^{-3}	13.74	1971
Min.	0.132	1.572	0.706	0.426	20	10	1.14×10^{-5}	2.00	1955
Max.	0.562	2.035	0.912	0.967	260	85	6.32×10^{-2}	34.29	2006
Median	0.262	1.643	0.846	0.859	127.5	32.0	1.00×10^{-3}	13.50	1965
First quartile	0.190	1.612	0.813	0.801	85.0	29.3	2.79×10^{-4}	9.37	1960
Third quartile	0.316	1.683	0.883	0.903	190.8	36.8	3.74×10^{-3}	18.07	1970
SD	0.089	0.090	0.045	0.109	60.7	9.2	8.61×10^{-3}	6.51	13.6
CV	0.338	0.054	0.053	0.131	0.452	0.273	2.08	0.47	6.88×10^{-3}
Skewness	0.825	1.900	−0.487	−1.557	0.154	1.799	4.07	0.46	1.605

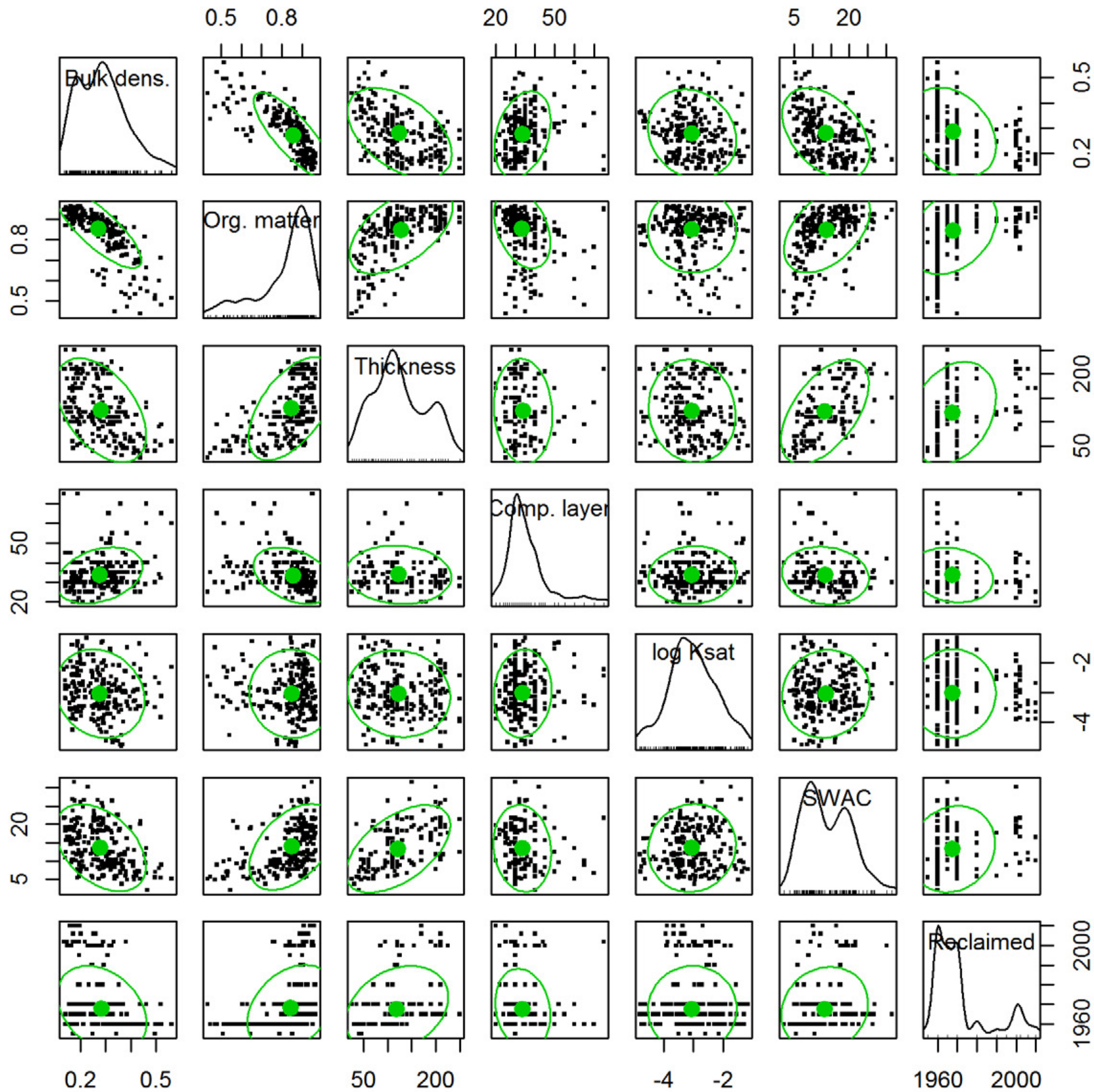

Fig. 2. Univariate distributions and bivariate scatter plots of bulk density (g cm^{-3}), organic matter content, thickness of the organic soil (cm), depth of the compacted layer (cm), logarithm of the saturated hydraulic conductivity (K_{sat}, cm s^{-1}), soil water available capacity (SWAC) for lettuce (cm), and year of reclamation. Concentration ellipses cover 90% of the data.

found in Table 2, we first discuss the physical properties of the peat samples and then continue with the profile characteristics and hydraulic properties.

Physical Properties

Bulk density varied between 0.132 and 0.562 g cm^{-3}, with a median of 0.262 (Table 1), and was strongly correlated with particle density (Pearson's $r = 0.730$; Table 2), which had values between 1.572 and 2.035 g cm^{-3}, with a median value of 1.643. The high organic content between 0.426 and 0.967, with a median value of 0.859, was negatively correlated with bulk density (Pearson's $r = -0.748$), indicating that oxidation goes hand in hand with compaction. For porosity, we measured values between 0.706 and 0.912 with a median of 0.846. The correlations between the physical parameters that were determined independently from one another (bulk density and organic matter) are in agreement with the findings of Okruszko (1971), who derived strong linear relationships based on an analysis of 2996 peat samples containing between 0.7 and 99% organic matter.

The distributions of soil physical properties (Fig. 2, down the diagonal) were often multimodal as a result of regional patterns, discussed below, and vertical patterns within the soil profile. Bulk density decreased with sample depth (Pearson's $r = -0.426$), with a median bulk density of 0.279 g cm^{-3} at a depth of 5 cm and 0.172 g cm^{-3} at a depth of 50 cm. Porosity, on the other hand, increased with sample depth (Pearson's $r = 0.378$), with a median porosity of 0.835 at a depth of 5 cm and 0.896 at a depth of 50 cm.

Profile Characteristics

The total thickness of the organic soil ranged between 20 and 260 cm (Table 1), with a median value of 127.5 cm and first and

Table 2. Correlation matrix of hydraulic and other properties of the organic soil (Pearson's product-moment correlation coefficients for pairwise complete data): bulk density (ρ_b), particle density (ρ_p), porosity (n), organic matter content (f_o), thickness of the organic soil layer (D_o), depth of the compacted layer (z_{cl}), saturated hydraulic conductivity (K_s), soil water available capacity (SWAC) for lettuce, and year of reclamation (Reclam. yr).

Parameter	ρ_b	ρ_p	n	f_o	D_o	z_{cl}	log K_s	SWAC	Reclam. yr
ρ_b	1	0.730	−0.983	−0.748	−0.426	0.340	−0.154	−0.322	−0.335
ρ_p	0.730	1	−0.609	−0.998	−0.479	0.334	0.097	−0.319	−0.335
n	−0.983	−0.609	1	0.627	0.378	−0.312	0.207	0.294	0.299
f_o	−0.748	−0.998	0.627	1	0.464	−0.325	−0.070	0.327	0.366
D_o	−0.426	−0.479	0.378	0.464	1	−0.154	−0.076	0.430	0.312
z_{cl}	0.340	0.334	−0.312	−0.325	−0.154	1	0.077	−0.069	−0.113
log K_s	−0.118	0.097	0.207	−0.003	−0.086	0.050	1	0.031	−0.061
SWAC	−0.322	−0.319	0.294	0.327	0.430	−0.069	0.160	1	0.137
Reclam. yr	−0.335	−0.335	0.299	0.366	0.312	−0.113	0.015	0.137	1

third quartiles at 85 and 190.8 cm, respectively. The first peak in the bimodal distribution of organic soil thickness (Fig. 2) represents data for the Lynx and Taurus districts, where the peat layer had a maximum thickness between approximately 90 and 130 cm, while the second peak corresponds with the Aquila district, where the peat layer was up to 190 to 220 cm thick. There is a weak positive correlation with organic matter content (Pearson's $r = 0.464$; see Table 2) and a weak negative correlation with bulk density (Pearson's $r = -0.426$).

A 5- to 10-cm-thick compacted layer was present in all profiles and found at a depth between 29 and 37 cm in 50% of the sampled locations. No relationship was identified between the depth of the compacted layer and the total thickness of the organic soil, mainly because the former was fairly homogenous throughout the study area.

Hydraulic Properties

Saturated hydraulic conductivity was between 1.14×10^{-5} and 6.32×10^{-2} cm s^{-1}, with a median of 1.00×10^{-3} cm s^{-1} (or 36 mm h^{-1}). No correlation was found with any of the other properties of the organic soil; however, a vertical trend was detected. The K_s was generally higher for samples taken at a depth of 35 cm below the surface (median of 1.61×10^{-3} cm s^{-1} or 57.96 mm h^{-1}) than for samples taken at 20 cm below the surface (median of 5.57×10^{-4} cm s^{-1} or 20.05 mm h^{-1}). The high variability of hydraulic conductivity is commonly acknowledged (Ivanov, 1953; Bondarenko et al., 1975) and evidenced here by the high coefficient of variation (2.08).

The SWAC for lettuce was between 2.00 and 34.29 cm, with a median of 13.50 cm, and had a weak correlation with the thickness of the organic soil (Pearson's $r = 0.430$) and organic matter content (Pearson's $r = 0.327$); however, there was no significant correlation with K_s. This confirms that the compacted layer was rarely dense enough to limit SWAC, a phenomenon observed for values lower than 10^{-4} cm s^{-1} (Lafond et al., 2015).

Spatial Patterns

Figures 3 to 6 show the spatial distribution of physical and hydraulic soil properties of the four districts, Aquila, Lynx, Orion, and Taurus, respectively. The generally low MAE of cross-validation (given in the same units as the corresponding variable) indicates a satisfactory performance for all of the interpolated surfaces except for K_s. Cross-validation performance for the Orion district (Fig. 5) was as high as for the other districts despite the small number of samples (34–37 per variable) and long distance between individual fields. Values for the smoothing parameter λ were high ($\lambda > 1000$) in all four districts for bulk density, organic matter, and K_s due to the high spatial variability of the observed values.

Physical Properties

The interpolated surface for bulk density yielded values between 0.25 and 0.40 g cm^{-3} at a depth of 20 cm, decreasing to 0.15 to 0.25 g cm^{-3} at a depth of 35 cm. Bulk density was quite variable for the Lynx and Taurus districts (Fig. 4 and 6), with high surface values (>0.35 g cm^{-3}) for shallow organic soils (<100 cm). In the Aquila district (Fig. 3), where the organic soil was relatively thick (160–200 cm), bulk density was more uniform than in the other three districts, with values between 0.25 and 0.30 g cm^{-3}.

While bulk density decreased with depth, organic matter increased from 0.70 to 0.90 near the surface to 0.75 to 0.96 at a depth of 35 cm. Organic matter content in the Aquila district (Fig. 3) was remarkably high and homogeneous (0.93–0.96) at a depth of 35 cm. High organic content (>0.85) in the Lynx district (Fig. 4) was observed for organic soils deeper than 100 cm. A comparable pattern was found in the Taurus district (Fig. 6), where organic content was lower (<0.85) and the organic layer less thick (<150 cm). In the Orion district (Fig. 5) we also observed a correlation between a thick organic soil (>180 cm) and high organic content.

Profile Characteristics

The interpolated depth of the compacted layer varied between 29 and 37 cm with a MAE of cross-validation between 5.8 and 6.7 cm.

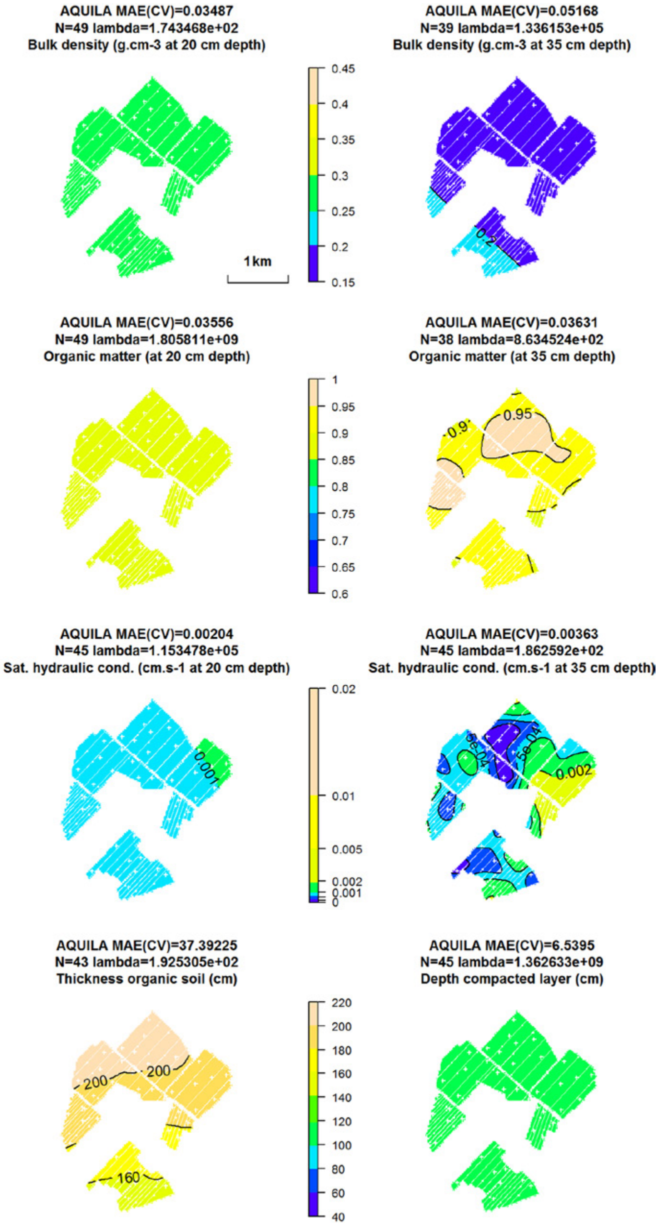

Fig. 3. Spatial distribution of the bulk density, organic matter content, and saturated hydraulic conductivity at the 20- and 35-cm depths and the thickness of the organic soil and depth of the compacted layer of peat soils in the Aquila district, with the mean absolute error (MAE) of cross-validation, number of samples N, and value of the smoothing parameter λ for each interpolation.

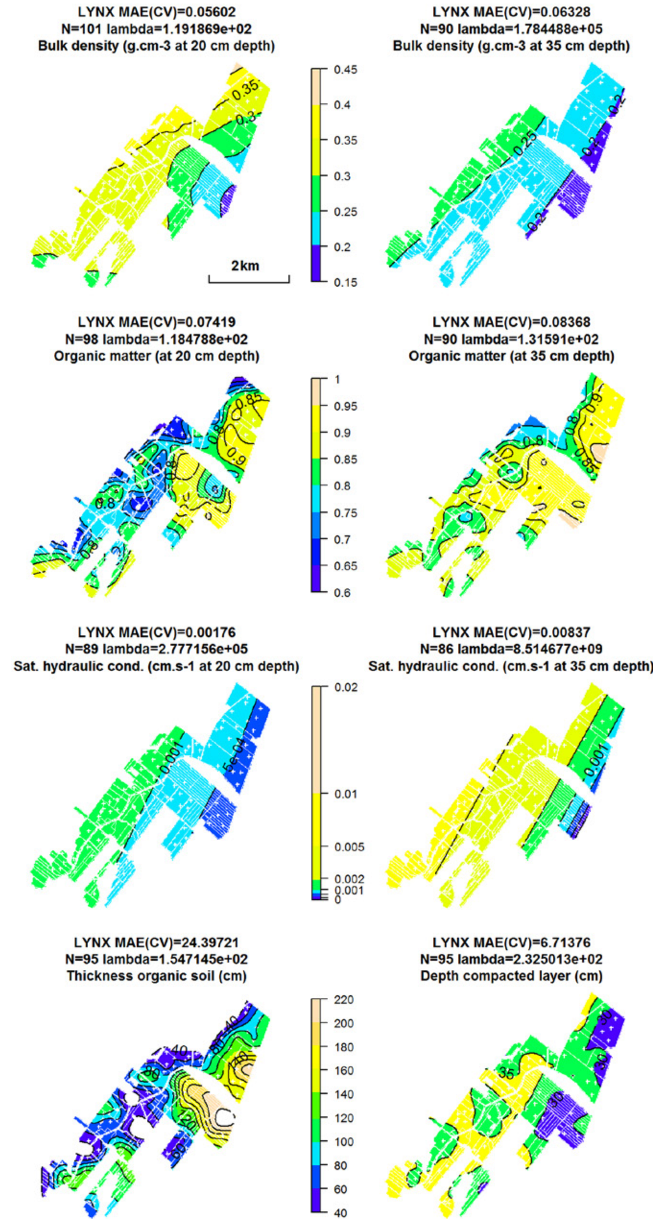

Fig. 4. Spatial distribution of the bulk density, organic matter content, and saturated hydraulic conductivity at the 20- and 35-cm depths and the thickness of the organic soil and depth of the compacted layer of peat soils in the Lynx district, with the mean absolute error (MAE) of cross-validation, number of samples N, and value of the smoothing parameter λ for each interpolation.

Note that this observed depth was not corrected for variations in the local relief, which were in the same order of magnitude as the MAE of cross-validation, viz. between 5 and 10 cm; however, the spatial pattern essentially indicated that the compacted layer was approximately horizontal in all four districts.

Hydraulic Properties

The spatial distribution of K_s seemed unrelated to that of any of the other soil variables and in addition varied greatly from one sample to the next. With an MAE of cross-validation in the same order of magnitude as the observed values, the interpolated surface did not seem to be a very good indicator of actual spatial trends, except in the case of the Aquila district where we observed a lower K_s at a depth of 35 cm associated with the area of high organic content near the center.

Origin of the Compacted Layer

A plausible geological theory for the area is that the organic soils superposing the clayey and sometimes sandy mineral deposits were formed in situ as a lake bottom deposit that evolved into a peat-accumulating fen, which is in accordance with the ruling theories on the origin of postglacial lakes in this region (e.g., Lavoie and

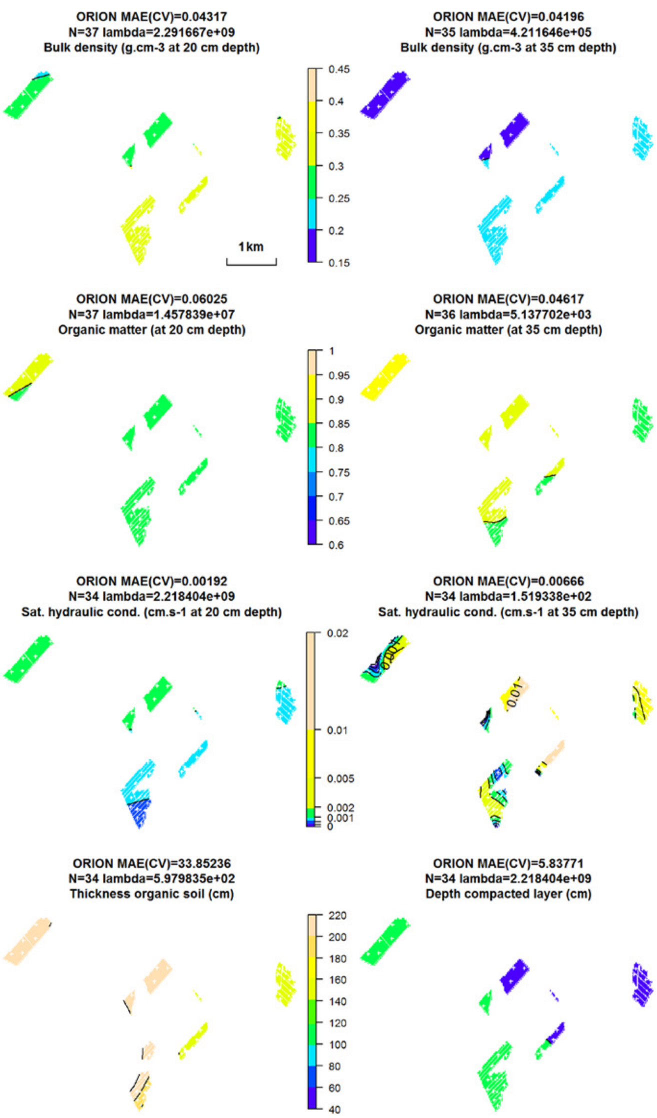

Fig. 5. Spatial distribution of the bulk density, organic matter content, and saturated hydraulic conductivity at the 20- and 35-cm depths and the thickness of the organic soil and depth of the compacted layer of peat soils in the Orion district, with the mean absolute error (MAE) of cross-validation, number of samples *N*, and value of the smoothing parameter λ for each interpolation.

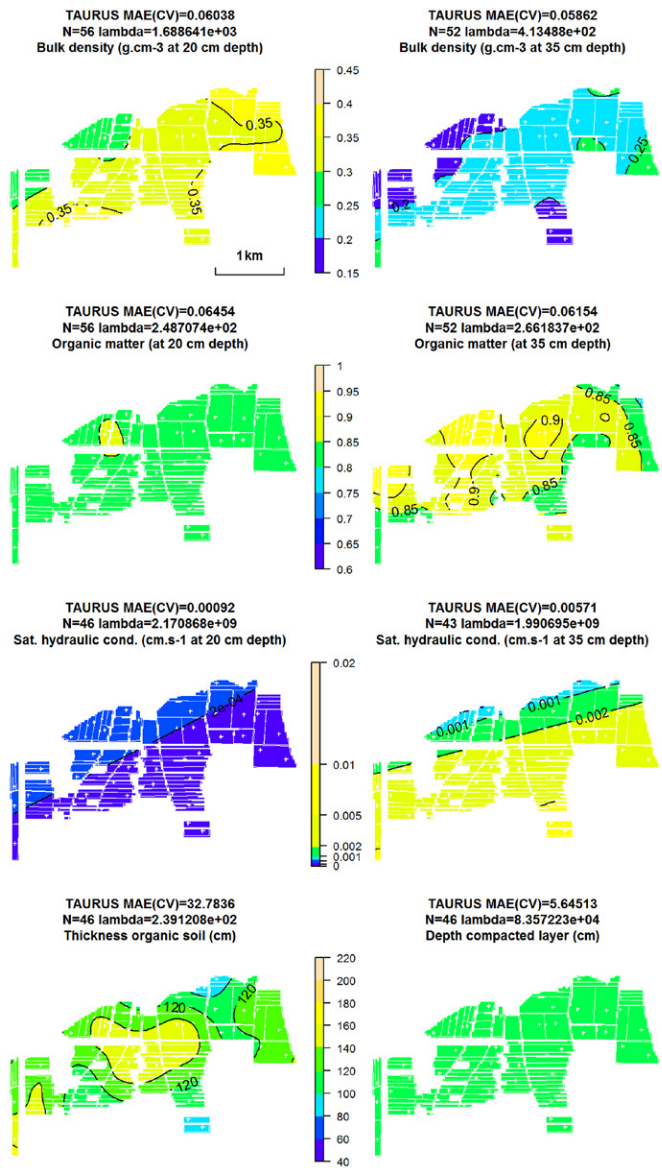

Fig. 6. Spatial distribution of the bulk density, organic matter content, and saturated hydraulic conductivity at the 20- and 35-cm depths and the thickness of the organic soil and depth of the compacted layer of peat soils in the Taurus district, with the mean absolute error (MAE) of cross-validation, number of samples *N*, and value of the smoothing parameter λ for each interpolation.

Richard, 2000). Another argument defending this hypothesis is that the total thickness of the organic soils in the Lynx and Taurus districts increases toward their respective centers, given that the outer limits of the lettuce fields correspond closely to the outer extent of the peat deposits. An existing soil map of Napierville County (Lamontagne et al., 2013) furthermore suggests that the organic soils in the Lynx and Taurus districts are part of one lacustrine deposit, while the Aquila and Orion districts are associated with separate systems, which corresponds with our data.

Given the MAE of cross-validation for the compacted layer depth and small variations in local relief, we expect that the compacted layer is approximately horizontal and found at the same depth in each district, although the homogeneous surface elevation of each district varies between 50 and 65 m. In the event that the compacted layer was formed by natural processes together with the rest of the organic soil, we would expect to find it at three cardinal depths associated with the three lacustrine deposits. However, given the unimodal distribution and narrow depth range of the compacted layer, it is more likely an unintended side effect of agriculture.

The factors that may have contributed to the development of the compacted layer include (i) tillage, which in the long term causes smear at the tillage depth between 25 and 35 cm, (ii) tractor wheel traffic, (iii) leaching of fine particles due to irrigation, and (iv) accumulation of decomposed roots below the tillage depth. The compacted layer is indeed found directly below the root zone of lettuce, which extends to depths up to 100 cm (Plamondon et al., 2011) but only 30 cm on average (FAO, 1989). The roots of lettuce have difficulty penetrating the compacted layer, and therefore continue to grow horizontally once they reach the compacted layer. With two growth cycles per year, this may have led to a buildup of decomposed root material at a depth between 29 and 37 cm, thereby decreasing the hydraulic conductivity while increasing the risk of waterlogging in the upper layer.

Evolution of Cultivated Peat Characteristics after Reclamation

Table 3 lists the p values for the Wilcoxon rank test comparing the distributions of each organic soil property (bulk density, organic matter, K_s, and SWAC) based on membership of the group containing samples coming from fields reclaimed either before or after the threshold year. The null hypothesis was that no distinction could be made between the two groups. We performed four tests using different threshold years (2000, 1990, 1980, and 1970), where each of these threshold years represented a new statistical test on all available data for a given soil property, to allow us to find the most significant threshold among these 4 yr (significant p levels are in bold type in Table 3).

Bulk density and organic matter were discernible for all four threshold years between 1970 and 2000 ($p < 0.05$), indicating ongoing transformation of these properties since reclamation. Density plots for threshold year 2000 (Fig. 7) indeed show that bulk density was lower and organic content higher for fields reclaimed after that year, where the more significant changes were observed at a depth of 20 cm (smaller p value).

Although K_s in the upper 20 cm seemed not to have changed significantly in the long term (p values > 0.05), it is difficult to draw conclusions from these high p values given the high coefficient of variation (2.08, cf. 0.338 for bulk density) associated with the spatial variability of K_s on the field. Nevertheless, K_s decreased remarkably (Fig. 7, $p = 0.0973$), with more samples having a $K_s < 2.0 \times 10^{-3}$ cm s^{-1} on fields reclaimed before vs. after 2000. The SWAC was between approximately 5 and 33 cm on fields reclaimed after 2000, while samples from fields reclaimed before 2000 had a lower SWAC between 2 and 23 cm (groups discernable at $p = 0.0203$; Table 3; Fig. 7). The p values <0.05 for threshold years 2000, 1990, and 1980 demonstrate that SWAC did not stabilize for at least 30 yr.

One interpretation of the higher bulk density and lower organic content, saturated water content Q_s, and K_s for fields reclaimed before 2000 is that within 6 to 10 yr after reclamation the peat became compacted due to a loss of water and decomposed rapidly due to exposure to the atmosphere. Low groundwater tables in combination with high overburden pressures are known causes of shrinkage in peat (Price and Schlotzhauer, 1999; Schlotzhauer and Price, 1999), so for a more complete picture it would be necessary to include other spatial factors in our evaluation, such as the change in overburden pressure with time, the initial organic composition, and the thickness of the soil at different locations within the study area. Local variations in elevation may also play a role, which is why a spatial analysis of short- and long-term evolution is required to explore these aspects more fully.

Conclusion and Perspectives

In this study, we addressed the effects of cultivation on the physical and hydraulic properties of organic soils, in particular on the formation of a compacted layer below the surface and the effects on drainage. The spatial distribution of this compacted layer in combination with the narrow range of depths at which it was found confirmed that it was caused by agriculture. Bulk density increased and continues to increase even 40 yr after reclamation

Table 3. The p values for the Wilcoxon rank test comparing the values of the properties of peat before and after the threshold year. For p values <0.05 (bold type), the soil properties of both groups are discernible at the 95% confidence level, meaning that they were significantly different for samples that fall into the group with fields reclaimed before vs. after the threshold year; z is the depth below the surface, and n gives the number of samples that fall into the group with fields reclaimed before vs. after the threshold year.

Threshold year	Statistic	Bulk density		Organic matter content		Saturated hydraulic conductivity		Soil water available capacity for lettuce
		z = 20 cm	z = 35 cm	z = 20 cm	z = 35 cm	z = 20 cm	z = 35 cm	
		g cm^{-3}		cm cm^{-3}		cm s^{-1}		cm
2000	p	**5.59 × 10^{-7}**	**4.68 × 10^{-4}**	**8.88 × 10^{-6}**	**7.10 × 10^{-4}**	0.0973	0.792	**0.0203**
	n	143/25	125/23	141/25	125/22	49/13	40/11	126/17
1990	p	**4.83 × 10^{-7}**	**7.04 × 10^{-4}**	**3.91 × 10^{-6}**	**8.19 × 10^{-4}**	0.167	0.973	**0.00904**
	n	140/28	123/25	138/28	123/24	48/14	39/12	123/20
1980	p	**4.97 × 10^{-7}**	**1.67 × 10^{-3}**	**3.97 × 10^{-6}**	**3.93 × 10^{-4}**	0.274	1	**0.042**
	n	134/34	117/31	133/33	117/30	47/15	38/13	117/26
1970	p	**6.73 × 10^{-4}**	**0.0312**	**2.97 × 10^{-4}**	**1.80 × 10^{-3}**	0.144	0.426	0.34
	n	97/71	78/70	96/70	78/69	44/18	36/15	82/61

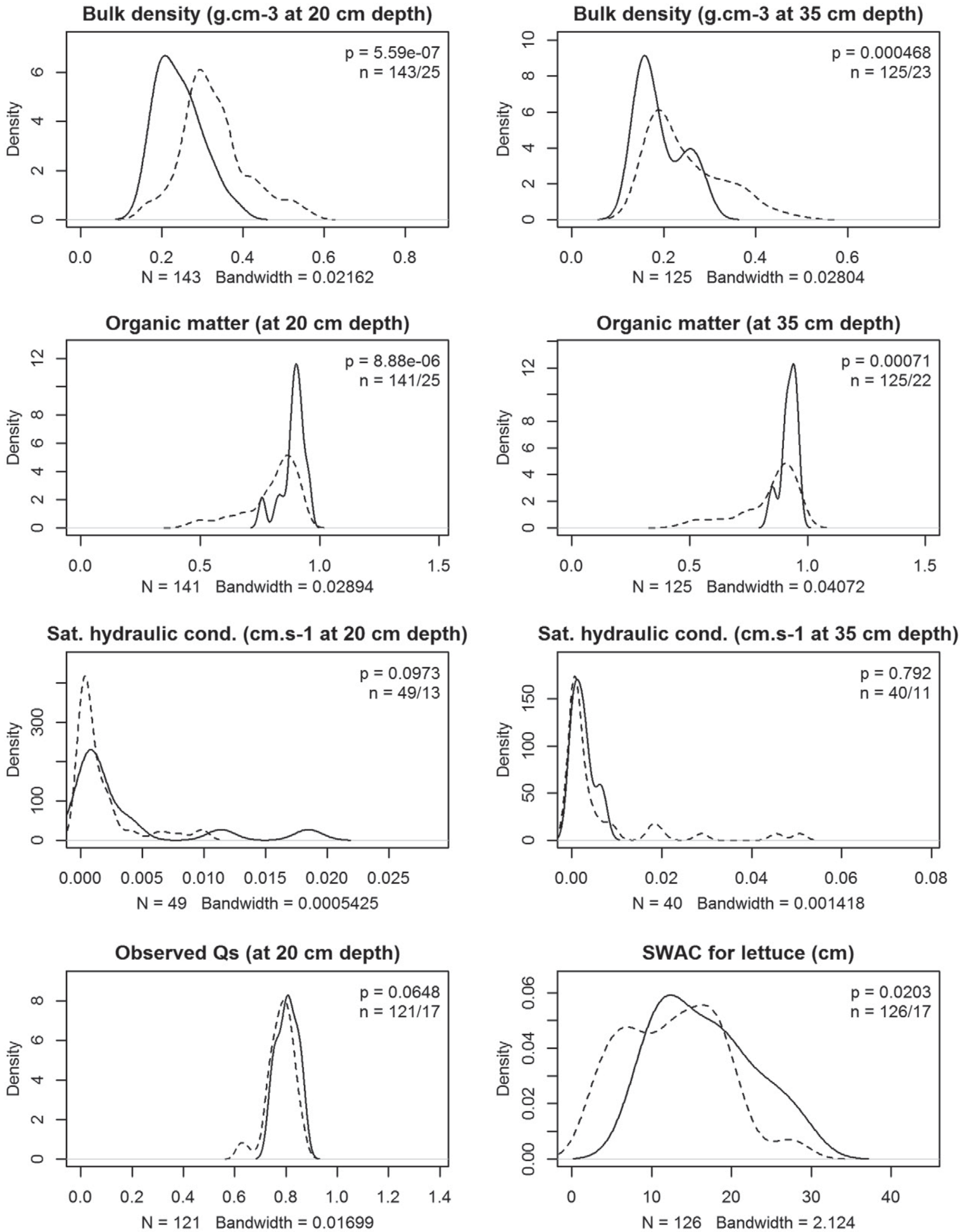

Fig. 7. Density plots and p values for the Wilcoxon rank test comparing the values of bulk density, organic matter content, and saturated hydraulic conductivity at the 20- can 35-cm depths and the observed saturated water content (Q_s) and soil water available capacity (SWAC) for lettuce before (dashed) and after the year 2000. The numbers of samples before and after the threshold year are given by N.

and drainage, while organic matter content and SWAC for lettuce decreased. Although K_s in the upper 20 cm of the soil had not yet decreased to a level where it would diminish SWAC, the Wilcoxon rank test did show that there were more samples having a $K_s < 2.0 \times 10^{-3}$ cm s^{-1} on fields reclaimed before vs. after 2000 (Fig. 7, $p = 0.0973$). The results suggest that the rate of transformation decreased with time while the compacted layer continued to evolve and caused K_s in the upper 20 cm and SWAC to decline. We hypothesize that the greatest rate of change in K_s and SWAC occurred at even shorter time scales, and data for new fields on organic soils would allow us to test the theory that the greatest change occurs within a year of reclamation.

While the effects of peatland cultivation on soil physical and hydraulic properties are significant, they are not necessarily irreversible. In the short term, shallow compacted layers like the ones observed in our field sites can be destroyed by tillage to the appropriate depth, but this would possibly accelerate the formation of a new compacted layer due to an increased exposure to the atmosphere. Solutions known to improve organic matter levels include the application of compost and reducing tillage or maintaining a zero tillage practice throughout the year.

Data on the chemical composition of the organic soil (N and P concentrations) and tracer studies can help in the evaluation of causes and possible long-term preventive measures. One measure to counter soil compaction is the reduction of traffic on fields by optimizing the production process and combining agricultural operations. This process is already observed around the world because it also leads to cost reduction. Crop rotation would require a more drastic change of operations but has a great potential to improve organic soil quality. Sod-based rotations benefit from an enhanced accumulation of organic matter facilitated by the extensive root systems of perennial grasses and have already proved their value in France and England (Albrecht, 1938).

Appendix

Thin Plate Spline Interpolation

Thin plate smoothing splines (Duchon, 1976; Wahba, 1990) can estimate spatial trends even for a small number of observed points without the need for an initial estimate of the spatial dependence of observed points. For this reason, thin plate splines are preferred to kriging for interpolating soil hydraulic properties (Gumiere et al., 2014). Other studies have used thin plate spline interpolation for estimating rainfall (Woldemeskel et al., 2013), potential evapotranspiration (Tait and Woods, 2007), and drought indexes (Akhtari et al., 2009).

In regular thin plate spline fitting, the distribution of residuals can be highly skewed or contain outliers that pull the fitted surface. Such is particularly the case for highly variable data such as hydraulic conductivity. We therefore combined a thin plate spline function with an algorithm that computes robust smoothing parameters based on Hubert weighting. The thin plate spline model is given by

$$y(x_i) = z(x_i) + ke(x_i), \quad i = 1, \ldots, n \qquad [5]$$

where the value of variable x at the ith location is calculated as the sum of a smoothing function $z(x_i)$ and a weighted error term $e(x_i)$, with n the number of observations. Observations with small residuals were awarded a weight of 1, and the larger the residuals, the smaller the weight. The weight function is defined as

$$w(e) = \begin{cases} 1 & \text{for } |e| \le k \\ \dfrac{k}{|e|} & \text{for } |e| > k \end{cases} \qquad [6]$$

where e is the residual value and k the tuning constant calculated as $k = 1.345\sigma$, with σ the standard deviation of the errors. The interpolation surface was found by minimizing

$$\sum_{i=1}^{n} \left(y_i - z_i\right)^2 + \lambda p_{\mathrm{m}}(z) \qquad [7]$$

where $p_{\mathrm{m}}(z)$ is a non-negative objective function for z, defined in terms of mth-order partial derivatives of z, and λ is a smoothing parameter found by iterative least squares fitting. The median of observed values was taken as the initial value for the estimated smoothing function $z(x_i)$. The weighting function yielded a more robust estimate of the smoothing parameters than would be possible with a traditional thin plate spline interpolation. In this study, we used the Fields software (Fields Development Team, 2006) to perform the thin plate spline interpolation.

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References

Akhtari, R., S. Morid, M.H. Mahdian, and V. Smakhtin. 2009. Assessment of areal interpolation methods for spatial analysis of SPI and EDI drought indices. Int. J. Climatol. 29:135–145. doi:10.1002/joc.1691

Alakukku, L. 1996. Persistence of soil compaction due to high axle load traffic: II. Long-term effects on the properties of fine-textured and organic soils. Soil Tillage Res. 37:223–238. doi:10.1016/0167-1987(96)01017-3

Albrecht, W.A. 1938. Loss of organic matter and its restoration. In: Yearbook of agriculture: Soils and men. U.S. Gov. Print. Office, Washington, DC. p. 347–360.

Andrejko, M.J., F. Fiene, and A.D. Cohen. 1983. Comparison of ashing techniques for determination of inorganic content of peats. In: P.M. Jarret, editor, Testing of peats and organic soils. ASTM STP 820. ASTM Int., West Conshohocken, PA.

Bloemen, G.W. 1983. Calculation of hydraulic conductivities and steady state capillary rise in peat soils from bulk density and solid matter volume. Z. Pflanzenernaehr. Bodenkd. 146:460–473. doi:10.1002/jpln.19831460407

Boelter, D.H. 1964. Water storage characteristics of several peats in situ. Soil Sci. Soc. Am. Proc. 28:433–435. doi:10.2136/sssaj1964.03615995002800030039x

Bondarenko, N.F., O.I. Danchenko, and N.P. Kovalenko. 1975. Studying the nature of filtration flow instability in peat. (In Russian with English summary.) Sov. Soil Sci. 10:137–139.

Carey, S.K., W.L. Quinton, and N.T. Goeller. 2007. Field and laboratory estimates of pore size properties and hydraulic characteristics for subarctic organic soils. Hydrol. Processes 21:2560–2571. doi:10.1002/hyp.6795

Duchon, J. 1976. Splines minimizing rotation invariant semi-norms in Sobolev spaces. Lect. Notes in Math. 571:85–100.

Elrick, D.E., R.W. Sheard, and N. Baumgartner. 1981. A simple procedure for determining the hydraulic conductivity and water retention of putting green soil mixtures. In: R.W. Sheard, editor, Proceedings of the 4th International Turfgrass Society Research Conference, Guelph, ON. 19–23 July 1981. Int. Turfgrass Soc., Guelph, ON, Canada. p. 189–200.

FAO. 1989. Guidelines for designing and evaluating surface irrigation systems. Irrig. Drain. Pap. 45. FAO, Rome.

Fields Development Team. 2006. Fields: Tools for spatial data. Natl. Ctr. Atmos. Res., Boulder, CO. http://www.image.ucar.edu/GSP/Software/Fields

Gesch, R.W., D.C. Reicosky, R.A. Gilbert, and D.R. Morris. 2007. Influence of tillage and plant residue management on respiration of a Florida Everglades Histosol. Soil Tillage Res. 92:156–166. doi:10.1016/j.still.2006.02.004

Grossman, R.B., and T.G. Reinsch. 2002. Bulk density and linear extensibility. In: J.H. Dane and G.C. Topp, editors, Methods of soil analysis. Part 4. Physical methods. SSSA Book Ser. 5. SSSA, Madison, WI. p. 201–228. doi:10.2136/sssabookser5.4.c9

Gumiere, S.J., J.A. Lafond, D.W. Hallema, Y. Périard, J. Caron, and J. Gallichand. 2014. Mapping soil hydraulic conductivity and matric potential for water management of cranberry: Characterisation and spatial interpolation methods. Biosyst. Eng. 128:29–40. doi:10.1016/j.biosystemseng.2014.09.002

Hallema, D.W., Y. Périard, J.A. Lafond, S.J. Gumiere, and J. Caron. 2015. Characterization of water retention curves for a series of cultivated Histosols. Vadose Zone J. 14 (this issue). doi:10.2136/vzj2014.10.0148

Hardy, R.M. 1965. Research on the shearing strength of muskeg and its application. In: Proceedings of the 10th Muskeg Research Conference. 21–22 May 1964. Tech. Memo 71. Natl. Res. Counc., Ottawa, ON, Canada. p. 25–32.

Hillis, S.P., and C.O. Brawner. 1961. The compression of peat with reference to the construction of major highways in British Columbia. In: I.C. MacFarlane and J. Butler, editors, Proceedings of the 7th Muskeg Research Conference, Hamilton, ON. 18–19 Apr. 1961. Tech. Memo 71. Natl. Res. Counc., Ottawa, ON, Canada. p. 204–227.

Ivanov, K.E. 1953. Wetland hydrology. (In Russian.) Gidrometeoizdat, Leningrad (St. Petersburg), Russia.

Kechavarzi, C., Q. Dawson, and P.B. Leeds-Harrison. 2010. Physical properties of low-lying agricultural peat soils in England. Geoderma 154:196–202. doi:10.1016/j.geoderma.2009.08.018

Lafond, J.A., S.J. Gumiere, D.W. Hallema, Y. Périard, S. Jutras, and J. Caron. 2015. Spatial distribution patterns of soil water availability as a tool for precision irrigation management in Histosols: Characterization and spatial interpolation. Vadose Zone J. 14 (this issue). doi:10.2136/vzj2014.10.0140

Lafond, J.A., E.B. Piette, J. Caron, and G.T. Rancourt. 2014. Evaluating fluxes in Histosols for water management in lettuce: A comparison of mass balance, evapotranspiration and lysimeter methods. Agric. Water Manage. 135:73–83. doi:10.1016/j.agwat.2013.12.016

Lamontagne, L., A. Martin, M.C. Nolin, and I. Perron. 2013. Étude pédologique du comté de Napierville (Québec). Soil map at 1:40,000 scale. Lab. pédologie et d'agriculture de précision, Soils and Crops Res. Dev. Ctr., Agric. and Agri-Food Canada, Quebec City, QC, Canada.

Lavoie, M., and P.J.H. Richard. 2000. Postglacial water-level changes of a small lake in southern Quebec, Canada. Holocene 10:621–634. doi:10.1191/095968300672141865

Okruszko, H. 1971. Determination of specific gravity of hydrogenic soils on the basis of their mineral particle content. (In Polish with English summary.) Wiad. Inst. Melior. Uzytkow Zielonych 10(1):47–54.

Paquet, J., J. Caron, and O. Banton. 1993. In situ determination of the water desorption characteristics of peat substrates. Can. J. Soil Sci. 73:329–339. doi:10.4141/cjss93-035

Parent, L.E., and J. Caron. 1993. Physical properties of organic soil. In: M.R. Carter, editor, Soil sampling and methods of analysis. Lewis Publ., Boca Raton, FL. p. 441–458.

Périard, Y., J. Caron, S. Jutras, J. A. Lafond, and A. Houlliot. 2012. Irrigation management of romaine lettuce in Histosols at two spatial scales: Water, energy, leaching and yield impacts. In: H. Bjornlund et al., editors, Sustainable irrigation and drainage IV: Management, technologies and policies. WIT Press, Ashurt, UK. p. 171–188.

Plamondon, L., L. Gaudreau, A. Gosselin, J. Caron, S. Jenni, and D. van Winden. 2011. Effect of soil depth on water management of romaine lettuce (*Lactuca sativa* L.) cultivated in a muck soil. Acta Hortic. 889:453–458.

Price, J.S., and S.M. Schlotzhauer. 1999. Importance of shrinkage and compression in determining water storage changes in peat: The case of a mined peatland. Hydrol. Processes 13:2591–2601. doi:10.1002/(SICI)1099-1085(199911)13:16<2591::AID-HYP933>3.0.CO;2-E

Reynolds, W.D. 1993. Saturated hydraulic conductivity: Laboratory measurement. In: M.R. Carter, editor, Soil sampling and methods of analysis. Lewis Publ. Boca Raton, FL. p. 589–598.

Schlotzhauer, S.M., and J.S. Price. 1999. Soil water flow dynamics in a managed cutover peat field, Quebec: Field and laboratory investigations. Water Resour. Res. 35:3675–3683. doi:10.1029/1999WR900126

Schwärzel, K., J. Šimůnek, H. Stoffregen, G. Wessolek, and M.Th. van Genuchten. 2006. Estimation of the unsaturated hydraulic conductivity of peat soils. Vadose Zone J. 5:628–640. doi:10.2136/vzj2005.0061

Shih, S.F., B. Glaz, and R.E. Barnes, Jr. 1998. Subsidence of organic soils in the Everglades Agricultural Area during the past 19 years. Proc. Soil Crop Sci. Soc. Fla. 57:20–29.

Soil Survey Staff. 1999. Soil Taxonomy: A basic system of soil classification for making and interpreting soil surveys. Agric. Handb. 436. 2nd ed. U.S. Gov. Print. Office, Washington, DC.

Tait, A., and R. Woods. 2007. Spatial interpolation of daily potential evapotranspiration for New Zealand using a spline model. J. Hydrometeorol. 8:430–438. doi:10.1175/JHM572.1

Verdonck, O.F., T.M. Cappaert, and M.F. de Boodt. 1978. Physical characterization of horticultural substrates. Acta Hortic. 82:191–200.

von Post, L. and E. Granlund. 1926. Soedra Sveriges torvtillgangar. 1. Arsb. 19, Ser. C. no. 335. Geol. Surv. Sweden, Stockholm.

Wahba, G. 1990. Spline models for observational data. Soc. Ind. Appl. Math., Philadelphia, PA.

Woldemeskel, F.M., B. Sivakumar, and A. Sharma. 2013. Merging gauge and satellite rainfall with specification of associated uncertainty across Australia. J. Hydrol. 499:167–176. doi:10.1016/j.jhydrol.2013.06.039