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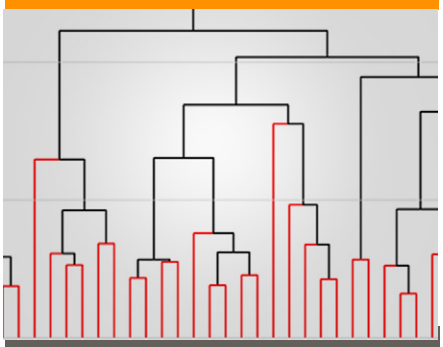

In this study, we characterized the water-holding characteristics of organic soils using various methods. This information is useful for computer models that help optimize water use in agriculture.

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Characterization of Water Retention Curves for a Series of Cultivated Histosols

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Water retention curves are essential for the parameterization of soil water models such as HYDRUS. Although hydraulic parameters are known for a large number of mineral and natural organic soils, our knowledge on the hydraulic behavior of cultivated Histosols is rather limited. The objective of this study was to derive characteristic water retention curves for a large cultivated peatland with lettuce (*Lactuca sativa* L.) and vegetable farming in southern Quebec, Canada. A comparison showed that the van Genuchten model fits better to the water retention data obtained with a Tempe pressure cell experiment than the Groenevelt–Grant model in terms of residual sum of squares; however, the difference in performance was quite small due to the high number of iterations used for fitting. Finally, an agglomerative cluster analysis of 85 peat samples allowed us to define two distinct water retention curves, where the first water retention curve described samples of relatively shallow (<150 cm) Histosols with an organic content <0.89 and a bulk density >0.3 g cm^{-3}, and the second curve characterized samples of the deepest (depth 150–230 cm) Histosols with an organic content of up to 0.97 and a bulk density >0.3 g cm^{-3}, which are the soils that suffered a more dramatic transformation as a result of agriculture. This characterization allows for a multitude of applications, including parameterization of the HYDRUS model for soil water movement, and presents an essential tool for the optimization of water management in cultivated peatlands.

Abbreviations: BFGS, Broyden–Fletcher–Goldfarb–Shanno.

Cultivation leads to a significant acceleration of soil-forming processes in Histosols (Kechavarzi et al., 2010; Kroetsch et al., 2011) and changes the soil physical and chemical properties (Rovdan et al., 2002; Chow et al., 2006). Farming operations such as tillage, fertilization, and tile drainage accelerate the oxidation and mineralization of organic matter, thereby altering the physical properties and general aspect of the profile. It is estimated that >5000 ha of peatland are used for vegetable farming in the Canadian province of Quebec, yet the water dynamics of these cultivated organic soils are poorly documented.

Water retention curves and hydraulic conductivity have been used in the past to formulate analytical models of the hydraulic response of soils (Brooks and Corey, 1964; van Genuchten, 1980; Vogel and Císlerová, 1988; Kosugi, 1996; Durner, 1994; Groenevelt and Grant, 2004). Water retention characteristics and hydraulic conductivity are known for most mineral soil types and can be estimated from the physical properties of the soil, such as bulk density, particle density, and organic matter content, using pedotransfer functions (Schaap et al., 1998) because the hydraulic and physical properties of the soil are closely related to each other (e.g., Gupta and Larson, 1979). Hydraulic properties have also been studied on undisturbed organic soils (Weiss et al., 1998; Gnatowski et al., 2002; Schwärzel et al., 2006; Gnatowski et al., 2010) but not on cultivated organic soils.

Knowledge of the hydraulic behavior of cultivated organic soils is important for the parameterization of subsurface flow models such as HYDRUS (Šimůnek et al., 1992, 2011), which was demonstrated in a study on the reduction of yield losses related to tip burn in Romaine lettuce cultivated on organic soils (Périard et al., 2012). Subsurface flow models are useful in analyzing the hydrologic response of organic soils to different scenarios of irrigation, tile drainage, land use, and climate change and are essential in providing farmers, government agencies, and water boards with recommendations for water management and farming policies. The objective of this study was to derive characteristic water retention curves for Histosols used for lettuce and vegetable farming, based on data from an experimental peatland in Canada. The approach was divided into three steps: (i) laboratory analysis of the physical parameters of peat samples of the Montérégie cultivated peatlands in Quebec, Canada, and a multistep outflow experiment in which we determine the relation between matric potential and outflow of these samples, i.e. water retention; (ii) calibration of three soil water retention models on the water retention data; and (iii) derivation of characteristic water retention curves for cultivated organic soils that can be used to predict water retention for unsampled cultivated organic soils.

Materials and Methods

The Montérégie Cultivated Peatland Complex

A field study was conducted between 2008 and 2011 on five commercial lettuce and vegetable farms in the Montérégie peatlands of southern Quebec, Canada (45°10′ N, 73°31′ W). This 18.7-km^2 area is mostly flat, has an elevation ranging between 50 and 65 m, and received an average rainfall of 844 mm per year distributed over an average of 124 d between the years 1970 and 2000 (data from the St. Rémi weather station, Environment Canada). The organic soils in this area were classified as Histosols according to the U.S. Soil Taxonomy (Soil Survey Staff, 1999) and have an Ohp layer at the surface, which extends to a depth of 29 to 37 cm and is compacted between 29 and 37 cm below the surface, and a fibrous (Of) to moderately decomposed (Om) layer between a depth of 35 and 120 cm on average. The total thickness of the organic deposit locally exceeds 250 cm. The Ohp layer at the surface was disturbed by plowing (p) and is in an advanced stage of decomposition as a result of oxidation (von Post scale 7 and higher; von Post and Granlund, 1926; Parent and Caron, 1993) although small amounts of wood fiber are still visible.

Experiments

The cultivated Histosols were sampled at depths of 20 and 35 cm using cylinders with a height of 5.5 cm and an internal diameter of 8.2 cm according to the procedure described by Grossman and Reinsch (2002). The cylinders, with a cutting edge at the bottom, were pushed into the soil by hand without the use of a sliding hammer to reduce smear along the edges of the core and minimize disruption of the soil and sampler.

Saturated Hydraulic Conductivity and Water Retention

The peat samples were brought to the laboratory, where we measured the hydraulic conductivity at natural saturation using the constant-head method (Elrick et al., 1981; Reynolds, 1993). First, core samples were trimmed to their cylinders and covered at the bottom with a nylon cloth, after which they were placed on a grill inside an empty tank. Next, the samples were completely saturated during the course of 48 h and placed in another tank where a constant head was maintained with a Mariotte reservoir while measuring the outflow recovered in a second reservoir with pressure transducers calibrated for measuring water height (Omega PX26). The saturated hydraulic conductivity was then calculated as the steady-state outflow divided by the horizontal cross-sectional area and the hydraulic gradient across the height of the sample using the Darcy equation.

Water retention characteristics were determined for two soil samples per profile, resulting in 80 samples from the Ohp layer near the surface at a depth of approximately 20 cm and 43 samples from the Of or Om layer at a depth of approximately 35 cm, with a total of 123 peat samples. The analysis was performed with a multistep outflow experiment using Tempe pressure cells (Dane and Hopmans, 2002), where we placed water-saturated samples on a porous ceramic plate (0.1-MPa rating), after which the pressure was increased stepwise. During this process, we continuously monitored the matric potential inside the sample using tensiometers and outflow using Omega PX26 pressure transducers. As soon as outflow stopped for a given pressure step, indicating hydrostatic equilibrium, we increased the water potential further until the entire water extraction range of lettuce was covered (potential steps of 20, 50, 100, 200, and 300 cm). The experiment lasted up to 7 d for a given sample. With the bulk density and the saturated water content, we were able to convert the measured outflow to volumetric water content, with up to 10,000 data points per desorption curve.

Bulk Density, Particle Density, Organic Content, and Porosity

The samples were then oven dried at 70°C for 24 to 48 h, measured with a digital caliper (to account for shrinking), and weighed, yielding a bulk density between 0.135 and 0.518 g cm^{-3}. The organic content determined by loss on ignition (16 h at 550°C; Andrejko et al., 1983) was between 0.609 and 0.966 (volume fraction). The particle density (r_p, g cm^{-3}) was estimated from 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):

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

where F is the ratio of organic content to ash content. The particle density of the peat samples ranged between 1.572 and 1.850 g cm^{-3}.

Total porosity was finally calculated as one minus the ratio of bulk density to particle density:

$$\phi = 1 - \left(\frac{\rho_b}{\rho_p}\right) \quad [2]$$

Sample porosity varied between 0.706 and 0.915 (volume fraction).

Water Retention Models

After obtaining the matric potential–water content (h,θ) pairs, we estimated for each sample the parameters of the van Genuchten water retention model and two variations of the Groenevelt–Grant model. The first variation was anchored to the wilting point and the second was anchored to both the point of natural saturation and the wilting point.

The van Genuchten model is formulated as (van Genuchten, 1980)

$$\theta(h) = \theta_r + (\theta_s - \theta_r)\left(1 + \alpha|h|^n\right)^{-m} \quad [3]$$

where h is the matric potential (cm), θ_r is the residual water content (cm^3 cm^{-3}), θ_s is the water content at saturation (cm^3 cm^{-3}), and α, n, and m are empirical parameters. The value of θ_s was fixed for all samples at the observed value, while θ_r, α, n, and m were calibrated.

The Groenevelt–Grant model is formulated as (Groenevelt and Grant, 2004)

$$\theta(h) = \theta_{wp} + k_1\left[\exp\left(\frac{-k_0}{h_{wp}^n}\right) - \exp\left(\frac{k_0}{h^n}\right)\right] \quad [4]$$

where θ_{wp} (cm^3 cm^{-3}) was taken as the water content observed at the wilting point of lettuce, $h_{wp} = -300$ cm (Périard et al., 2012), while k_1, k_0, and n are empirical parameters found through calibration. Initial values of k_0 and n were based on values reported by Groenevelt and Grant (2004) and are also listed in Table 1.

Another formulation of the Groenevelt–Grant model includes parameters defining the point of natural saturation and the wilting point (Groenevelt and Grant, 2004; Grant et al., 2010):

$$\theta(h) = \theta_s - (\theta_s - \theta_{wp})\left\{\exp\left[\left(\frac{k_0}{h_{wp}}\right)^n - \left(\frac{k_0}{h}\right)^n\right]\right\} \quad [5]$$

In this variation of the Groenevelt–Grant model, fitting parameter k_1 is eliminated and replaced with parameter θ_s, the saturated water content, which received the same initial value as in the van Genuchten model. Again, θ_{wp} was taken as the vegetation-specific wilting point of lettuce at $h_{wp} = -300$ cm (Périard et al., 2012).

Calibration Procedure

We calibrated the retention model parameters and, to increase the likelihood of finding the global optimum fit for each of the water retention models and for each of the samples, we compared the performance of the four following optimization algorithms.

Conjugate Gradient Method

This nonlinear method requires the calculation of the gradient of the p-dimensional objective function, p being the number of parameters in the water retention model, which converges to zero for the optimal solution (minimal fitting error). The parameter space is explored by moving in the direction of the best improvement in model performance (steepest decline in error) relative to the preceding iteration (Fletcher and Reeves, 1964).

Nelder and Mead Simplex Algorithm

The Nelder and Mead (1965) simplex algorithm does not require the calculation of derivatives and is therefore faster than the other three algorithms. It uses a simplex, which is a polytope (geometric object) of $p + 1$ vertices, to find the global minimum of the objective function. The method consists in comparing function values at the vertices of the simplex and replacing the vertex with the highest value by another point that potentially yields a higher performance. If such is indeed the case, the simplex is stretched out along the new point. Conversely, if the new point results in a higher value for the objective function, the simplex is converged toward a better point, ultimately converging to the global minimum.

Broyden–Fletcher–Goldfarb–Shanno Quasi-Newton Method

Also known as a variable metric algorithm, this method relies on an approximation of the Hessian matrix (the square matrix of second-order partial derivatives of the objective function) using ranked gradient evaluations (Broyden, 1970; Fletcher, 1970; Goldfarb, 1970; Shanno, 1970). Although this approximation requires more time per iteration than the conjugate gradient method, which uses

Table 1. Initial parameter values of the van Genuchten and Groenevelt models describing the hydraulic properties of peat samples.

Parameter	Initial value
Residual water content (θ_r), m^3 m^{-3}	0.1763†
van Genuchten shape parameter α, cm^{-1}	0.0231†
van Genuchten shape parameter n	1.292†
van Genuchten shape parameter m	0.226
Groenevelt parameter k_0, one anchor	11.63‡
Groenevelt parameter k_1, one anchor	0.426‡
Groenevelt parameter n, one anchor	1.589‡
Groenevelt parameter k_0, two anchors	11.63‡
Groenevelt parameter n, two anchors	1.589‡

† Based on Gnatowski et al. (2010).
‡ Based on Groenevelt and Grant (2004).

only the first-order derivative, the BFGS quasi-Newton method can converge in fewer steps.

Simulated Annealing

Simulated annealing is a stochastic algorithm that generates random sets of parameters around their respective initial values and progressively narrows down the search area around the sets, resulting in a minimum for the objective function (Belisle, 1992).

Initial values for the water retention parameters were based on Gnatowski et al. (2010) and Groenevelt and Grant (2004) and are listed in Table 1. Parameter m received an initial value calculated as $1 - 1/n_i$ but was treated as an independent parameter in the calibration. The water content at saturation (θ_s) was based on sample measurements. The number of iterations was limited to 500 per water retention curve, while for simulated annealing we imposed a limit of 500 function evaluations. No box constraints were imposed on the calibration parameters.

Performance was evaluated using an objective function that minimizes the root mean square error (RMSE) of the retention model fitted against the retention data obtained with the Tempe pressure cells, using

$$\mathrm{RMSE}\left(\hat{\theta}\right)=\sqrt{\frac{\sum_{i=1}^{N}\left(\hat{\theta}_i-\theta_i\right)^2}{N}} \qquad [6]$$

where $\Sigma_{i=1}^{N}(\hat{\theta}_i-\theta_i)^2$ is the sum of squared deviations between predicted water content $\hat{\theta}_i$ and observed water content θ_i for N data points. The sum of squared deviations is scaled by dividing by N and then taking the square root.

Cluster Analysis

We performed an agglomerative hierarchical cluster analysis on the peat samples to which we fitted the water retention models. The procedure was based on Gnatowski et al. (2010) and can be divided into three steps.

First Step

Each of the physical soil parameters (bulk density, particle density, porosity, organic matter, total thickness of the organic soil, and depth of a 5–10-cm-thick compacted layer), hydraulic soil parameters (hydraulic conductivity at saturation), and parameters of the soil water retention models (van Genuchten θ_s, θ_r, α, n, and m and Groenevelt–Grant θ_s, θ_{wp}, k_1, k_0, and n) were logarithmically transformed, centered by subtracting the means of the log-transformed parameters, and subsequently scaled by division through the standard deviation of the log-transformed parameters. This was necessary because the parameters have different ranges and inherently nonlinear (skewed) distributions.

Second Step

The next step was to calculate the $n \times n$ distance matrix with, for all sample pairs, a measure of dissimilarity defined as

$$d(i,j)=\sqrt{\sum_{m=1}^{p}\left(x_{im}-x_{jm}\right)^2} \qquad [7]$$

where $d(i,j)$ is the Euclidian distance between the ith and jth samples calculated as the square root of the sum of squared differences between i and j for the value x of soil parameters m through p.

Third Step

Finally, clustering was performed according to Ward's minimum variance method (Ward, 1963), which aims to minimize the within-cluster sum of squared errors (i.e., the squared error of ANOVA). This error is calculated as

$$E_k=\sum_{m=1}^{p}\sum_{i=1}^{n_k}\left(x_{im}-\overline{x}_{m(k)}\right)^2, \quad i\in k \qquad [8]$$

where n_k peat samples are assigned to the kth cluster and $\overline{x}_{m(k)}$ is the mean of m in the kth cluster. The cluster analysis started with a total of n clusters equal to the number of samples. Next, the clustering algorithm formed $n - 1$ clusters that were most similar in terms of the physical soil parameters, hydraulic soil parameters, and parameters of the soil water retention models. At each progressive iteration, clusters were merged based on a minimum increase in E_k. Slicing the resulting dendrogram at k_c clusters allowed us to determine median values for the soil parameters per cluster and subsequently define characteristic water retention curves for the peat samples.

Results

Calibration of Water Retention Models

The three water retention models, i.e., van Genuchten, Groenevelt–Grant with one anchor point, and Groenevelt–Grant with two anchor points, were fitted to the outflow data obtained with the Tempe pressure cells for 123 peat samples. A comparison of the residual sum of squares between four optimization algorithms using the same initial retention parameters without constraints (Table 2) showed that the Nelder–Mead method converges toward the best fit expressed as the average and median RMSE of all peat samples (average RMSE between 4.214×10^{-3} and 5.262×10^{-3} and median RMSE between 4.552×10^{-3} and 6.038×10^{-3}), closely followed by the BFGS quasi-Newton method and conjugate gradient method.

Simulated annealing yielded greater error values for all three water retention models (average RMSE between 3.055×10^{-2} and 4.741×10^{-2} and median RMSE between 3.257×10^{-2} and 5.046×10^{-2}) because the algorithm does not keep track of the best solution during the process of optimization. Therefore, this method requires more function evaluations than the allowed limit of 500 to find optimal solutions for the parameterization problem.

The lowest average and median RMSEs were calculated for the van Genuchten model, and therefore this water retention model

Table 2. Best fit of water retention models obtained with the conjugate gradient, Nelder–Mead, Broyden–Fletcher–Goldfarb–Shanno (BFGS), and simulated annealing methods.

Water retention model	Optimization algorithm	Median RMSE for samples ($\times 10^{-3}$)	Avg. RMSE for samples ($\times 10^{-3}$)
van Genuchten	conjugate gradient	6.490	8.012
	Nelder–Mead	4.214	4.552
	BFGS	4.691	5.087
	simulated annealing	47.41	50.46
Groenevelt (one anchor point)	conjugate gradient	5.809	6.826
	Nelder–Mead	4.935	5.675
	BFGS	5.207	6.684
	simulated annealing	30.55	32.57
Groenevelt (two anchor points)	conjugate gradient	31.54	31.37
	Nelder–Mead	5.262	6.038
	BFGS	11.34	11.78
	simulated annealing	33.49	33.80

yielded the best performance out of the three tested models. Based on the comparison of the four optimization algorithms, we decided to use the Nelder–Mead optimized water retention models in the cluster analysis.

Characteristic Water Retention Curves for Cultivated Organic Soils

The agglomerative cluster analysis was performed on the log-transformed parameters of 85 peat samples for which a large number of parameters were known (56 samples taken at a depth of 20 cm and 29 samples at a depth of 35 cm). The resulting dendrogram is plotted in Fig. 1, with the individual peat samples along the *x* axis and the Euclidian distance between clusters based on the scaled values of these soil parameters along the *y* axis. The first critical level was found at distance 23.9, where two main clusters can be distinguished. Cluster 2 contains the greatest number of samples, 55, while Cluster 1 contains 30 samples.

Table 3 and Fig. 2 show that samples in Cluster 1 have only a slightly lower organic content (median value of 0.860 vs. 0.844 in Cluster 2) but a significantly higher bulk density (median of 0.316 g cm^{-3} in Cluster 1 vs. 0.257 g cm^{-3} in Cluster 2), which is in agreement with the negative correlation between these two properties. The lower porosity of samples in Cluster 1 coincides with lower values for parameter θ_s (water content at saturation) in the water retention models. Note that θ_s is based on laboratory measurements and therefore has the same values for both the van Genuchten and Groenevelt–Grant water retention models.

Cluster 1 contains 26 samples taken at a depth of 20 cm and only four samples taken at a depth of 35 cm, while Cluster 2 contains a nearly equal distribution between the two depths, with 30 samples taken at a depth of 20 cm and 25 at a depth of 35 cm. The cluster analysis shows that the behavior of shallow Histosols (Cluster 1; median total depth of 145 cm) is different from that of deeper Histosols (Cluster 2; median total depth of 200 cm), where the former had a bulk density mostly >0.3 g cm^{-3} and the latter a bulk density mostly <0.3 g cm^{-3} (Fig. 2).

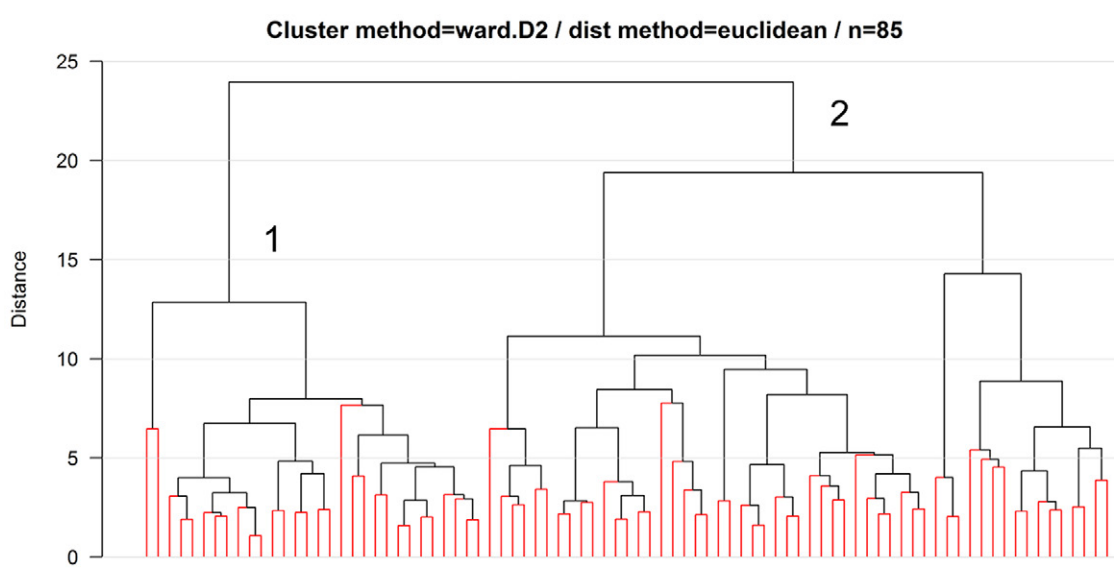

Fig. 1. Dendrogram with the result of Ward's agglomerative hierarchical cluster analysis of scaled physical soil parameters, hydraulic soil parameters, and parameters of three water retention models, all determined for 85 peat samples. Individual soil samples are shown in red on the *x* axis and the Euclidian distance between clusters is plotted on the *y* axis.

Table 3. Median values of physical soil parameters, hydraulic soil parameters, and parameters of the soil water retention models (van Genuchten, Groenevelt–Grant with one anchor point, and Groenevelt–Grant with two anchor points) for Clusters 1 and 2.

Parameter	Cluster 1	Cluster 2
Observations, no.	30	55
Bulk density, g cm^{-3}	0.316	0.257
Particle density, g cm^{-3}	1.645	1.628
Porosity	0.809	0.844
Organic matter	0.860	0.885
Thickness of organic soil, cm	145	200
Depth to compacted layer, cm	32.5	34.0
Saturated hydraulic conductivity, cm s^{-1}	1.462×10^{-4}	2.290×10^{-3}
Saturated water content (θ_s), m^3 m^{-3}	0.799	0.826
van Genuchten model		
Residual water content (θ_r), m^3 m^{-3}	−0.038	0.117
Shape parameter α, cm^{-1}	3.159×10^{-3}	2.408×10^{-2}
Shape parameter n	0.771	0.955
Shape parameter m	0.262	0.165
Groenevelt–Grant with one anchor point		
Wilting point water content (θ_{wp}), m^3 m^{-3}	0.663	0.604
Parameter k_1	2.509	0.813
Parameter k_0	10.855	6.313
Parameter n	0.208	0.265
Groenevelt–Grant with two anchor points		
Wilting point water content (θ_{wp}), m^3 m^{-3}	6.389×10^7	4.856×10^2
Parameter k_0	30	55
Parameter n	0.316	0.257

The deeper Histosols in Cluster 2 drained better, as reflected by the values of the retention model parameters. Figure 3 provides an indication of characteristic response based on median parameter values for each of the retention models. Parameter θ_s for each cluster is positively correlated with organic matter content and porosity and negatively correlated with bulk density. Values are low (median θ_s of 0.799) for the peat samples in Cluster 1 and higher (median θ_s of 0.826) for the samples in Cluster 2, which results in the characteristic van Genuchten curve for peat samples in Cluster 1 reflecting a generally lower water content at lower matric potentials than that for the samples in Cluster 2 (Fig. 3a). The same is true for both variations of the Groenevelt–Grant model (Fig. 3b and 3c). Cluster medians of θ_r (the fitted residual water content of the van Genuchten model) are −0.038 (Cluster 1) and 0.117 (Cluster 2), and these out-of-feasible-range values are not surprising given that we only fitted the model to the range of potentials between the point of saturation (matric potential of 25 cm) and the wilting point of lettuce (matric potential of 300 cm).

The hydraulic behavior of the cultivated Histosols was dominated by the compacted Oh layer, with a thickness of 5 and 10 cm, found at a depth between 29 and 37 cm below the surface. The presence of this compacted layer in all profiles within this narrow range of depth below the surface suggests that it formed in situ as a result of agricultural practices, possibly due to a combination of (i) tillage, which initially allows higher infiltration rates by opening up the surface layer of the soil but in the long term causes smear at the depth of tillage, (ii) tractor traffic, which leads to compression of the surface layer, (ii) leaching and accumulation deeper in the profile of fine particles as a result of irrigation, and (iv) accumulation of decomposed roots directly below the tillage depth.

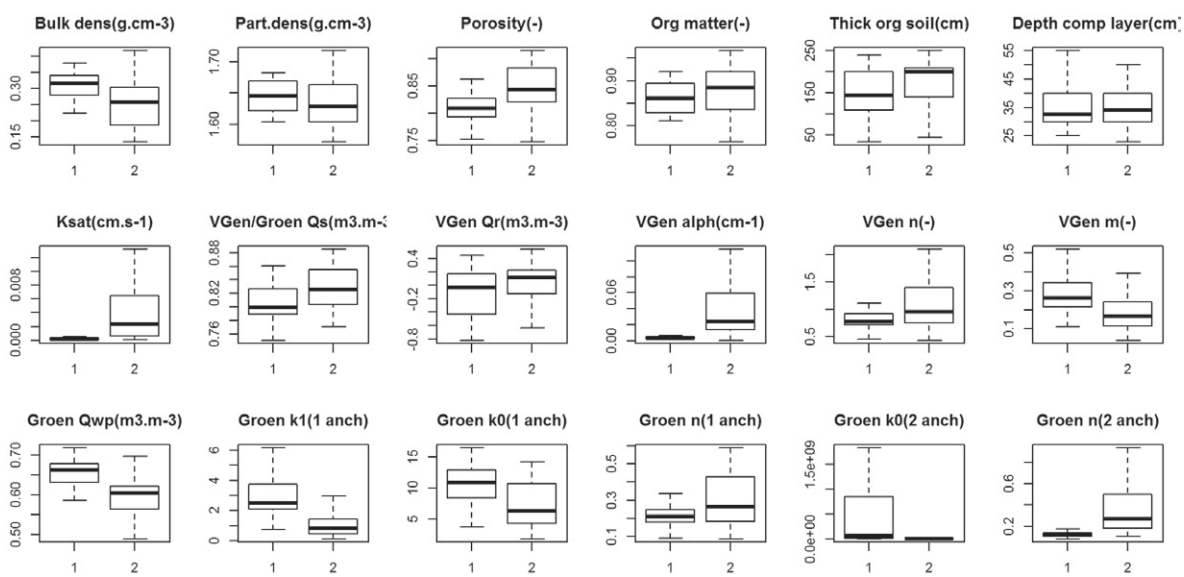

Fig. 2. Distributions of physical soil parameters, hydraulic soil parameters, and parameters of the soil water retention models for Clusters 1 and 2, with from left to right and top to bottom, bulk density, particle density, porosity, organic matter, thickness of the organic soil, depth of the compacted layer, saturated hydraulic conductivity (K_{sat}), water content at saturation in the van Genuchten and Groenevelt–Grant models (Q_s); van Genuchten parameters for residual water content (Q_r), a, n, and m; parameters of the Groenevelt–Grant model with one anchor point for the wilting point of lettuce (Q_{wp}), k_1, k_0, and n; and parameters of the Groenevelt–Grant model with two anchor points k_0 and n.

Lettuce production in this area follows a scheme with two growth cycles per year, which leads to a significant accumulation of decomposed root material. These processes lead to reduced percolation and explain why cultivated Histosols like the ones evaluated here develop serious drainage issues not typically found in undisturbed Histosols.

Conclusions

In this study, we characterized water retention curves for Histosols in southern Quebec (Canada) cultivated with lettuce and vegetables. A comparison between the van Genuchten and Groenevelt–Grant retention models showed that the best performance was obtained for the van Genuchten model, and out of four tested algorithms, the Nelder–Mead algorithm yielded the best solutions within an imposed limit of 500 iterations per sample.

The agglomerative cluster analysis of 85 peat samples allowed us to define two distinct water retention curves for each sample based on physical and hydraulic parameters, where the first water retention curve describes samples of relatively shallow (<150 cm) Histosols with an organic content <0.89 and a bulk density >0.3 g cm^{-3}, and the second curve characterizes samples of the deepest (150–230-cm depth) Histosols with an organic content of up to 0.97 and a bulk density >0.3 g cm^{-3}, which are the soils that suffered a more dramatic transformation as a result of agriculture. This characterization allows for a multitude of applications, including parameterization of the HYDRUS model for soil water movement, and presents an essential tool for the optimization of water management in cultivated peatlands.

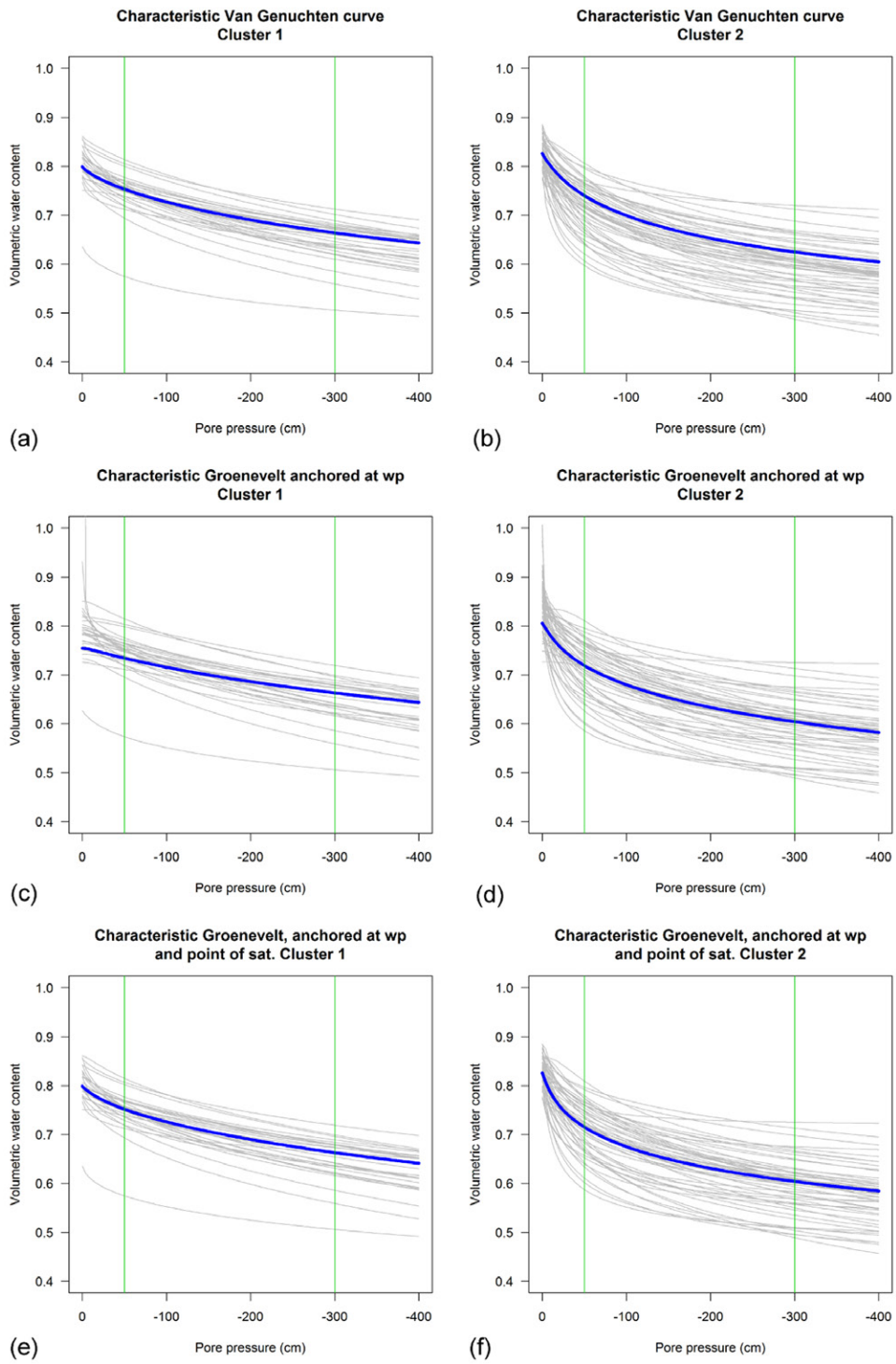

Fig. 3. Characteristic water retention curves (blue) based on median calibrated parameter values for the (a) van Genuchten model, (b) Groenevelt–Grant model anchored at the wilting point of lettuce at −300 cm, and (c) the Groenevelt–Grant model anchored at the point of saturation and the wilting point of lettuce.

Acknowledgments

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