Change in particle density and other hydrophysical properties with depth in a northern boreal bog peatland

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Abstract

Advances in peatland ecohydrological modelling require higher resolution depth profiles of important soil physical properties, which exist as a continuum from *Sphagnum*-dominated surface cover to highly decomposed peat at depth. We determined the bulk and particle density, porosity, saturated hydraulic conductivity (K_{sat}), and von Post score at 5 locations in a northern bog to a depth of ~200 cm in 5-cm intervals. The bulk and particle densities and von Post scores increased, and porosity decreased with depth. The particle density had a relatively abrupt shift near ~75 cm changing from ~0.8 g cm^{-3} to a relatively consistent ~1.4 g cm^{-3}. The variability measured was small in the upper ~25 cm, larger at depths of ~25 – 125 cm, and became more moderate at depths > ~125 cm (but not particle density). The variability of bulk density at the deeper depths results in the observed variability of porosity. The larger variability in physical properties roughly coincides with the abrupt shift in the magnitude of measured properties suggesting that contemporary processes and/or past events (e.g., wildfire, or vegetation succession and peat botanical type) could be responsible for this pattern. Bulk and particle density and porosity exhibited a relationship with the von Post score with a shift in values between von Post scores of 3 and 4. Detailed examination of peatland soil properties, in particular particle densities which are not commonly reported, will improve the robustness and reliability of models and may reveal additional information on the history and processes of formation.

Keywords

Peatlands, *Sphagnum* litter, particle density, bulk density, von Post, humification

Introduction

Peatlands, covering only 3% of the Earth's surface, store more terrestrial carbon than the world's forests combined (Gorham 1991; Yu et al 2010; Xu et al 2018). The biogeochemical cycles responsible for this carbon sequestration are largely controlled by the hydrology of the system, which in turn is controlled by the soil's hydraulic and physical properties, and the weather. As ecohydrological modelling gets more computationally complex, with it comes the need for higher resolution datasets and not simply literature-sourced or -assumed values (Lewis et al 2012). This is especially true for peat soils where some soil hydraulic and physical properties can vary by five orders of magnitude over as little as 50 cm vertically (Price et al 2003; Golubev and Whittington 2018; Golubev et al 2021). Despite their global importance, peat soils are still relatively poorly understood compared to mineral soils (Liu and Lennartz 2018).

Recently, Whittington et al. (2021) suggested that the literature accepted value of 1.4 g/cm^3 for the particle density of peat should not be used for *Sphagnum* litter, and, instead, a value of 0.75 g/cm^3 should be used. Because peatland soils shift from a live *Sphagnum*-dominated surface cover moss layer, to a partially decomposed organic *Sphagnum* litter layer, to the highly decomposed peat at depth (Malmer and Wallén 1993), using the term "peat" for both peat and litter can be misleading to readers as a gradation of soil physical properties is expected (Boelter 1969; Ingram 1978; Grover and Baldock 2013) from moss, to litter, to peat. Whittington et al.'s (2021) study was limited to the upper 25 cm of the profile (i.e., all *Sphagnum* litter), and thus this paper attempts to expand to a full peatland depth profile (i.e., moss surface to underlying mineral sediment).

The importance of understanding how these properties vary within a profile is highlighted by recent work by Morris et al. (2022) who used an extensive dataset of saturated hydraulic conductivity (K_{sat}) values from northern peatlands across the globe and developed linear models capable of predicting K_{sat} from other variables, notably depth, bulk density and humification (von Post). They found that dry bulk density and degree of humification are incredibly important predictors and increased the model skill greatly, highlighting the need for these data (in continuous profiles) in the literature.

Recent advances in unsaturated hydraulic conductivity (K_{unsat}) measurements (Price et al 2008; McCarter et al 2017) of *Sphagnum* moss/litter and the modeling of water fluxes in these systems (Golubev and Whittington 2018; McCarter et al 2020; Golubev et al 2021) highlight the need for accurate characterization of the soil hydraulic properties (K_{sat}, K_{unsat}) as well as the soil water retention curve fitting parameters (van Genuchten et al 1991). These soil water retention curves are anchored by the soil's porosity, and Whittington et al. (2021) note that the volumetric method to measure porosity is too inaccurate (~4% variability) for precise determination of porosity, and the density method (Eq. 3, below) should be used, which requires bulk and particle density; therefore assuming a uniform particle density (e.g., 1.4 g/cm^3 for litter) may lead to errors in the model. As peatland ecohydrological models become more complex, the ability to vary the soil hydraulic properties with depth also increases. Having detailed bulk and particle density, humification (von Post), porosity, and saturated hydraulic conductivity profiles in the literature is particularly useful. Understanding how, and where, these properties vary with depth can inform where modellers should target higher vertical resolution data to improve prediction accuracy. For example, the meta-analysis conducted by Morris et al. (2022) indicates that hydraulic measurements primarily occur at depths of about 0.3, 0.5, and 1.0 m, implying that smaller scale variations remain relatively uninvestigated. Exploring spatial (lateral) variability has also been shown to be important to include in sampling designs and data reporting (Whittington et al, 2021).

The purpose of this short communication is to show several (5) complete (~ 200 cm) bulk and particle density, and porosity profiles in 5-cm increments collected along a transect extending from treed to open canopy from a bog peatland in southeastern Manitoba, Canada. Detailed profiles of particle density are rare in the peatland literature, and those that include bulk density, saturated hydraulic conductivity and von Post are rarer still.

Study Site and Methods

Five complete depth profiles (A to E) which spanned from the moss surface to a depth of 200 cm (or to 10 cm above the peat-clay interface) (Table 1) were taken every ~60 m along a 300 m transect from an undisturbed peatland in southeastern Manitoba near the town of Elma, MB (near the treed canopy sites at Elma outlined in Whittington et al. (2021)). The transect extended from a moderately treed area (profile A) to a more open area (profile E). Based on the 1981–2010 climate normal for Pinawa MB (~30 km northeast), the average January and July temperatures are −16.6 and 19.3 ˚C, respectively, with annual precipitation of 578.3 mm, with 113.9 mm falling as snow (Climate ID: 5032162; Environment & Climate Change Canada, 2021). The treed bog is dominated by a surface cover of different peat mosses: *Sphagnum divinum, Sphagnum fuscum,* and *Sphagnum capillifolium*. The trees present are *Picea mariana* and *Larix laricina*. Growing among the peat mosses, the shrub *Rhododendron groenlandicum* is common.

Collection of relatively undisturbed litter or peat samples from the surface to a depth of ~75 cm samples were extracted by cutting large monoliths with a hand saw which were placed into 20 litre circular buckets (diameter 30 cm, depth 35 cm). The monoliths were then frozen and then were subsampled into 5-cm layers (Table 1 “Monolith”). Once extracting the sample in the field with the hand saw became impractical (either the pit filled with water, or the depth was too cumbersome to be able cut underneath the sample), a Russian peat corer was used to complete the profile (Table 1 “Russian”). When the Russian corer was brought to the surface, the peat was cut into 5-cm layers and placed in individual plastic bags before being transported back to the laboratory at Brandon University.

A highly detailed laboratory methodology for the samples obtained using the monolith method is outlined in Whittington et al. (2021); briefly, litter was subsampled from the monoliths and placed into containers of known volume ($Volume_{total}$); the samples were oven dried to obtain $Mass_{dry}$ of the sample and bulk density [g/cm^3] was calculated (Eq. 1).

$$Bulkdensity = \frac{Mass_{dry}}{Volume_{total}} \qquad [1]$$

The dried sample was ground and homogenized using a mortar and pestle. Based on Archimedes' principle of volume displacement of a liquid (kerosene) of known density (Lal and Shukla 2004), the $Volume_{soil}$ was determined and particle density calculated (Eq. 2).

$$Particledensity = \frac{Mass_{dry}}{Volume_{soil}} \qquad [2]$$

For samples obtained with the Russian corer: samples were placed into the same containers and oven dried to get the $Mass_{dry}$ of the sample; however, the volume of the sample ($Volume_{total}$) was calculated as 49.08 cm^3 ($V = (\pi r^2 d)/2$; where *r* is the radius of the Russian peat corer (2.5 cm) and *d* is the length of the sample (5 cm)). These samples then followed the same procedure as outlined above and in Whittington et al. (2021) to calculate the particle density. A total of 188 samples (Table 1) were processed for bulk and particle densities (Buckets = 74, Russian = 114). Due to the issues surrounding precision and accuracy of the volumetric method of estimating porosity (Whittington et al. 2021), porosity [-] was calculated using Eq. 3.

$$Porosity = 1 - \frac{bulkdensity}{particledensity} \quad [3]$$

von Post [-] was determined for surface samples (i.e., monolith method), up to a depth of 65-80 cm, on the material remaining immediately laterally adjacent to where the sample was taken in the monolith. A separate core, taken with the Russian peat corer, was collected adjacent for the lower depths which avoided disturbing the sample being used for bulk density analysis and was assumed to be the same as the sample used for the other physical properties. In addition to removing samples within 10 cm of the peat/clay interface (samples were taken and analyzed, but have been removed from this paper), a few samples (~2) at slightly shallower depths were removed when field notes indicated clay-like material was present in the sample.

Saturated hydraulic conductivity (K_{sat}) was determined using 2.54 cm PVC pipes with 10 cm slotted intakes covered with a 250 µm Nytex screen. Two pipes (shallow and deep) were used per nest and installed immediately adjacent (but not in) to the soil pit where the "monolith" was located, at two starting depths (e.g., 60 cm and 120 cm). Pipes were installed in a hole created by using an auger with a diameter slightly smaller than the pipe. Pipes were allowed to fill with water overnight and developed (water agitated several times and then evacuated) to ensure a clean well-screen. Bail tests (Hvorslev, 1951 as outlined in Freeze and Cherry 1979) were conducted to determine the K_{sat} and were either measured manually, or with an automated water level recorder, until head recovery exceeded, ideally, 80%. Pipes were then removed, and a further 10 cm augured out of the same hole, and pipes reinstalled, allowed to fill, and developed. This process was repeated in 10 cm increments until the entire profile was covered. The initial depth (e.g., 60 cm) varied based on local water table the day of the K test and some shallower depths/tests (e.g., 50 cm) were removed due to poor quality or an incompletely covered well-screen. No laboratory measurements of K (saturated or unsaturated) were conducted.

The basic lag time parameter was calculated using the slope (the m in y = mx, intercept = 0) of the head recovery (equation 4) vs. time and solving for a y-value of -0.43 (i.e., the log of 0.37 as per the method) and K calculated according to equation 5,

$$\log \frac{H - h_x}{H - H_0} \quad [4]$$

$$K = \frac{r^2 \ln\left(\frac{L}{R}\right)}{2 L T_0} \quad [5]$$

where H is the head (water level in the pipe) before the test began, H_0 is the water level immediately following the water removal (i.e., time 0), and h is the head a some time x during the recovery (there were ideally > 12 individual h values), r and R are the internal and external radii of the pipe, respectively, and L the length of the slotted intakes (10 cm).

All K tests with an R^2 greater than 0.99, percent recovery above 80%, and a visual inspection of the recovery rated as “2” or lower (Likert scale 1 to 5, with 1 being the best) were used (n = 60, N = 71). As this first cut left ~15% of the data unused, we then went through the remaining 11 tests to assess individually if they should be included. We deemed 9 more tests (n = 69) to be acceptable (R^2 > 0.90, % recovery > 70, and “3” or lower). There were 2 tests that, despite meeting those criteria, were not used as the recovery curves were not deemed acceptable. A few representative recovery plots of tests that were used, and rejected tests (not used) are shown in Fig. S1.

Using depth, bulk density, and von Post scores the saturated hydraulic conductivity was predicted using the four models outlined in Morris et al. (2022). The four models use peat depth, dry bulk density (BD) and von Post (vP) in different combinations (model 1: depth, BD, vP; model 2: depth, vP; model 3: depth; model 4: depth, BD) in addition to categorical properties (e.g., treed vs. open, climate). The categorical parameters were set as follows: microform was unspecified, trophic type was a raised bog, no disturbance (pristine), unspecified tree cover, and a Kerner oceanity index of 3.3 (i.e., continental). Using data across all five cores, the mean absolute error (MAE) was used to assess the performance of each of the four models.

Table 1: Summary of depth (start/end in cm) profiles and counts of samples along the transect from treed (A) to open (E).

	Monoliths			Russian Corer			Hydraulic conductivity		
Core	Start	End	Count	Start	End	Count	Start	End	Count
A (treed)	0	80	16	80	190	22	60	200	14
B	0	80	16	80	200	24	60	200	14
C	0	75	15	75	200	25	60	200	14
D	0	70	14	75	170	20	60	175	12
E (open)	0	65	13	65	180	23	60	175	12
		Total	74		Total	114		Total	66

Results and Discussion

The bulk density of the peatland soil profile increases with depth ranging from an average of 0.021 g cm^{-3} near the surface to 0.195 g cm^{-3} at a depth of 200 cm (Fig. 1a). The increase with depth was not consistent with little change, or a slight reversal, at some depths (e.g., 55 – 80 cm) and notably a steep increase between 120 and 145 cm. The variability between the different profiles (Fig. S2a) is minimal near the surface (< 40 cm), increases at depths between 40 – 130 cm, and is more moderate towards the bottom of the profile (depths > 130 cm). There is no clear pattern between the different sampling locations at the start (treed; darker green) or end (open; lighter green) of the transect; however, where the variation is the greatest (~80 to 130 cm) the lowest values are found at profile A (treed) and increases towards the other end of the transect (profile E) (Fig. 1a). This may be the rooting zone of the trees which helps to break up the soil, or provide structural stability to reduce compression/compaction which would decrease the bulk density.

Like bulk density, the overall particle density increases with depth (and von Post score, Figs. 1b, S3b) and ranges from a minimum average of 0.753 g cm^{-3} near the surface to a maximum of 1.38 g cm^{-3} near the bottom of the profile (Fig. 1b). There is a consistent increase from the surface to a depth of 65 cm, between 65 – 90 cm there an shift and below this there is little change with depth. The variation between locations is relatively uniform with depth except for the increase at the abrupt change profile (Fig. S2b). There is no clear pattern between the different sampling locations (A-E) along the profile (Fig. 1b).

The profile of the calculated porosity is almost the mirror image of the bulk density in terms of the pattern of average values and variability with depth (Figs. 1c and S2c). This indicates that the pattern in the calculated porosity values is driven primarily by the pattern observed in bulk density and not particle density. Therefore, the changes in calculated porosity will directly influence hydraulic conductivity. The average particle density for the upper 25 cm was 0.79 ± 0.11 g cm^{-3} which is marginally higher than the value reported in Whittington et al. (2021) (for the upper 25 cm only), but still well below the typical assumed value of 1.4 g cm^{-3}. However, at depths greater than 75 cm the average particle density was 1.32± 0.09 g cm^{-3}, which is much closer to the traditionally assumed value. The two vertical lines on Fig. 1b show the values of 0.75 and 1.4 g cm^{-3} and that the data closely match these literature values. Therefore, assuming a single value for particle density may not be appropriate and the values of particle density should vary between the near surface litter and the well decomposed peat at depth. For example, using the bulk densities of the average surface (0.025 g cm^{-3}), overall average (0.09 g cm^{-3}), and average bottom (0.19 g cm^{-3}) with particle densities of 0.79 and 1.32 g cm^{-3} would result in an absolute difference in porosity of 1.3, 4.6, and 9.7 % , respectively (Eq 3). Therefore, the porosity of the low bulk density litter near the surface is not that sensitive to the range of particle densities found at this study site.

The measured saturated hydraulic conductivity at depths of 0.6 to 1.9m spanned four orders of magnitude from 1.56×10^{-8} to 1.17×10^{-4} m s^{-1} with a median of 3.26×10^{-6} m s^{-1} (Figs. 1d and S2d). This is well within the range reported in the literature (e.g., Morris et al. 2022). Overall, the saturated hydraulic conductivity decreased with depth (Figs. 1d and S2d) similar to the porosity. This is expected as porosity is one of the main soil physical properties influencing hydraulic conductivity; however, in addition to the total porosity, the size and connectivity of the pores are the main control. There is some indication that the saturated hydraulic conductivity becomes smaller as the vegetation transitions from treed (core A; dark green) to more open (core E; light green); however, there is overlap between the cores (Fig. 1d). This may relate to differences in solar radiation and evapotranspiration demand which may impact moss/litter growth and decay characteristics, or the role of tree roots in creating large and well-connected pores. The degree of similarity between measured and predicted hydraulic conductivity, was poorer in the lower depths, particularly in Core D and E (Fig. 2). In comparing modelled to measured saturated hydraulic conductivity, Models 2 and 3 performed the best with MAE ranging from 5.64×10^{-6} to 6.51×10^{-6} m s^{-1}, respectively (Fig. 2). Model 1, reported by Morris et al. (2022) to be the most skillful, did not perform as well with an MAE of 1.40x10^{-5} m s^{-1}. These results support the use of a rapid field test method (i.e., Model 2; omits bulk density) to estimate hydraulic conductivity (Fig. S4).

Both depth and the von Post score appears to influence all other measured properties; however, there is not a consistent/gradual change with increasing humification and depth but rather a more abrupt shift in the properties. This may be due to changing botanical composition between *Sphagnum* and *Carex* peats (Szajdak et al 2016). The location of shift is not consistent across the transect as the shift in properties for more treed profiles A-C occurs deeper, relative to the surface, in the profile and at a higher von Post score as compared to the more open profiles (D-E) (Figs. 1 and S3). The transition in bulk density, porosity, and hydraulic conductivity occurs between von Post scores of 4 and 5 for profiles A-C and 3 to 4 for profiles D-E. For bulk density, this is slightly less dense peat (0.15 g cm^{-3}) than the threshold that Liu and Lennartz (2018) found of 0.2 g cm^{-3}. Similarly, the transition in particle density occurs at scores of 3 and 4 and 2 to 3 for profiles A-C and D-E, respectively. The observed changes along the transect suggest that changes in vegetation type, tree cover and/or the underlying environmental conditions may impact the vertical profile of soil properties. As a result, longitudinal variability should be considered in higher resolution hydrologic monitoring and modelling studies. Additionally, changes in botanical composition due to peatland succession from fen to bog may also contribute to the observed changes in physical properties with depth (Szajdak et al 2016).

The overall increase in bulk density with depth is largely related to the degree of humification (Figs. 1 and S3) and weight of the overlying soil. The humification process reduces the rigidity and strength of the of the material. The increase in the degree of humification and corresponding loss of strength coupled with the increasing compression from the overlying soil would collapse the larger pores typically found in more recently deposited litter. However, the inconsistent changes with depth have been noted elsewhere (Price et al 2003; Whittington et al 2007) and may, in part, be due to past changes in climate. These changes in climate would impact the rates of decomposition and accumulation, water table levels and fluctuations, fire frequency and severity, and the composition of mosses and other vegetation present. A detailed palaeoecological study at this site would be extremely informative but was well-beyond the expertise of the researchers and the scope/budget for the project. Data on botanical composition would also be informative.

The increase in particle density with depth may be due to changes in the botanical or chemical composition (e.g., lignin, cellulose) of the litter materials due to the preferential decomposition of easily mineralizable carbon molecules (Drollinger et al 2020). Szajdak et al. (Szajdak et al 2016) found that *Sphagnum* peat soils had a statistically significantly lower bulk density and higher porosity than *Carex* dominated peat soils. The more abrupt change in particle density occurs at a depth which corresponds to the approximate boundary between the acrotelm and catotelm. This would be a zone of fluctuating water table height creating a unique soil ecosystem with saturated (anerobic) and unsaturated (aerobic) periods. Above this zone the soil is generally unsaturated and decomposition is quicker; below this depth the soil remains saturated and decomposition is slower (Clymo 1983; Ingram 1983), however, it is at the interface (zone of water table fluctuation) where decay is the fastest (Belyea and Clymo 2001). Additionally, wildfires will also impact the particle density of peat as the remaining minerogenic ash would have a higher density relative to the peat. This ash may also move though the soil profile as water moves through the profile. The particle density is positively correlated to the bulk density ($r^2 = 0.59$, $p < 0.001$) (Fig. S5). Despite the correlation, it is interesting to note that the shift in particle density does not correspond to a similar increase in bulk density. This would suggest that the bulk density is more sensitive to the volume of pores than the density of the material itself.

Conclusions

This study highlights the continuous change in soil physical and hydraulic properties, both vertically and longitudinally, in a northern bog peatland. Additionally, this study also confirms that the physical properties of the peatland change in a predicable direction (increase or decrease) with depth; however, rather than a gradual change, abrupt changes in physical properties occur, highlighting the need for similar studies to see if the depths of these abrupt changes are consistent across northern bogs, or are unique to each site's developmental history. This would also allow peatland practitioners to make informed sampling decisions, such that 3-4 samples across the entire depth profile maybe sufficient to accurately represent the physical properties curve with depth, saving time and money on field work and lab analysis. Furthermore, the change in bulk and particle densities do not occur at same depth. This finding confirms that the shift in the calculated porosity which coincides with bulk density measurements is in fact due to reduction in total pore volume and not a shift in particle density.

This study highlights the need for accurate and consistent language and classification of moss, litter, peat, acrotelm, and catotelm when reporting on a peat soil's physical and hydraulic properties, as values appropriate for the deeper parts of the peatland (e.g., catotelm peat) are not appropriate for the shallow parts (e.g., acrotelm *Sphagnum* litter vs. catotelm peat). On the theme of sampling design, we would recommend not sampling every 5 cm when using the Russian corer, but instead using half of the samples (i.e., every other 5 cm increment) to determine the von Post value. This would be much more efficient than second depth profile immediately adjacent to the first. Lastly, the profiles present here may also point to changes in the peatland's past growth possibly due to changing environmental conditions, such that coupling studies like this one, with palaeoecological studies may be able to shed light on how the world's largest terrestrial carbon sink may respond to a changing climate.

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Figure 1. Profile data from each core (A to E) for a) bulk density b) particle density, c) porosity, d) hydraulic conductivity, and von Post scores. Cores are arranged from greatest tree cover (A; dark green) to most open (E; light green).

Figure 2. Measured and modelled hydraulic conductivity for each of the five cores. For additional model details see Morris et al. (2022). Cores are arranged from greatest tree cover (A) to most open (E).

Figure S1. Six examples of bail test data sets used to estimate the Ksat values. Tests A10 and A50 show typical high quality bail tests (ranking of “1”). Tests A80 and A70 show initial data (poor quality, and not used, “4” or “5”) and the acceptable re-tests.

Figure S2. Each point represents the average of the five cores and grey shading representing ±1 standard deviation for a) bulk density b) particle density, c) porosity, and d) hydraulic conductivity.

Figure S3 Boxplots (whisker extends to the largest/smallest value no further than 1.5 * IQR) showing the range of the physical properties across all five cores (colour shading; arranged from greatest tree cover (A; dark green) to most open (E; light green)) as a function of the von Post value for a) bulk density b) particle density, c) porosity, and d) hydraulic conductivity.

Figure S4. Comparison of modelled and measured hydraulic conductivity for each of the five cores. Black line represents 1:1 relationship and the mean absolute error (MAE) for each model is noted. Cores are arranged from greatest tree cover (A; dark green) to most open (E; light green).

Figure S5. Relationship between particle and bulk densities coloured by depth for all the cores (A-E) combined.

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Statements and Declarations

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Competing Interests

The authors have no relevant financial or non-financial interests to disclose.

Author Contributions

Both authors contributed to the study conception and design. Sample attainment (field) were performed by Haley Lobreau, Michael Falufosi and Frank Yamoah, and lab work by Jana Botha (as noted in the acknowledgments) with instruction/assistance of both from Whittington. The first draft of the manuscript was writing by Whittington (Intro, Study Site, Methods, Conclusion) and Koiter (Results and Discussion). Most of the data analysis and figure creation was completed by Koiter. All authors read and approved the final manuscript.

Data Availability

The datasets generated during and/or analysed during the current study are available from the corresponding author on reasonable request.