Water Resources Research

RESEARCH ARTICLE

10.1029/2020WR028624

Key Points:

- Land use such as agriculture and peat extraction alter the physical and hydraulic properties of the peat more strongly than other land uses
- The top 30 cm peat depth was most affected by agriculture and peat extraction, as indicated by the bulk density, specific yield, and porosity values
- The van Genuchten-Mualem soil water retention model was applied successfully to different layers of peat under different land use

Supporting Information:

Supporting Information may be found in the online version of this article.

Correspondence to:

M. W. Menberu,
Meseret.Menberu@oulu.fi

Citation:

Menberu, M. W., Marttila, H., Ronkanen, A.-K., Haghighi, A. T., & Kløve, B. (2021). Hydraulic and physical properties of managed and intact peatlands: Application of the van Genuchten-Mualem models to peat soils. *Water Resources Research*, *57*, e2020WR028624. https://doi.org/10.1029/2020WR028624

Received 17 AUG 2020
Accepted 15 JUN 2021

Hydraulic and Physical Properties of Managed and Intact Peatlands: Application of the Van Genuchten-Mualem Models to Peat Soils

Meseret Walle Menberu[1,2], Hannu Marttila[1], Anna-Kaisa Ronkanen[1], Ali Torabi Haghighi[1], and Bjørn Kløve[1]

[1]Water, Energy and Environmental Engineering Research Unit, University of Oulu, Oulu, Finland, [2]Freshwater Centre, Finnish Environment Institute (SYKE), Oulu, Finland

Abstract Undisturbed peatlands are effective carbon sinks and provide a variety of ecosystem services. However, anthropogenic disturbances, especially land drainage, strongly alter peat soil properties and jeopardize the benefits of peatlands. The effects of disturbances should therefore be assessed and predicted. To support accurate modeling, this study determined the physical and hydraulic properties of intact and disturbed peat samples collected from 59 sites (in total 3,073 samples) in Finland and Norway. The bulk density (BD), porosity, and specific yield (Sy) values obtained indicated that the top layer (0–30 cm depth) at agricultural and peat extraction sites was most affected by land use change. The BD in the top layer at agricultural, peat extraction, and forestry sites was 441%, 140%, and 92% higher, respectively, than that of intact peatlands. Porosity decreased with increased BD, but not linearly. Agricultural and peat extraction sites had the lowest saturated hydraulic conductivity, Sy, and porosity, and the highest BD of the land use options studied. The van Genuchten-Mualem (vGM) soil water retention curve (SWRC) and hydraulic conductivity (K) models proved to be applicable for the peat soils tested, providing values of SWRC, K, and vGM-parameters (α and n) for peat layers (top, middle and bottom) under different land uses. A decrease in peat soil water content of ≥10% reduced the unsaturated K values by two orders of magnitude. This unique data set can be used to improve hydrological modeling in peat-dominated catchments and for fuller integration of peat soils into large-scale hydrological models.

1. Introduction

Peatlands are unique ecosystems, which, in pristine condition, provide many ecological functions and ecosystem services, such as carbon sequestration, water regulation, and biodiversity. Globally, peatlands cover only 3% of the earth's land surface (about 400 million ha), but contain one-third of the global soil carbon pool (Greenup et al., 2000; Krimly et al., 2016). The northern hemisphere contains around 87% of global peatland resources (Strack, 2008), with the greatest peatland cover in boreal and arctic landscapes. For example, about 30% of total Finnish land area (9.15 million ha) is peatland (Turunen, 2008). However, 14%–20% of global peatland resources have been affected by anthropogenic disturbances (Strack, 2008). In Finland alone, around 55% of the total peatland area has been used for forestry (Peltola et al., 2014), around 0.8% for agriculture, and 2% for peat extraction purposes (Heikkilä et al., 2012).

The biogeochemical processes in peatlands are controlled primarily by peat moisture content (Weiss et al., 1998), which is in turn controlled by the water table depth (Asmuß et al., 2019). The water table interacts with soil organic carbon, which is a significant determinant of soil-organic-carbon dynamics (Ise et al., 2008). Reduced water levels are thought to increase oxygen availability in the surface soil, resulting in faster organic matter decomposition and, as a result, increased peat density (Laiho, 2006). Hydraulic properties are highly significant in explaining water, energy, and carbon exchange between the land surface and the atmosphere (Montzka et al., 2017). By nature, peat soils are extremely complex, porous media with a high degree of vertical and lateral heterogeneity. From an agricultural, forestry, and ecological perspective, effective management of peat soils requires a good understanding of the processes that control water flow and storage at a particular site (Schwarzel et al., 2006). Understanding how these complex peat processes might behave due to land use changes is crucial for hydrological modeling and sustainable management. Modeling water and solute transport under unsaturated conditions using the available hydrological models (e.g., HYDRUS, HydroGeoSphere, DRAINMOD) requires proper parameterization of the soil water retention curve (SWRC) and the hydraulic conductivity function (Jaros et al., 2019; Weber et al., 2017a). However, the broader literature on peat properties is incomplete. Availability of comprehensive empirical data on the physical and hydraulic properties of different peat materials would help to improve the accuracy of hydrological models at the local, regional, and continental scale, thus assisting in management of this major global soil carbon pool.

The most common form of peatland disturbance is artificial drainage to lower the water table and make the land suitable for forestry, agriculture, and other human uses. Drainage of peatlands results in significant changes to the hydraulic and physical properties of the peat, through rapid peat decomposition and subsidence due to consolidation of dry peat, which alters the natural functions of peatlands (Holden et al., 2006). Lowering the water table increases aeration of the overlying peat layer, which accelerates oxidation and mineralization of the organic matter, leading to enhanced carbon dioxide emissions (Hallema et al., 2015). It also causes collapse of the upper peat layer, resulting in shrinkage and a significant increase in bulk density of the material (Silins & Rothwell, 1998). Bulk density is related to many other peat physical properties (Liu & Lennartz, 2019). The bulk density and fiber content primarily define the porosity and pore size distribution, and are linked to differences in peat physical properties (Boelter, 1969). In peat soils with low bulk density and high fiber content, many large pores occur, allowing up to 80% of their saturated water content to drain and allowing rapid water movement. Fiber content decreases as decomposition progresses, resulting in increased bulk density and a higher proportion of small pores (Boelter, 1968), thereby restricting water flow due to a reduction in hydraulic conductivity (Rezanezhad et al., 2010). On the contrary, smaller pores have more suction, which increases volumetric water content and, hence, unsaturated K values (Price et al., 2008). However, reduced pore size and the altered geometry of air-filled pores in highly decomposed peat soils may still reduce unsaturated K values (Rezanezhad et al., 2010). In general, bulk density is a good indicator of any peat disturbance caused by compression (Golubev & Whittington, 2018), so any change in bulk density alters the hydrological properties of peat soils (Boelter, 1964).

Measuring the hydraulic properties of unsaturated soils, either in situ or in a laboratory is time-consuming, laborious, and expensive, and it is difficult to find values, which are representative of field conditions for large catchment scales. Acquiring representative values for peat soils is especially difficult, due to the changes in physical and hydraulic properties across the landscape (Lewis et al., 2012), with depth (Könönen et al., 2015) and when subjected to anthropogenic disturbances, for example, volume change due to dewatering (Holden et al., 2004). The alternative is to use theoretical models to predict hydraulic properties that are difficult and costly to measure (e.g., unsaturated hydraulic conductivity), using parameters that are relatively easier to measure, such as SWRC and saturated hydraulic conductivity.

In recent decades, van Genuchten-Mualem (vGM) SWRC and hydraulic conductivity models (Mualem, 1976; van Genuchten, 1980) have been extensively applied to mineral soils and have been proven to work well (Pan et al., 2019; Roy et al., 2018; Van Genuchten & Nielsen, 1985). However, application of the vGM models to peat soils is limited (Dettmann et al., 2014; Liu & Lennartz, 2019; McCarter & Price, 2014; Schwärzel et al., 2006; Weber et al., 2017b). Hydrological modeling, such as HYDRUS-1D, which requires vGM parameters (quantified using vGM models) was used on peat soils to investigate the effect of *Sphagnum* moss volume change on the unsaturated hydraulic conductivity (Golubev & Whittington, 2018; McCarter et al., 2017) and hydro-physical properties (Gauthier et al., 2018). In a study conducted on regenerated *Sphagnum* moss, the vGM parameters were calculated using direct curve fitting and inverse modeling, leading to the observation that the vGM parameters calculated using inverse modeling represented the field soil moisture dynamics better (Elliott & Price, 2020). In slightly decomposed sphagnum peat soils, bimodal or trimodal vGM models may better describe the unsaturated hydraulic conductivity curves (Dettmann et al., 2014; Weber et al., 2017a, 2017b). However, unsaturated hydraulic parameters in a variety of peat soils have been successfully estimated using the vGM unimodal model (Liu & Lennartz, 2019; Simhayov et al., 2018; Wallor et al., 2018). In this study, we used measured SWRC and saturated hydraulic conductivity values for peat soils under different land uses to derive the vGM parameters, a representative SWRC, and a hydraulic conductivity curve for each land use across peat layers, using the respective model. The specific objectives of the study were: (a) to parameterize the hydraulic and physical properties of peat soils under different land uses, (b) to test the applicability of the vGM models for peat soils subjected to different

10.1029/2020WR028624

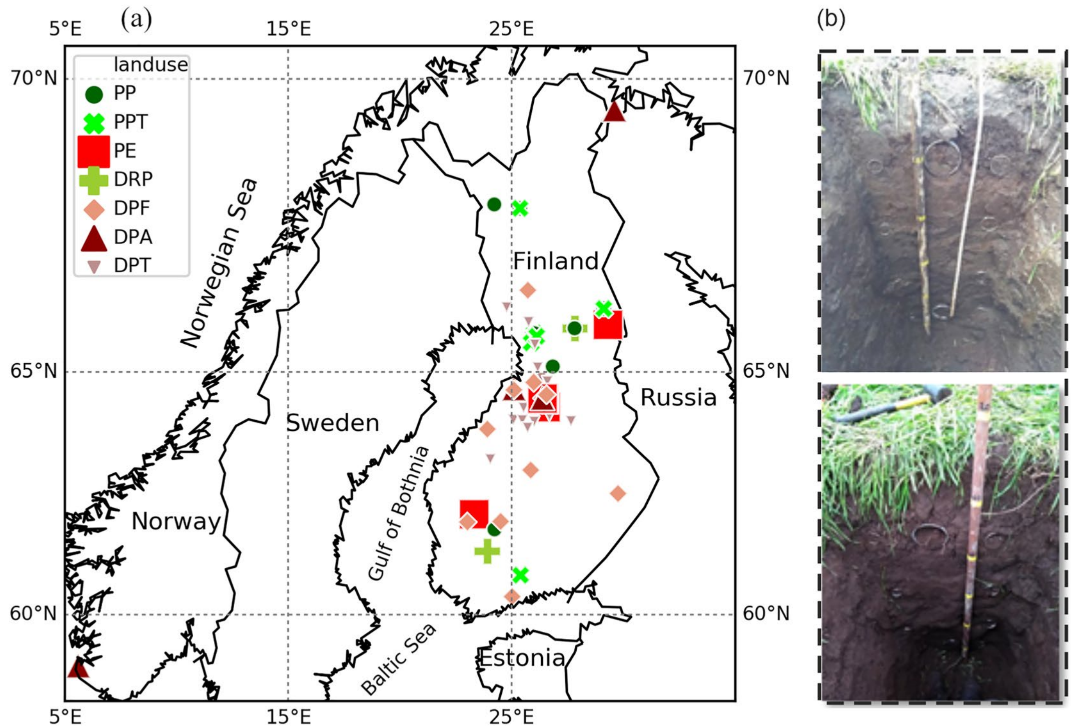

Figure 1. (a) Locations of the study sites in Finland and Norway, and (b) images showing the peat sampling technique using cylinders applied at one of the peatland agricultural sites.

management regimes, and (c) to examine the relationship between peat soil properties and to evaluate the predictive power of these relationships.

2. Materials and Methods

2.1. Study Sites

The analysis was conducted using the data on a set of managed and intact peatlands in Finland and Norway (Figure 1a). The peat types studied are mainly fen and bog types, with a few unknown peat types. A total of 59 peatland sites (Table S1) were included (57 in Finland and two in Norway), represented by a total of 3,073 samples. In this study, the degree of degradation and disturbance that the land use cases pose for peatlands was qualitatively assigned. Peatlands, which were used intensively for energy (peat extraction), agriculture and forestry, were considered to be the most disturbed areas. The peatland sites in Finland were selected to be spatially representative of the different peatland types and management practices found in Finland. The sites represented the following land use management practices:

1. Pristine (undisturbed) peatlands (PP).
2. Intact treatment peatlands, used to treat wastewater from mines or peat extraction sites (PPT).
3. Drained (not intensively) treatment peatlands, used to treat wastewater from mines or peat extraction sites (DPT).
4. Drained restored peatlands, originally drained for forestry but restored by drain blocking (or other means) to re-establish suitable hydrological conditions for peat formation (DRP).
5. Peatlands drained for forestry purposes (DPF).
6. Peatlands drained for agricultural purposes (DPA).
7. Peatlands used for peat extraction purposes (PE).

Table 1
Grouping of Peat Into Different Layers Based on Measurement Depth

Peat layer	Sampling/measurement peat depth range (cm)
Top	≤30
Middle	>30 to ≤60
Bottom	>60

2.2. Data Collection and Preparation, and Statistical Analyses

All the data used in this study were collected in ongoing and past research projects at the Water, Energy, and Environmental Engineering Research Unit, University of Oulu, Finland. The data were the outcome of measurements and analyses in the laboratory and in the field over the past ~10 years. The method of peat sampling used at certain study sites is unknown. However, peat samples for laboratory analysis were typically collected from undisturbed soil cores or an exposed soil profile using a "toecutter auger" (cross-section 8 × 8 cm, length 70 cm) (Mustamo et al., 2016). Consequently, known-volume (e.g., diameter 4 cm, volume 50 cm^3) sharpened steel cylinders (Figure 1b) and plastic bags were used to hold the samples. To avoid any biochemical reaction, samples collected for laboratory examination were stored in a dark room at a temperature of about 5°C (Boelter, 1968). The peat properties database included the data on saturated hydraulic conductivity (K_{sat}, n = 2,077), unsaturated hydraulic conductivity (K, n = 22), bulk density (BD, n = 439), porosity (n = 444), specific yield (Sy, n = 284), and SWRC (n = 284) for different peat layers, determined in field and/or laboratory studies. Several conventional methods were used to measure K_{sat}. For most study sites, K_{sat} was measured either in the field (infiltrometer, piezometer slug tests, and falling head direct push piezometer) or in the laboratory (constant-head permeameter, flexible-wall permeameter, and rigid-wall permeameter). For some sites, it was measured in both. Bulk density was determined by dividing the weight of oven-dried soil (dried for 24 h at 65°C until a constant mass) by the total volume (Boelter, 1968). The density of water (1 gm cm^{-3}) is assumed to be equal to the weight of water. Porosity was calculated by subtracting the mass of oven-dried soil from the mass of saturated soil and dividing by the total volume (Mustamo et al., 2016). The SWRC of most samples was determined using a standard pressure plate apparatus, by placing saturated peat samples inside a pressure chamber (Dettmann et al., 2014; Schwärzel et al., 2006). Continuous unsaturated K and SWRC were measured at some study sites using high-capacity tensiometers (Chen et al., 2015), where the maximum applied pressure was −15,000 cm H_2O (pF = 4.18) with 1 cm H_2O pressure intervals. The SWRC measurements at some study sites were recorded at different pressure intervals than at other sites. Hence, the fitted vGM model (Equation 1) for the corresponding site was used to fill the gap. As a result, SWRC analysis, such as the average SWRC at a given pressure for a certain land use with several sites, could be calculated.

Statistical analyses of peat properties were performed for all the data, and aggregated based on land use and peat layer. Typically, peat can be grouped into two distinct horizontal layers, based on degree of decomposition, as acrotelm (oxic layer) and catotelm (anoxic layer). Recently, a third layer, called the mesotelm (mostly anoxic, but sometimes oxic), has been included (Tfaily et al., 2014). In this study, the peat properties data for each land use type was grouped into three distinct layers (top, middle, and bottom layers) based on depth of measurement, and descriptive statistics on the main peat properties were produced accordingly (Table 1). Any superficial layer of living Sphagnum or disturbed milled peat present (peat extraction sites) was not included in the analysis.

From measured SWRC, the field capacity (FC) and wilting point (WP) of each peat sample were estimated at −0.01 MPa (pF 2) and −1.5 MPa (pF 4.2), respectively (Mezbahuddin et al., 2016), where $\mathrm{pF} = \log\left|\mathrm{h}\right|\left[\mathrm{cm}\right]$, where h (cm) is pressure head. Plant-available moisture (AM), that is, the amount of water held between FC and WP, was calculated as the difference in water content between FC and WP (Peverill et al., 1999).

The major datasets (K_{sat}, BD, Sy, porosity) in this study were not characterized by a perfectly normal distribution based on the Shapiro-Wilk test (P < 0.05). Thus, non-parametric statistical techniques, such as Spearman's correlation coefficient (rho), were used to evaluate any potential monotonic relationship between peat properties across all the data. Principal component analysis (PCA) was performed on all the data to identify patterns and relationships between peat variables under different land uses, and potentially to remove some unnecessary variables, for example, for regression models used in later stages. Two-way ANOVA was used to analyze the interactions between land use and peat layer on peat properties and determine the significance of these interactions. The Shapiro-Wilk test revealed that the residuals of the variables used in the ANOVA were not normally distributed (P < 0.05), so normality was not assumed. Furthermore,

10.1029/2020WR028624

non-parametric statistical tests, such as the Kruskal-Wallis test with a post hoc Dunn test with adjusted *p*-values, were used for not normally distributed data.

The Sy of peat can describe the change in water storage following a change in the water table and is thus a very important parameter. The Sy depends on porosity, which in turn depends on peat degree of decomposition and peat depth (Menberu et al., 2016, 2018). Here, Sy was calculated from a simple drainage test in the laboratory and missing Sy values were estimated by calculating the difference in water content at 0 and 0.01 MPa in the SWRC (Letts et al., 2000; Ronkanen & Kløve, 2005). The drainage test was performed on intact peat cores that were 10, 20, and 30 cm thick and gravity drained on a wire tray for 7 days (top layer) to 13 days (middle and bottom layers). Evaporation was prevented by covering the samples and storing them in a cool, dark environment (Ronkanen & Kløve, 2005). As a result, the Sy was determined as the ratio of water released to initial soil volume at the end of the drainage. However, acquiring representative Sy values for a given peat type is challenging, due to the spatial and vertical variability of peat properties. Hence, multivariate linear regression (MLR), linear mixed effect models (LME), and partial least squares regression (PLSR) models were tested here for their ability to describe Sy as a function of other important peat properties. From the RF feature importance model, predictor parameters were selected from among the most important parameters for Sy, which were relatively easier to measure in the laboratory and/or in the field. Hence, the data were split into training (70% of the data) and testing (30% of the data) datasets. The performance of the models was assessed using the testing data set and the best model was identified based on the coefficient of determination (R^2). All statistical analyses were performed in the Python programming language and some statistical diagrams were plotted using Seaborn, Python's statistical data visualization library (Waskom et al., 2017).

2.2.1. SWRC Model

The vGM model, which parameterizes soil hydraulic properties (Equation 1), was fitted to all measured SWRC and the average vGM fitting parameters of each land use as a function of the corresponding peat layer were quantified. The vGM fitting parameters were then used in Equation 2 to quantify the relative hydraulic conductivity (K_r), while the unsaturated hydraulic conductivity (K) of each data point was quantified using Equation 3 (Mualem, 1976; van Genuchten, 1980).

$$\theta(h) = \theta_r + \frac{(\theta_s - \theta_r)}{\left(1 + (\alpha h)^n\right)^m} \tag{1}$$

$$K_r(\theta) = \frac{\left\{1 - (\alpha h)^{n-1}\left[1 + (\alpha h)^n\right]^{-m}\right\}^2}{\left[1 + (\alpha h)^n\right]^{m/2}} \tag{2}$$

$$K = K_{\text{sat}} \times K_r(\theta) \tag{3}$$

where h (cm) is pressure head and is positive, θ, θ_s, θ_r (cm^3 cm^{-3}) is measured, saturated, and residual water content, respectively; K_{sat} is the geometric mean of saturated hydraulic conductivity measured in the corresponding peat layers for each land use; and α (cm^{-1}), n (−), and m are the vGM fitting parameters, where $m = 1 - 1 / n$ are empirical parameters evaluated by inserting measured $\theta(h)$ into Equation 1 using the nonlinear least square optimization technique in the Python "curve fit" function in the SciPy module.

During optimization, the value of parameters α and n was allowed to vary from 0 to 1 and 1 to 5, respectively, while that of θ_r was allowed to vary from 0 to the minimum of measured $\theta(h)$ + 0.1 and θ_s was allowed to vary from the maximum of measured $\theta(h)$ to 1. Parameter α is inversely proportional to the air entry pressure head, while parameter n is related to particle size distribution and influences the slope of the SWRC

10.1029/2020WR028624

Table 2
Mean Peat Specific Yield (Sy), Bulk Density (BD), Porosity and GMean Saturated Hydraulic Conductivity (K_{sat}) in Peat for Each Land Use and Measurement Layer

		Sy		BD (g cm^{-3})		K_{sat} (m s^{-1})		Porosity		Sample depth (cm)	
Land use	Peat layer	Mean	SEM	Mean	SEM	GMean	GStd	Mean	SEM	Mean	SEM
PP	Top	0.40	0.03	0.08	0.01	5.91E-05	11.83	0.93	0.01	18.44	0.61
	Middle	0.33	0.03	0.09	0.01	2.99E-05	13.43	0.93	0.01	46.98	0.69
	Bottom	0.23	0.03	0.15	0.01	3.54E-06	27.29	0.91	0.01	90.40	1.69
PPT	Top	0.32	0.01	0.11	0.00	4.30E-04	9.54	0.91	0.01	15.71	0.68
	Middle	0.26	0.01	0.12	0.01	4.63E-05	22.35	0.92	0.01	47.73	0.76
	Bottom	0.26	0.01	0.11	0.00	1.77E-06	5.49	0.91	0.02	69.59	0.38
DPT	Top					5.53E-05	20.84			19.84	0.43
	Middle					2.75E-06	24.05			50.00	0.43
	Bottom					1.77E-06	14.86			71.07	0.39
DRP	Top	0.38	0.03	0.09	0.01	2.46E-05	10.23	0.93	0.01	20.18	0.89
	Middle					1.51E-05	12.33			40.00	0.00
DPF	Top	0.21	0.02	0.15	0.01	2.24E-05	23.62	0.91	0.01	17.70	0.49
	Middle	0.21	0.02	0.13	0.01	1.69E-06	23.09	0.92	0.01	47.41	0.50
	Bottom			0.12	0.01	4.13E-06	18.73	0.89	0.02	77.95	3.46
DPA	Top	0.11	0.01	0.42	0.02	5.30E-08	8.26	0.78	0.01	15.67	0.65
	Middle	0.14	0.02	0.18	0.01	2.67E-08	7.71	0.88	0.01	48.11	0.64
	Bottom	0.19	0.02	0.16	0.00	5.85E-08	2.85	0.92	0.01	77.81	2.55
PE	Top	0.15	0.01	0.19	0.01	8.57E-08	15.23	0.86	0.01	15.60	0.61
	Middle	0.11	0.01	0.14	0.00	2.36E-08	10.39	0.90	0.01	46.78	0.64
	Bottom	0.19	0.01	0.12	0.00	2.76E-08	5.03	0.89	0.01	73.74	1.30

Notes. GMean = geometric mean, GStd = geometric standard deviation, SEM = standard error of the mean, PP = pristine peatland, PPT = pristine treatment peatland, DPT = drained treatment peatland, DRP = drained restored peatland, DPF = forestry-drained peatland, DPA = drained peatland for agriculture and PE = peat extraction site. For the number of samples analyzed refer to Table S3.

(Liu & Lennartz, 2019; van Genuchten, 1980). Average SWRC, vGM parameters, and $K_r(\theta)$ were computed for each peatland under different land uses as a function of the corresponding peat layer.

3. Results

3.1. Descriptive Statistics for the Hydraulic and Physical Properties of Peat

The PP top layer and middle layer, the DRP top layer, and the PPT top layer had Sy values greater than 0.3, the highest for any land use and peat layer group. All layers in the two degraded peatland types (PE, DPA) had Sy values less than 0.2 (Table 2). The Sy values tended to decrease with depth under most land uses, but in PE and DPA, Sy behaved differently and seemed to increase with depth (Table 2, Figure 2). The top layer of DPA showed the highest BD (0.42 g cm^{-3}), followed by the top layer of PE (0.2 g cm^{-3}). The BD decreased with depth in PE, DPA, and DPF, but not in other types of peatland studied (Figure 2). The two degraded peatland types (PE, DPA) had the lowest K_{sat} values, while the highest geometric mean K_{sat} (4.30E-04 m s^{-1}) was measured in the top layer in PPT (Table 2). The value of K_{sat} tended to decrease with depth under almost all land uses studied (Figure 2). The porosity behaved like Sy in most peat layers under all land uses (Figure 2). The top layers of DPA and PE had the lowest porosity values, 0.78 and 0.86, respectively (Table 2).

A total of 105 different land use and peat layer combinations were analyzed for differences in peat properties (e.g., DPA bottom layer vs. DPA top layer). Statistically significant differences in BD, K_{sat}, porosity, and Sy were observed for a total of 32, 59, 24, and 31 unique land use-peat layer combinations, respectively

10.1029/2020WR028624

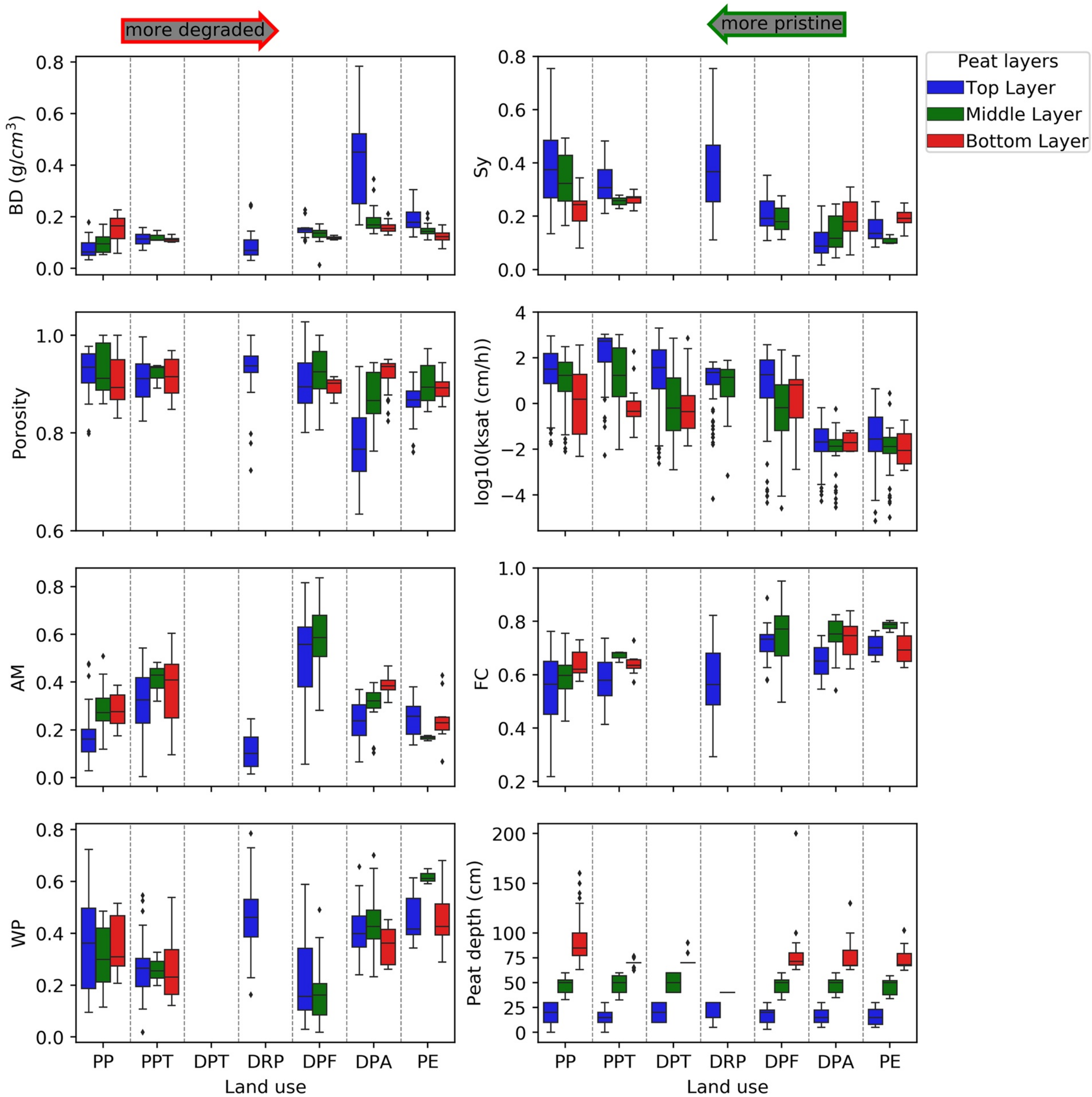

Figure 2. Boxplot showing summary of peat properties, where BD is bulk density, K_{sat} is saturated hydraulic conductivity, Sy is specific yield, AM is available moisture, FC is field capacity, and WP is wilting point. Peat depth is the sampling/measurement depth. Rightward arrow indicates towards more degradation and leftward arrow towards lesser degradation or more pristine. PP = pristine peatland, PPT = pristine treatment peatland, DPT = drained treatment peatland, DRP = drained restored peatland, DPF = forestry-drained peatland, DPA = drained peatland for agriculture and PE = peat extraction site.

(Figure 3). The two groups shown in Figure 3 are statistically signficant ($P < 0.05$), as their respective confidence intervals do not overlap. The top layer Sy and BD values of pristine and intact (PP and PPT) sites were significantly higher than the values estimated for the top layer of most disturbed sites (DPA and PE). However, the bottom layer Sy and BD values of pristine and intact sites (PP and PPT) were not significantly different from the values measured at the bottom layers of strongly disturbed sites (DPA and PE); for comparison of the remaining peat properties across similar peat layers, see Figure 3. The top layer AM value of PP sites was significantly lower than the values measured only for the top layers of PPT and DPF sites. However, the bottom layer AM values at the least disturbed and strongly disturbed sites were not significantly different. The top layer FC value for pristine PP sites was significantly lower than the values measured for the top layers of strongly disturbed sites (DPF, DPA, and PE). However, the FC value for the bottom layers

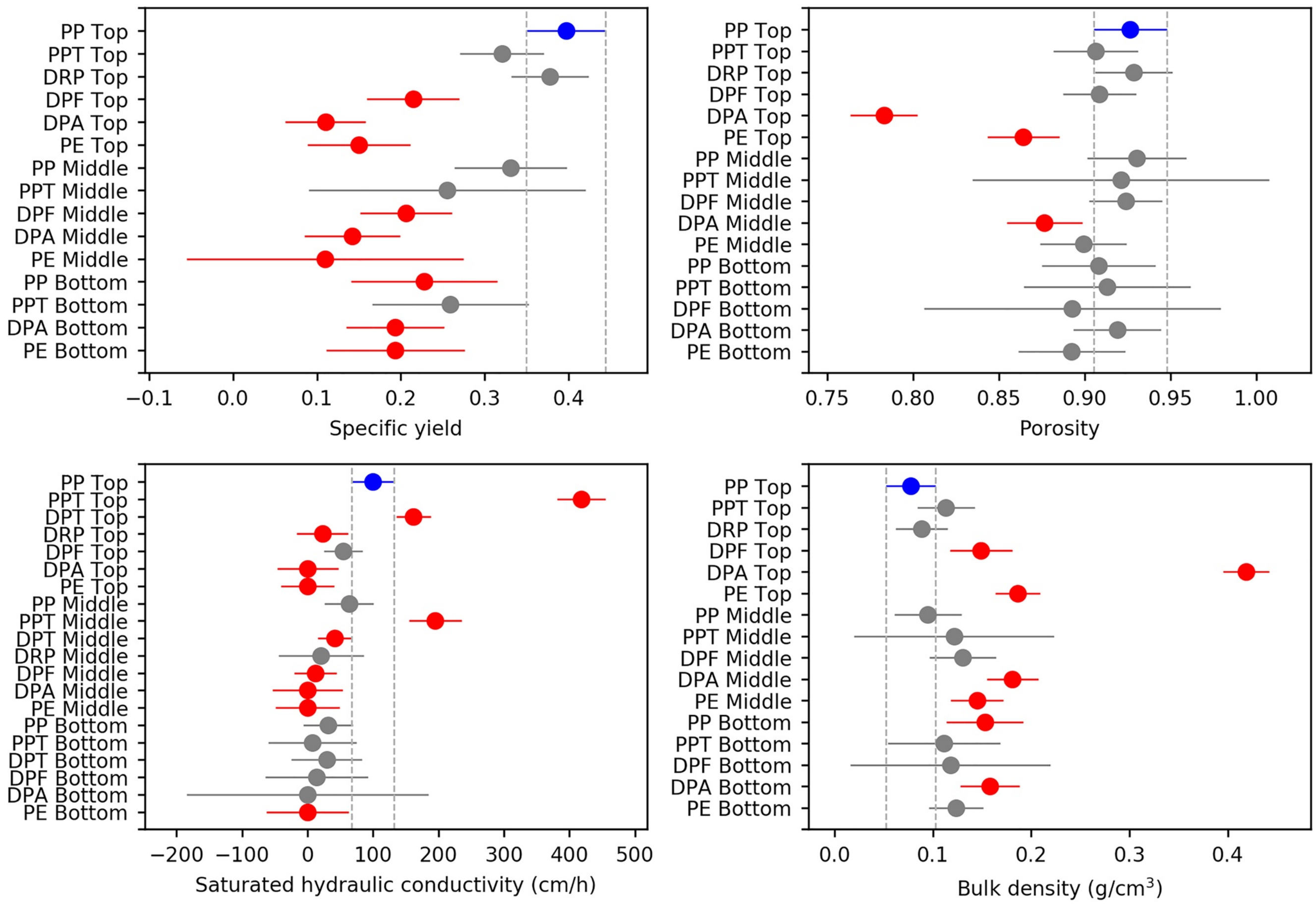

Figure 3. Diagrams visualizing significant differences in specific yield, porosity, saturated hydraulic conductivity, and bulk density between group means (bars show 95% confidence interval) for different land uses and peat layers. The red groups are significantly different from the blue group (PP Top Layer, gray dashed lines show confidence interval of PP Top), since their confidence intervals do not overlap. These diagrams highlight significant differences between PP and disturbed peatlands layers, but significant differences between disturbance types can also be seen where confidence intervals do not overlap. PP = pristine peatland, PPT = pristine treatment peatland, DPT = drained treatment peatland, DRP = drained restored peatland, DPF = forestry-drained peatland, DPA = drained peatland for agriculture and PE = peat extraction site.

of pristine and intact sites (PP and PPT) was not significantly different from the values measured for the bottom layers of strongly disturbed sites (DPA and PE) (Figure 4). Analysis of variance of peat properties based on land use revealed statistically significant differences in BD, K_{sat}, porosity, and Sy for a total of 7, 12, 8, and 11 unique land use-based group means, respectively (Figure 5). On average, the highest BD and the lowest porosity, Sy, and K_{sat} values were observed at sites drained for agriculture (DPA), followed by peat extraction sites (PE) (Figure 5).

3.2. SWRC and Associated Parameters for Peat Soils

In total, 286 measured SWRC for peat under all land uses were fitted using Equation 1, with the R^2 between fitted and measured SWRC ranging from 0.73 to 1. The mean value of the vGM fitted parameters α, n, and θ_r for all peat soils (all land uses and peat layers) ranged from 0.02 to 0.08, 1.23 to 2.00, and 0.02 to 0.56, respectively (Table 3). From a total of 105 land use and peat layer group interactions, the only significant difference found ($P < 0.05$) was for α in the DPF middle layer ($\alpha = 0.02$) compared with that in the DRP top layer ($\alpha = 0.08$) and PP top layer ($\alpha = 0.08$). However, the vGM parameters n and θ_r were significantly different for 19 and 26 unique land use-peat layer group interactions, respectively (Table S2). Calculation of vGM parameters based on land use is shown in Table 2 as Site Total.

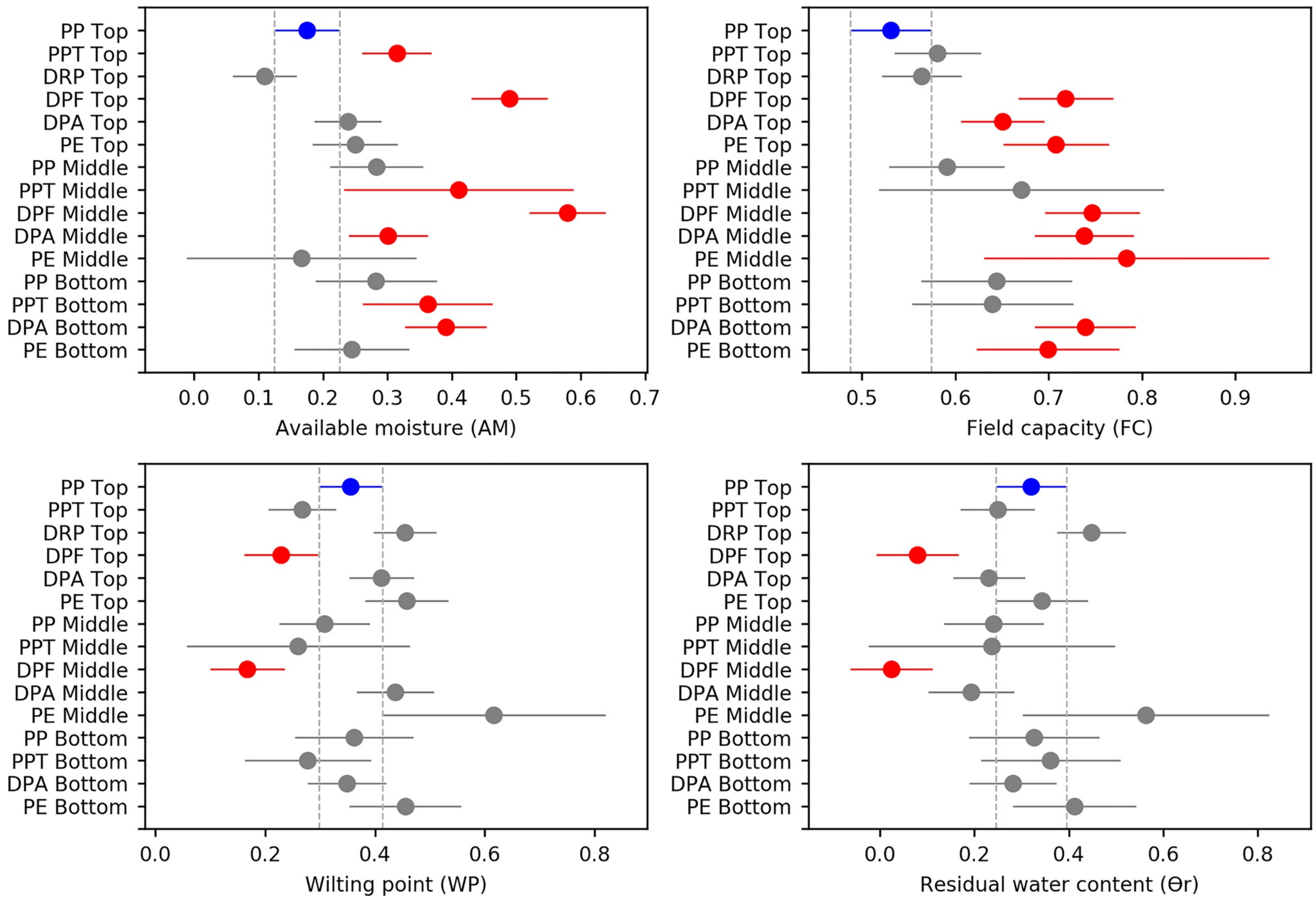

Figure 4. Diagrams visualizing significant differences in available moisture, field capacity, wilting point and residual water content between group means (bars show 95% confidence interval) for different land uses and peat layers. The red groups are significantly different from the blue group (PP Top Layer, gray dashed lines show confidence interval of PP Top), as their confidence intervals do not overlap. These diagrams highlight significant differences between PP and disturbed peatlands layers, but significant differences between disturbance types can also be seen where confidence intervals do not overlap. For land use abbreviations refer to Figure 3 caption.

Sites with the lowest Sy values (PE, DPA, and DPF) had the highest FC of all land uses. The highest water content at WP was observed at PE sites (about 0.62) and the lowest at DPF sites (about 0.17). DPF sites had the greatest amount of plant-available water (AM) while the PP top layer, PE middle layer, and DRP top layer had the smallest amounts (Table 3). The FC and AM of the peat tended to increase with depth for most land uses studied, while WP did not show any correlation with depth (Table 3, Figure 2).

From the total of 286 measured SWRC, the mean SWRC for each land use and peat layer was calculated to obtain a representative SWRC for each land use as a function of depth (Figure 6). The mean SWRC of each land use and peat layer was fitted using Equation 1. The vGM parameter values calculated using mean SWRC and those calculated using individual samples (Table 3) were not significantly different. Hence, the mean fitted SWRC of each land use and peat layer with the corresponding BD value is shown in Figure 6. The PP top layer and PPT top layer lost about 10% of their water content when the pressure head was increased from pF 0 to pF 1, while the other layers lost less than 5% (Figure 6).

All peat layers in PP and PPT had the highest water content loss when the pressure head was increased from pF 0 to pF 2, with the change in water content ranging from 25% to 37% (Figure 6). Peat layers with relatively lower BD and high Sy values lost more water when the pressure head increased to pF 2, whereas at higher pressure head changes (water content lost between pF 2 and pF 3), peat layers with higher BD and lower Sy values lost more water (Figure 6).

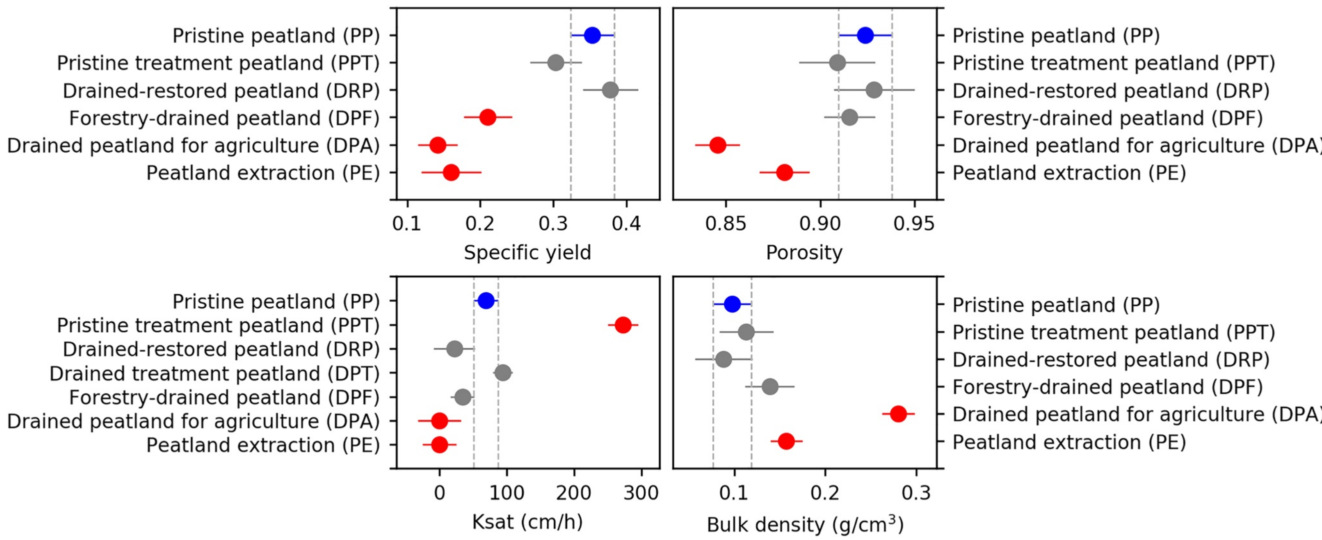

Figure 5. Diagrams visualizing significant differences in specific yield, porosity, saturated hydraulic conductivity (K_{sat}), and bulk density between group means (bars show 95% confidence interval) based on land use only. The properties depicted by the red lines and the blue line (pristine peatland, confidence interval shown by gray dashed lines) are significantly different. K_{sat} is saturated hydraulic conductivity. These diagrams highlight significant differences between pristine peatlands and disturbed peatlands, but significant differences between disturbance types can also be seen where confidence intervals do not overlap.

Table 3
Mean Values of the van Genuchten-Mualem Parameters (α, n), Residual Water Content (θ_r), Available Moisture (AM), Field Capacity (FC), and Wilting Point (WP) in Different Layers of Peat Under Different Land Uses

Land use	Layers	ns	α (cm^{-1}) Mean	SEM	n Mean	SEM	θ_r Mean	SEM	AM Mean	SEM	FC Mean	SEM	WP Mean	SEM
PP	Top	34	0.08	0.01	1.75	0.08	0.32	0.03	0.18	0.02	0.53	0.03	0.36	0.03
	Middle	15	0.05	0.01	1.50	0.07	0.24	0.04	0.28	0.03	0.59	0.02	0.31	0.03
	Bottom	9	0.04	0.01	1.53	0.10	0.33	0.05	0.28	0.03	0.64	0.02	0.36	0.04
	Site Total	58	0.07	0.01	1.65	0.05	0.30	0.02						
PPT	Top	29	0.05	0.01	1.87	0.15	0.25	0.03	0.31	0.03	0.58	0.01	0.27	0.02
	Middle	3	0.02	0.01	1.72	0.34	0.24	0.12	0.41	0.05	0.67	0.01	0.26	0.04
	Bottom	8	0.02	0.00	2.00	0.19	0.36	0.04	0.36	0.07	0.64	0.02	0.28	0.06
	Site Total	40	0.04	0.01	1.89	0.12	0.27	0.03						
DRP	Top	36	0.08	0.01	1.95	0.08	0.45	0.02	0.11	0.01	0.56	0.02	0.45	0.02
DPF	Top	23	0.05	0.02	1.39	0.04	0.08	0.04	0.49	0.04	0.72	0.01	0.23	0.04
	Middle	23	0.02	0.00	1.42	0.04	0.02	0.02	0.58	0.03	0.75	0.02	0.17	0.02
	Site Total	46	0.03	0.01	1.40	0.03	0.05	0.02						
DPA	Top	32	0.05	0.02	1.23	0.03	0.23	0.03	0.24	0.01	0.65	0.01	0.41	0.02
	Middle	21	0.06	0.03	1.30	0.05	0.19	0.05	0.30	0.02	0.74	0.02	0.44	0.03
	Bottom	20	0.02	0.00	1.47	0.04	0.28	0.03	0.39	0.01	0.74	0.01	0.35	0.02
	Site Total	73	0.05	0.01	1.31	0.03	0.23	0.02						
PE	Top	18	0.03	0.01	1.43	0.07	0.34	0.05	0.25	0.02	0.71	0.01	0.46	0.02
	Middle	3	0.04	0.02	1.38	0.16	0.56	0.04	0.17	0.01	0.78	0.01	0.62	0.02
	Bottom	10	0.03	0.00	1.61	0.13	0.41	0.04	0.24	0.03	0.70	0.02	0.46	0.04
	Site Total	31	0.03	0.00	1.48	0.06	0.39	0.03						

Notes. SEM = standard error of mean (SEM), ns is number of samples, for land use abbreviations see Table 2.

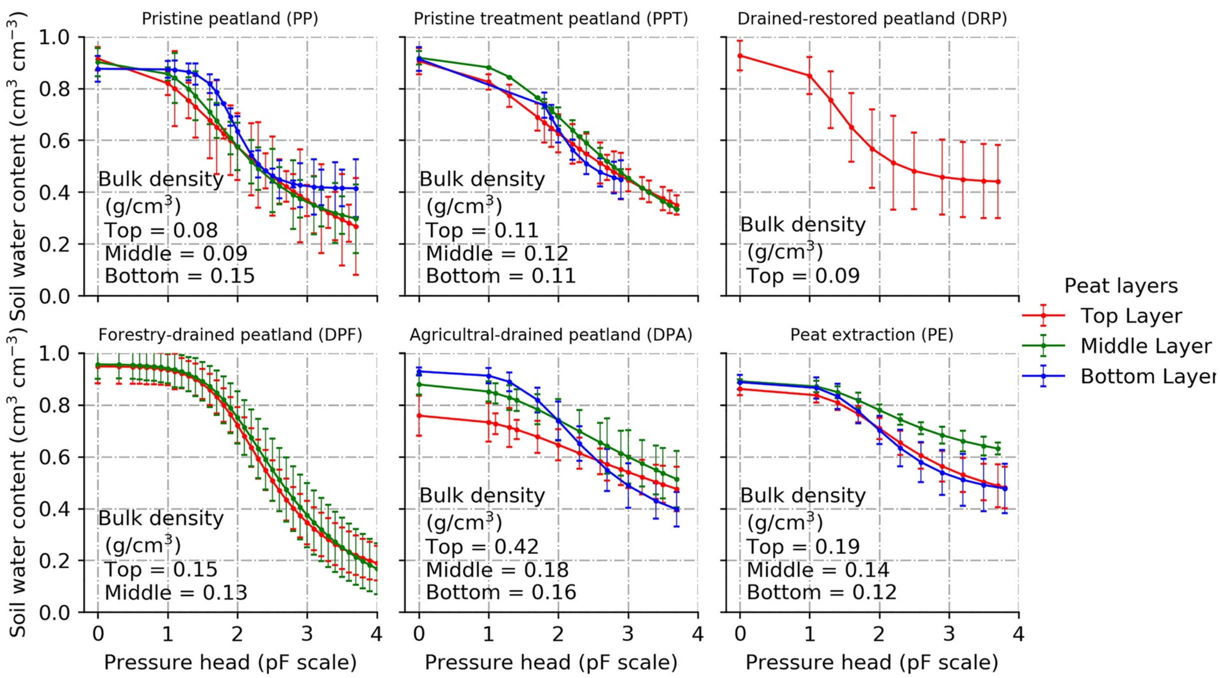

Figure 6. Fitted soil water retention curve (SWRC) based on measured mean SWRC and the corresponding bulk density (BD) values in different peat layers under different land uses. The error bars show the standard deviation of measured values. $\mathrm{pF} = \log\left|h\right|\left[\mathrm{cm}\right]$ where h (cm) is pressure head.

In this study, unsaturated K values were measured at some of the DPF sites, and this information was used to verify the accuracy of the predicted K values. An example of measured and fitted SWRC, predicted K_r and K is provided in Figure S1 in Supporting Information. Predicted K and measured K in that example showed a high correspondence ($R^2 = 0.81$) (Figure S1). The unsaturated K (log scale) in different peat layers under different land uses increased linearly with increasing soil water content in most cases except at DRP sites, where the increase remained non-linear (Figure 7).

As the soil progressed from less saturation to saturation, the slope of the unsaturated K versus soil water content became steeper at the most disturbed sites (PE and DPA) but gentler at pristine and intact sites (PP and PPT). An increase in pressure head from pF 0 to pF 1 resulted in relatively higher water content loss from the PP top layer and PPT top layer of around 10%, thereby decreasing unsaturated K in those layers by 93%. An increase in pressure head from pF 0 to pF 2 resulted in a decrease in water content of 13%–27% for all land uses (Figure 6) but decreased unsaturated K by 98%–100% for all peat layers under all land uses (Figure 7). A pressure head change from pF 2 to pF 3 resulted in a 16%–52% decrease in water content, while the unsaturated K decreased by 99%–100% in all cases.

3.3. Relationship Between Peat Properties

The PCA analysis revealed the overall distribution of the data on the main peat properties by grouping positively related properties together (e.g., Sy, porosity, and θ_s), and negatively correlated variables on opposite sides (e.g., Sy vs. WP, FC, and BD) (Figure 7). The first two principal components (PC1 and PC2) explained most of the variation (about 67%) in the peat properties data, as shown in the PCA scree plot (Figure 8). The DPA and PE sites, which had higher BD, FC, and WP values (Figure 2, Table 2), formed a distinct cluster to the right in the PCA biplot (Figure 8). The PP, PPT, and DRP sites, which had relatively higher Sy, porosity, θ_s and K_{sat} values (Figure 2, Table 2), were mostly clustered to the left (Figure 8).

For a better understanding of, among other things, the significance or strength of the monotonic relationship between peat properties, Spearman's correlation coefficient was calculated for all the aggregated data (Figure 9), and also for the data aggregated based on land use and peat layers (Figure S2). It was found that BD had a significantly ($P < 0.05$) positive monotonic correlation with FC, and significantly negative

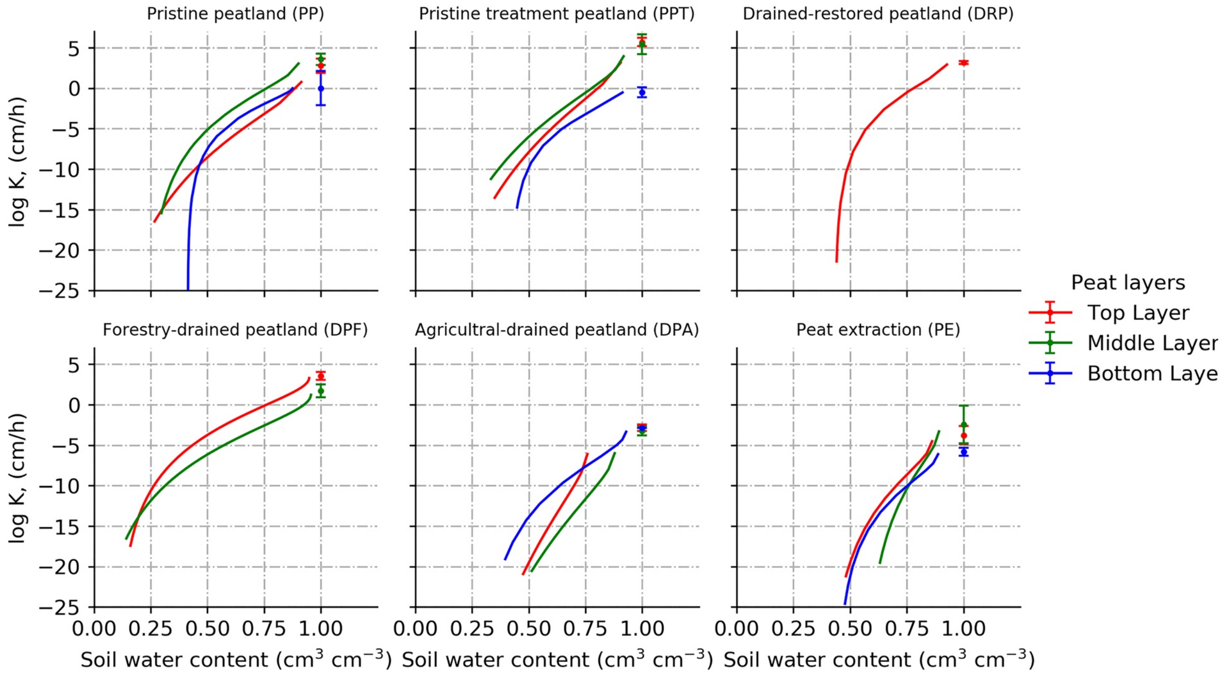

Figure 7. Predicted unsaturated hydraulic conductivity (*K*) on log scale plotted against the predicted soil water retention curve for different peat layers under different land uses. Error bars show the 95% confidence interval of the geometric mean saturated hydraulic conductivity.

monotonic correlations with θ_s, θ_r, *n*, K_{sat}, porosity, and Sy (Figure 9b). The vGM parameter α showed the strongest negative correlation with AM (rho = −0.34). It also showed a weak but statistically significant positive correlation with Sy and weak but statistically significant negative correlations with soil depth, FC, and vGM parameter *n* (Figure 9). The parameter *n* showed statistically significant strongly negative correlations with FC, AM, and BD, and strongly positive correlations with θ_s, θ_r, Sy, porosity, and K_{sat} (Figure 9).

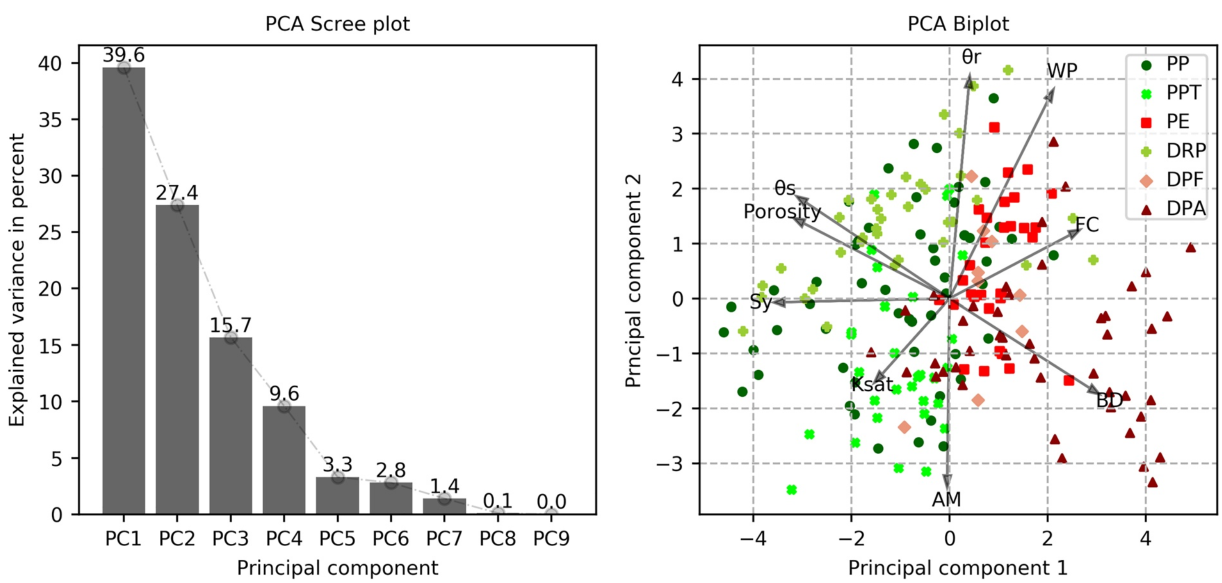

Figure 8. Principal component analysis (PCA) scree plot (left) and biplot (right) for peat properties data, where θ_s and θ_r are saturated and residual water content, respectively, Sy is specific yield, K_{sat} is saturated hydraulic conductivity, AM is available moisture, BD is bulk density, FC is field capacity, and WP is wilting point. For land use abbreviations, see Table 2.

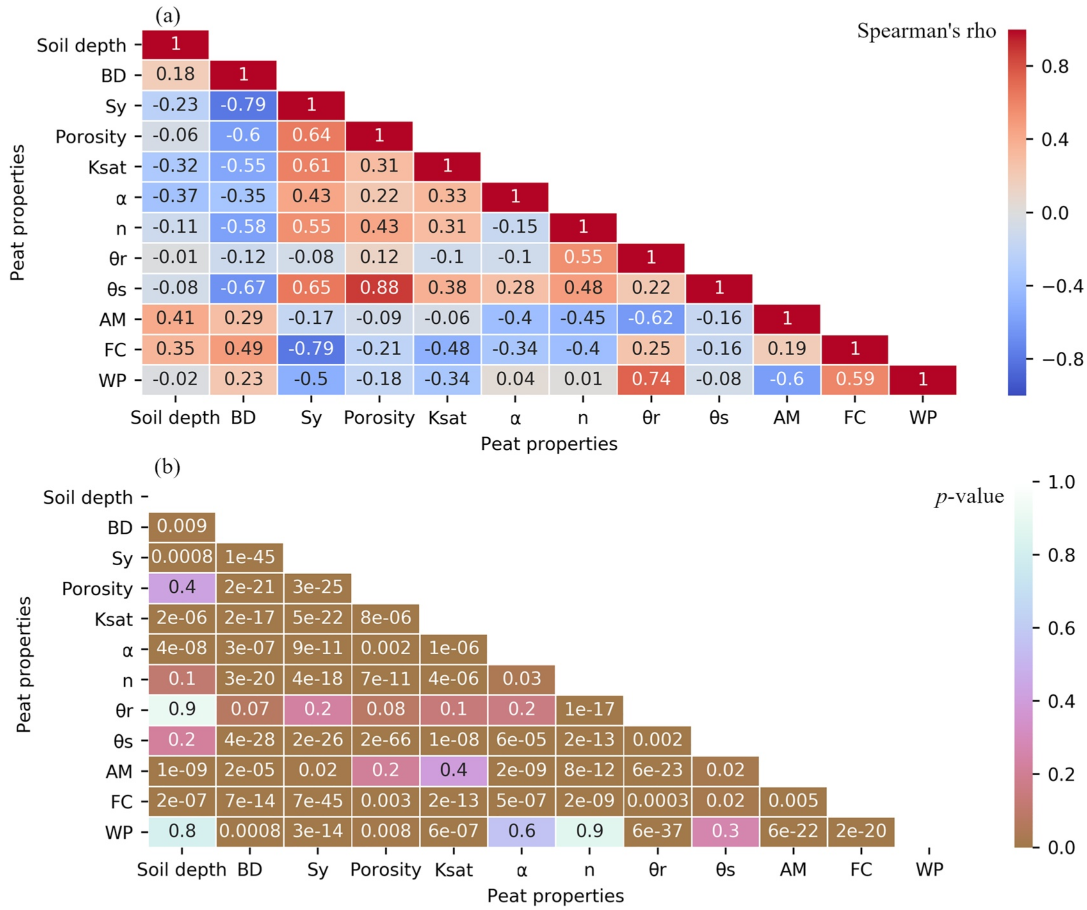

Figure 9. (a) Spearman's correlation coefficient (rho) and (b) corresponding significance level heatmaps for aggregated data on peat properties, where BD is bulk density, Sy is specific yield, K_{sat} is saturated hydraulic conductivity, α and n are van Genuchten-Mualem parameters, θ_r and θ_s, are residual and saturated water content, respectively, AM is available moisture, FC is field capacity, and WP is wilting point.

3.4. Estimating Specific Yield Using Regression Models

To predict Sy, peat properties that could be measured inexpensively and easily, and which are routinely measured, were used (BD, soil depth). After transforming the data using natural logarithms, both the multivariate linear regression model ($R^2 = 0.74$, root mean square error [RMSE] = 0.086) and the partial least squares regression model ($R^2 = 0.74$, RMSE = 0.086) predicted Sy satisfactorily, as shown in Figure 10. However, the models tended to overpredict at low values and underpredict at high values. The multivariate linear regression model using BD, and soil depth to predict Sy was:

$$Sy = m1 \times BD + m2 \times \text{soil depth} + b \tag{4}$$

where Sy is a decimal fraction, BD is in g cm^{-3}, and soil depth is in cm and all variables in Equation 4 are in natural logarithmic scale. Each coefficient's value and 95% confidence interval are as follows: $m1 = -0.697$ (-0.819, -0.574), $m2 = -0.104$ (-0.193, -0.014), and $b = -2.640$ (-3.040, -2.241). Both BD and soil depth were significantly important for the model. However, the standardized regression coefficient in absolute values for BD (0.44) was numerically greater than soil depth (0.09), indicating that BD was relatively more important than soil depth for predicting Sy. Furthermore, an LME model was developed using BD and soil depth as fixed effects, and land use as a random effect. The LME model further revealed that BD was the most significant ($P < 0.05$) predictor of Sy, with land use differences accounting for 25.7% of Sy variance.

10.1029/2020WR028624

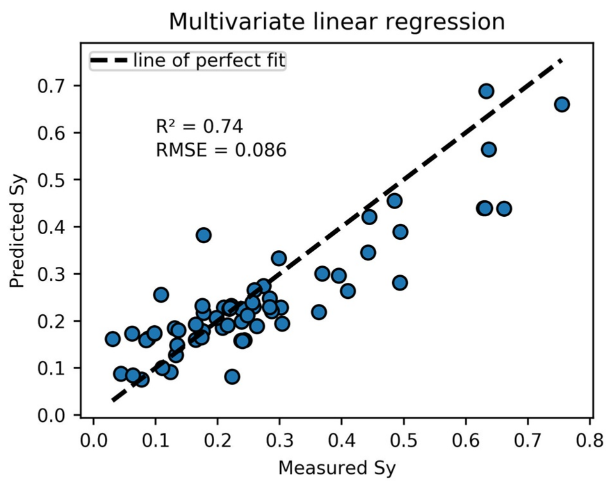

Figure 10. Plots of predicted specific yield (Sy) values obtained using (left) a multivariate linear regression and (right) a partial least squares regression model by equating the remaining test data (30% of data) and the corresponding measured Sy values. R^2 = coefficient of determination, RMSE = root mean square error.

4. Discussion

Accurate data on the physical and hydraulic properties of peat soils are needed for hydrological modeling and to support sustainable land use and management. However, peatlands under different land uses have not been intensively studied or well documented to date, due to their complex and heterogeneous pore structures and associated changes in volume during water level drawdown (Schwärzel et al., 2006). Peatlands under different land uses may undergo different degrees of peat decomposition, thereby affecting the degree of change in their physical and hydraulic properties. Hence, this study analyzed the measured data on the hydraulic and physical properties of disturbed and pristine peatlands at 59 sites in Finland and Norway, with the aim of providing a unique data set and insights for peatland researchers, hydrological modelers, and stakeholders. Here, the effect of peatland management activities on the most significant physical and hydraulic properties of peat were thoroughly discussed. We also explored and suggested key peat properties as predictors.

4.1. Impacts of Peatland Management on Peat Properties

Land use change alters the physical and hydraulic properties of peat. Use of peatlands for agriculture, peat extraction, and forestry requires the water table (which is mostly near the ground surface in pristine peatlands) to be lowered. This is typically achieved by creating a network of drainage ditches. The lowering of the water table causes the upper peat layer to collapse and increases aeration and decomposition of peat, resulting in subsidence of the peat (Menberu et al., 2016; Price & Schlotzhauer, 1999; Silins & Rothwell, 1998). Peat subsidence as a result of compaction, consolidation, and loss of peat volume is reflected in the BD of peat (Minkkinen & Laine, 1998). Silins and Rothwell (1998) in Canada found that 7 years after the drainage of a peatland for forestry, the BD of the top 40 cm peat layer had increased by 63%. In the present study, the most disturbed sites (DPA, PE, and DPF) had higher BD values in all peat layers than the least disturbed sites (Figure 11). Compared with the mean BD value of undisturbed PP sites (0.10 g cm^{-3}), the mean BD of DPA (0.28 g cm^{-3}), PE (0.16 g cm^{-3}), and DPF (0.14 g cm^{-3}) sites increased by 187%, 61%, and 42%, respectively. The mean and median BD in peatland drained for agriculture was significantly higher ($P < 0.05$) than under other land uses (Figures 5 and 11). Peat extraction sites had the second highest mean and median BD values, significantly higher than at PP and DRP sites (Figure 5 and 11).

Mean BD and Sy in the most disturbed peatlands (DPA, PE, and DPF) ranged from 0.14 to 0.28 g cm^{-3} and 0.14 to 0.21, respectively. However, mean BD and Sy in formerly disturbed, now restored (DRP) and intact peatlands (PP, PPT) ranged from 0.09 to 0.11 g cm^{-3} and 0.30 to 0.38, respectively. The highest and lowest Sy values (0.40 and 0.11) were found for the top layer (30 cm depth) of pristine peat (PP) and highly

10.1029/2020WR028624

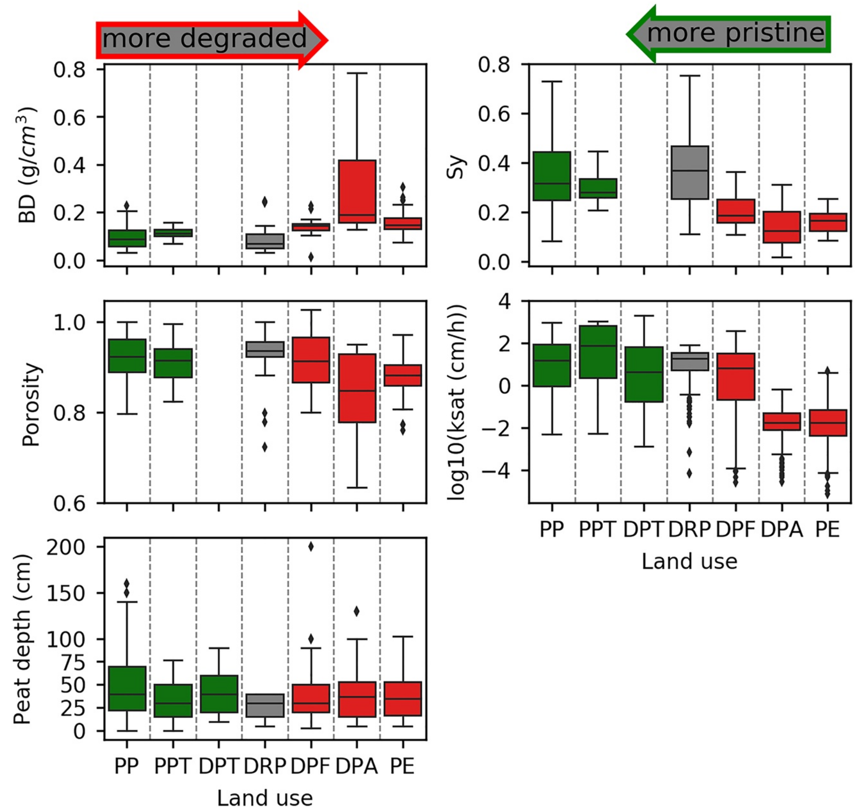

Figure 11. Boxplots summarizing peat properties for each land use, where BD is bulk density, K_{sat} is saturated hydraulic conductivity, Sy is specific yield, and peat depth is sampling/measurement mean depth. The most disturbed sites (peat extraction, agriculture, or forestry) are plotted in red.

decomposed agricultural peatland (DPA), respectively, indicating the presence of a higher proportion of large pores in less decomposed intact peat. Large differences in K_{sat} values under different land uses and between peat layers were observed (Table 2). The lowest and highest geometric mean K_{sat} values (4.01E-08 m s^{-1} and 8.20E-05 m s^{-1}) were found for the most disturbed peat (DPA) and intact treatment peatland (PPT), respectively (Figure 11). A previous study reported median K_{sat} values for relatively undecomposed fibric peat and deeply humified sapric peat of 2.8E-4 m s^{-1} and 1.0E-7 m s^{-1}, respectively (Chason & Siegel, 1986; Letts et al., 2000). A previous study had reported K_{sat} values of 4.50E-06 m s^{-1} and 7.00E-6 m s^{-1} for well and moderately decomposed peat, respectively (Boelter, 1968).

The most disturbed sites in the present study (DPA and PE) had the highest BD values, which was reflected in their low Sy, porosity, and K_{sat} values (Figure 11). Compared with undisturbed PP, the mean Sy in DPA, PE, and DPF were lesser by 60%, 55%, and 41%, respectively. This was also reflected in the geometric mean K_{sat} values in DPA, PE, and DPF, which were lesser by 100%, 100%, and 68%, respectively, compared with that in PP (Figures 5 and 11). However, the Sy and BD in formerly disturbed, now restored peat (DRP) showed no significant differences from the values in intact peatlands, indicating peat recovery from disturbance (Figure 5).

The percentage change in peat porosity due to land use change was smaller than observed for BD and Sy. Previous studies of organic soils showed that greatly increased BD might not be accompanied by a marked decrease in total porosity (Päivänen, 1973; Silins & Rothwell, 1998), as was the case in this study. A study by Rothwell et al. (1996) on drained peatland in Canada found high water content near drainage ditches, an area where greater peat subsidence and higher BD were expected and concluded that water content was unaffected by ditch spacing. Despite the increase in BD due to peatland land use change found in the present study, mean porosity in all land use cases was high (range 0.85–0.93). The porosity in DPA and PE were lesser by 8.5% and 4.6%, respectively, compared with PP, differences which were statistically significantly (Figure 5).

The BD at the most disturbed sites (DPA, PE, and DPF) decreased with peat depth, but not at the undisturbed sites (Figure 2). The Sy in undisturbed peat decreased with depth due to an increase in degree of peat decomposition, while in the most degraded peatlands types (PE, DPA) it increased with depth. This indicates that peat compaction and decomposition were greater in the top layer than in the other layers (middle and bottom) of peatlands used for agriculture and peat extraction. It has been reported that intensive drainage and preparation of peatlands for peat extraction and agricultural use can lead to significant degradation of the upper peat layers (Kechavarzi et al., 2010). This can increase the BD in the top layer by 100%–300%, and that in the subsoil by 50%–100% (Parent & Ilnicki, 2002). The increase in BD in the top layer of highly disturbed peat could be due to a process called moorshing, which includes biological, chemical, and physical changes in the top layer as a result of water content loss and increased aeration (Oleszczuk et al., 2007). Furthermore, at agricultural peatland sites, some farmers add sand or silt to the field to improve soil fertility and trafficability. Preparation of sites for peat extraction involves the removal of the top layers, so that the relatively decomposed middle layer becomes the top layer and is subjected to further compaction.

In this study, the BD of the top layer in DPA, PE, and DPF increased by 441%, 140%, and 92%, respectively, compared with the top layer in intact PP. Silins and Rothwell (1998) in Canada reported similar changes after 6 years of drainage, when the BD of the top 30 cm peat layer was 90% greater than that of a reference undrained layer. This was primarily due to the loss of macropores in the top layer, causing subsidence and significant change in BD. The BDs in the middle layer in DPA, PE, and DPF were greater by 91%, 53%, and 37%, respectively, compared with the middle layer in PP. However, this was not the case for the bottom layer at the most disturbed sites, where BD had lowered by 19% and 23% in PE and DPF, respectively, and was greater by only 3.3% in DPA compared with the bottom layer in PP, indicating that most of the disturbance occurred in the first two layers of peat (above 60 cm depth). In pre- and post-compression laboratory testing, *Sphagnum* moss samples from the 15–20 cm and 10–15 cm peat layers in Québec, Canada, showed a significant increase in BD of 63% and 53%, respectively (Gauthier et al., 2018). The change in Sy across peat layers closely followed the opposing trend observed in BD. However, the K_{sat} values lowered with depth for all land use cases (Table 2, Figure 2). This is generally the case in peat (Morris et al., 2015; Päivänen, 1973) due to the increased degree of decomposition with increasing depth, especially in intact peatlands. Under compression, physical changes in the structure of moss result in a general decrease in the K_{sat}. As compression progresses, large pores become smaller, resulting in a decrease in K_{sat} where the most saturated flow occurs (Golubev & Whittington, 2018). The K_{sat} in each peat layer at the two degraded peatland types (PE, DPA) lowered by 100%, and lowered on average by 60% at DPF sites, compared with the corresponding peat layer in PP (Table 2). However, the impact of microtopography (hummock and hollow) on peat properties should not be overlooked, especially for pristine or intact peatlands, which are covered with alternating hummock-hollow microtopography. For equivalent depths below the surface, the K_{sat} value beneath hollows was lower than that measured beneath hummocks (Morris et al., 2015). Possible differences in K_{sat} between different sites could be due to dependency of K_{sat} on scale of measurement (Schulze-Makuch et al., 1999). Davis et al. (1996) showed that measured K_{sat} values increased as sample size increased, and also reported that measured K_{sat} values in surface soils differed significantly (1–3 orders of magnitude) between measurement techniques; however, variation decreased as depth increased.

4.2. SWRC and Hydraulic Conductivity Functions of Peat

At the lowest pressure tested (pF 0), the water content in the top peat layer was lower at the most disturbed sites, DPA and PE (0.76 $cm^3\ cm^{-3}$ and 0.86 $cm^3\ cm^{-3}$, respectively), while under the other land uses it was greater than 0.9 $cm^3\ cm^{-3}$. At pF 0, the soil water content at the middle and bottom layers ranged from 0.88 $cm^3\ cm^{-3}$ to 0.96 $cm^3\ cm^{-3}$ (Figures 6 and 12). Volumetric water content increased from top to bottom peat layers at the highly disturbed sites (DPA, PE), due to a decrease in BD with depth, but not at the other sites (Table 2, Figure 6). Increasing the pressure head by 10 cm (pF 1) resulted in a greater percentage change in water content (around 10%) in the top layers of undisturbed PP and intact PPT, and less than 5% change in water content under the other land uses. At pF 1, there was a decrease in unsaturated K of at least 50%, with the highest percentage change (93%) observed in the top layers of PP and PPT (pristine and intact

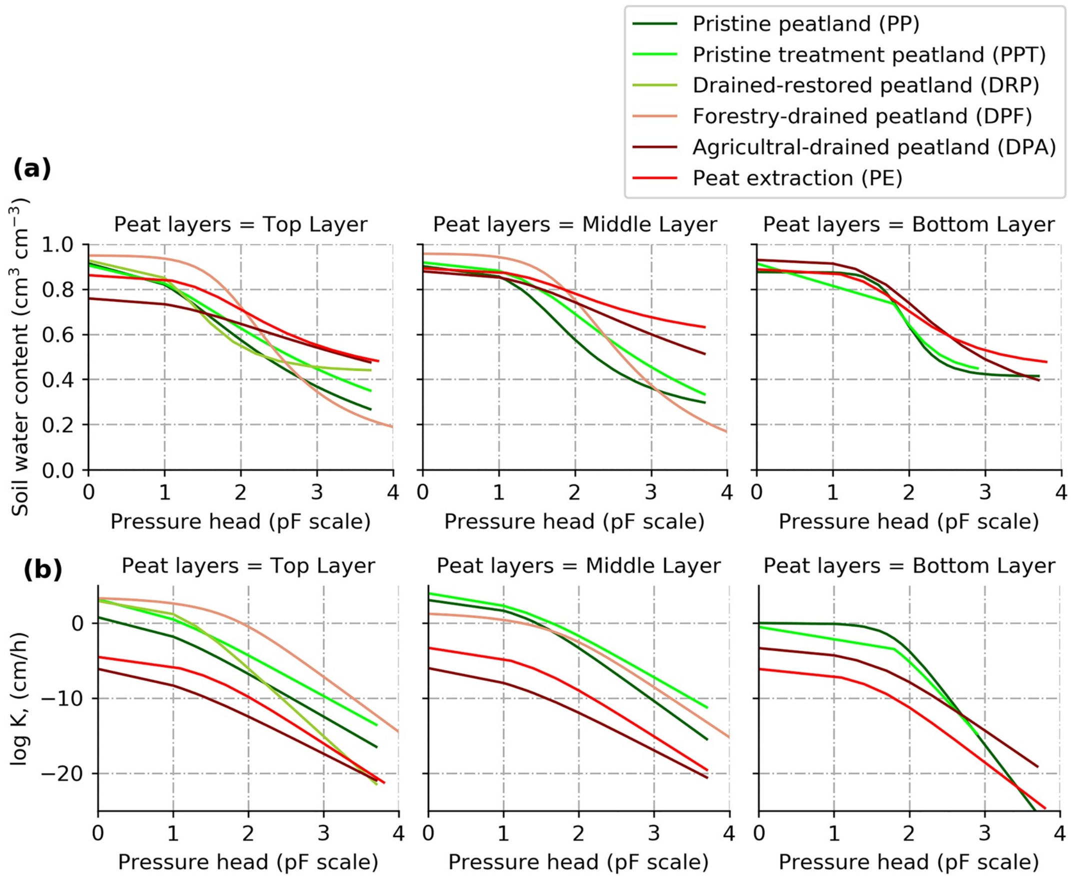

Figure 12. (a) Fitted soil water retention curve and (b) modelled hydraulic conductivity (k) curve for the (left) top peat layer, (center) middle peat layer, and (right) bottom peat layer under different land uses. Red shading (more disturbed sites), green shading (less disturbed and more pristine sites). pF $= \log\left|h\right|\left[cm\right]$ where h (cm) is pressure head.

sites). The matric suction and water retention characteristics of the soil structure determine how much water is retained in the soil. The hydraulic conductivity, which is constant in saturated soils and defined as a function of matric suction in unsaturated soils, is the primary cause of water flow variation in saturated and unsaturated soils (Ng & Shi, 1998).

A previous study reported a volumetric water loss of 54% and 15% from slightly decomposed *Sphagnum* peat and reed peat, respectively, and a loss of between 4% and 6% from highly decomposed reed peat at pF 1.7 (Parent & Ilnicki, 2002). At pF 1.7, the least decomposed top layer of intact peatland in the present study (PP) lost about 30% of its moisture content, while the most decomposed PE and DPA sites (the two most degraded peatland types) lost 8% and 13%, respectively, of their moisture content (Figure 12a). Overall, for pF between 1.7 and 3.0, the least disturbed sites lost more water, so the volumetric water content in highly disturbed peat was higher. However, the unsaturated *K* at disturbed sites remained lower than at less disturbed or intact sites. This may be due to the reduced pore size and altered geometry of air-filled pores in highly disturbed sites (Rezanezhad et al., 2010). However, Price et al. (2008) on *Sphagnum* mosses found that at 25 cm (pF 1.4) water pressure, the deeper (25 cm) samples had higher unsaturated *K* than the upper (5 cm) samples due to higher water retention at deeper layers. In our study, unsaturated *K* values in the bottom layer of heavily disturbed sites were found to be higher than in pristine and intact sites at pF > 3.0 (Figure 12). Porosity under all land uses was high (Table 2), but at higher pF values (>1.7) water retention showed significant differences between land uses and peat layers, indicating greater importance of pore size distribution than porosity. The change in *K* differed by orders of magnitude between sites and/or peat layers, but the changes in other peat properties were smaller. This could be due to the dominant role of macropores in water movement in peat, with macropores greater than 50 μm and less than 1 μm reported in intact and drained peat, respectively (Lennartz & Liu, 2019; Mustamo et al., 2016). Overall, the moisture content near saturation (lower pF) in the top and middle layers of strongly disturbed sites (PE, DPA) was lower than in intact peatland. However, at high tension, the moisture content at strongly disturbed sites was higher than in intact peat, indicating the dominance of micro- and macropores in disturbed and intact peat, respectively (Figure 12). As soil BD increases, macropores shrink while meso- and micropores increase, affecting pore diameter and distribution, and, hence, soil hydraulic properties (Indoria et al., 2020). However, Liu and Lennartz (2019) found that macroporosity in peat soils decreased as BD increased from 0.01 to 0.2 g cm^{-3}, but there was no clear trend for macroporosity as BD increased from 0.20 to 0.76 g cm^{-3}. All but one (DPA top layer, BD = 0.42 g cm^{-3}) of the peat land use cases analyzed in this study had a mean BD value of less than 0.2 g cm^{-3} (Table 2).

The values of unsaturated K of the middle and bottom layers of intact peatlands (PP and PPT) were similar, but the top layer showed slight differences, especially at higher tensions (divergence). Similar divergence in the unsaturated K curve was observed between highly disturbed sites (DPA and PE), but at high tensions they showed slight convergence (Figure 12).

Peat samples from relatively less decomposed peat layers are susceptible to shrinkage at high pressure heads during SWRC measurements, which could lead to underestimation of volumetric water content if volume changes are discarded (Schwärzel et al., 2002; Wallor et al., 2018). Hence, the water content at high pressure head (θ_r) was optimized in this study, as described in the methods section. Peat samples from the highly disturbed and decomposed peat (PE) had the highest θ_r (0.56), and samples from the DPF site had the lowest ($\theta_r = 0.02$) (Table 3). The FC determined from the SWRC was greater for highly disturbed peat (PE, DPA, and DPF) than intact peat (Table 3). This was because extremely disturbed sites had lower drainable porosity (lower Sy values; Table 2) due to a higher degree of peat decomposition resulting in smaller pores, enabling a significant amount of water retention at high tension. Peat soil samples from intact peatlands had large pores (minimally decomposed peats) and could hold a greater amount of water at saturation, but quickly drained out even at low-pressure heads due to their relatively higher Sy values (Table 2) and slightly lower FC values (Table 3). In this study, highly disturbed and intact peatlands had FC values ranging from 0.65 to 0.78 and 0.53 to 0.67, respectively. Reported measured FC values for hemic peat (moderately decomposed peat) ranged from 0.48 to 0.70 (Boelter, 1969; Dunne & Willmott, 1996). An increase in volumetric water content at WP has been related to an increase in degree of peat decomposition (Parent & Ilnicki, 2002), as was also found in this study (Table 2, Table 3).

For all land use cases, the mean value of the vGM parameter α ranged from 0.03 cm^{-1} to 0.08 cm^{-1} and was related to peat depth, Sy, vGM parameter n, AM, and FC. Spearman correlation analysis revealed that parameter α was significantly negatively correlated with peat depth (Figure 9). This could indicate that less decomposed peat layers or intact peatlands have relatively smaller air entry pressure and drain faster due to the presence of macropores (Kechavarzi et al., 2010; Liu & Lennartz, 2019). A previous study on the hydraulic properties of fen peat soils used for grassland found that α ranged in value from 0.0042 cm^{-1} to 0.1659 cm^{-1}, with a mean value of 0.0231 cm^{-1} (Gnatowski et al., 2010). It has also been shown to be negatively correlated with depth (Wallor et al., 2018). On the other hand, the shape parameter n in this study ranged in value from 1.31 to 1.95 for all land use cases, with the highest values for intact peatland (PP, PPT). In the study by (Gnatowski et al., 2010), the value of n ranged from 1.1 to 1.7 (mean 1.3) for fen peat used for grassland. A decrease in n with increasing BD, as found here (Figure 9), has also been reported in other studies (Liu & Lennartz, 2019; Weiss et al., 1998). Price et al. (2008) found that the vGM model did not predict the unsaturated K satisfactorily when only using the water retention data. In our study, the vGM model fitted parameters predicted the unsaturated K satisfactorily. However, the following sources of error in the vGM predictive model should be noted: (a) measurement (instrument) errors (b) limited validation data (e.g., unsaturated hydraulic conductivity) (c) variations in a scale of measurement (field-scale vs. laboratory-scale) and corresponding methods used, for example, K_{sat} was measured both at field and laboratory scales using a variety of methods. For example, Bittelli and Flury (2009) showed that the pressure plate apparatus are prone to significant errors at low water potentials, especially at water potentials less than −20 m H_2O.

4.3. Bulk Density: The Most Important Indicator of Other Peat Properties

Based on the results, BD was the most important physical property determining water retention capacity in peat and affecting other important peat properties. The data on BD are needed to calculate the volumetric nutrient concentration in peat and changes in element balances due to land use change (Minkkinen & Laine, 1998). For example, an increase in total nitrogen concentration and dissolved organic carbon has been reported in drained peatlands (Menberu et al., 2017) due to increased peat decomposition (Holden et al., 2004; Wells & Williams, 1996). An increase in BD could also increase soil thermal conductivity, a property responsible for many soil processes such as freeze-thaw cycles, which could influence N_2O emissions (Mustamo et al., 2019). BD could be used to estimate annual N_2O emissions and pore water DOC concentrations (Liu et al., 2019). Peatland drainage lowers the water table and increases air-filled porosity, thereby enhancing the microbial activity and promoting aerobic decomposition of peat, which increases the BD (Holden et al., 2006).

Most peat physical and hydraulic properties examined in this study were found to be either positively or negatively correlated to BD (Figure 9), indicating its importance. Peat fiber content and BD provide significant information about peat physical characteristics and have been used to identify types of peat material (Boelter, 1969) by taking BD as a proxy for degree of peat decomposition (Boelter, 1968). Based on BD and degree of decomposition, peat materials have been classified as sapric (most decomposed, BD > 0.195 g cm^{-3}), hemic (moderately decomposed, BD 0.075–0.195 g cm^{-3}), and fibric (least decomposed, BD < 0.075 g cm^{-3}) (Boelter, 1968, 1969). In our study, the top layers of DPA (BD = 0.42 g cm^{-3}) and PE (BD = 0.19 g cm^{-3}) could be classified as sapric, the top layer of PP (BD = 0.077 g cm^{-3}) resembled fibric peat, and the other peat layers under different land uses were hemic peat (Table 2). The BD was shown to be the most important property in describing K_{sat}, porosity, and Sy (Figure 9). Liu and Lennartz (2019) showed that the hydraulic properties of peat soils could be estimated using the BD as proxy for peat decomposition and compaction; they further demonstrated a relationship between the various hydraulic properties and BD. Water yield (Sy) was correlated significantly with BD (Figure 9). Hence, by combining BD with other easily measurable peat properties (peat depth and porosity), it was possible to predict the Sy of peatland with a high degree of accuracy (Figure 10). Many peatland hydrological functions, including flood attenuation, baseflow contribution to rivers, and sustaining groundwater levels in surficial aquifers, are influenced by peat Sy (Bourgault et al., 2017). The water storage capacity of peat, which is measured by calculating the Sy, is crucial in planning peatlands for wastewater treatment (Heliotis, 1989).

Liu and Lennartz (2019) showed that peat soils with BD > 0.20 gm cm^{-3} behave hydraulically rather like mineral soils. In this study, the most disturbed top layer in peatland drained for agriculture had a BD value greater than 0.20 gm cm^{-3}, while in the disturbed top layer of peat extraction sites, it was around this threshold. As a result, in degraded and compressed peatlands, soil erosion, and runoff will increase, especially near-surface or overland flow runoff during precipitation, reducing peatlands' characteristic water storage capacity (Heinemeyer et al., 2019).

5. Conclusions

Use of peatlands for a variety of human uses has significantly changed the physical and hydraulic properties of the peat. In analyses of the data based on 3,073 samples from 59 peatland sites, we have shown that peatland uses such as agriculture and peat extraction alter the physical and hydraulic properties of the peat more strongly than other land uses (e.g., forestry, water treatment). The top peat layer (30 cm depth) was most affected by agriculture and peat extraction, as indicated by the bulk density, specific yield, and porosity values. At these disturbed sites, the bulk density decreased with depth, while specific yield and porosity increased. Overall, disturbed sites had higher bulk density, lower hydraulic conductivity, and lower drainable porosity as a result of greater compression. The van Genuchten-Mualem soil water retention model was applied successfully to different layers of peat under different land uses. A SWRC, hydraulic conductivity curve, and associated van Genuchten-Mualem parameters were computed for the different land uses and peat layers. Overall, α and n ranged in value from 0.03 to 0.08 cm-1 and 1.31 to 1.95, respectively, and both were strongly related to available moisture, field capacity, and Sy. Less disturbed sites lost significantly more moisture at lower matric tensions (below pF 1.7). At higher tensions, the volumetric water content of strongly disturbed sites was higher than at intact sites, indicating the importance of pore size distribution. However, at all tension levels applied, the unsaturated K values at strongly disturbed sites remained lower than those at intact sites. Our results can be of great value to hydrological modelers and stakeholders, for better parameterization of hydrological models, integration of peat soils into large-scale models, and improved peatland management and restoration options.

Data Availability Statement

All data will be uploaded online (Research data storage service IDA, DOI: https://doi.org/10.23729/cc4c1daa-2671-43a7-b9bf-8c3d786db787) step by step when ongoing projects finalized.

Acknowledgments

Data were collected as part of many past and ongoing projects. We thank all data providers who made this study possible. Writing and data analysis were conducted as part of the PeatWise project (project number 4400T-1002) funded by FACCA ERA-GAS, the WaterPeat project (project number 326848) funded by WaterWorks ERA-NET, the WaterAgri project (project number 858375) funded by Horizon2020, the MYR project (project number 281109) funded by the Norwegian Research Council, the BioWater project (project number 82263) funded by the Nordic Centre of Excellence, FRESHABIT LIFE IP (LIFE14/IPE/FI/023) project funded by the LIFE program of the European Union and a postdoctoral project funded by the Finnish Cultural Foundation. There is no conflict of interest related to this research work.

References

Asmuß, T., Bechtold, M., & Tiemeyer, B. (2019). On the potential of sentinel-1 for high resolution monitoring of water table dynamics in grasslands on organic soils. *Remote Sensing*, *11*(14), 1659.

Bittelli, M., & Flury, M. (2009). Errors in water retention curves determined with pressure plates. *Soil Science Society of America Journal*, *73*(5), 1453–1460. https://doi.org/10.2136/sssaj2008.0082

Boelter, D. H. (1964). Water storage characteristics of several peats in situ. *Soil Science Society of America Journal*, *28*(3), 433–435. https://doi.org/10.2136/sssaj1964.03615995002800030039x

Boelter, D. H. (1968). Important physical properties of peat materials. In Paper presented at the Third International Peat Congress, (pp. 150–154).

Boelter, D. H. (1969). Physical properties of peats as related to degree of decomposition. *Soil Science Society of America Journal*, *33*(4), 606–609. https://doi.org/10.2136/sssaj1969.03615995003300040033x

Bourgault, M., Larocque, M., & Garneau, M. (2017). Quantification of peatland water storage capacity using the water table fluctuation method. *Hydrological Processes*, *31*(5), 1184–1195. https://doi.org/10.1002/hyp.11116

Chason, D. B., & Siegel, D. I. (1986). Hydraulic conductivity and related physical properties of peat, lost river peatland, Northern Minnesota. *Soil Science*, *142*(2), 91–99. https://doi.org/10.1097/00010694-198608000-00005

Chen, R., Liu, J., Li, J. H., & Ng, C. W. W. (2015). An integrated high-capacity tensiometer for measuring water retention curves continuously. *Soil Science Society of America Journal*, *79*(3), 943–947. https://doi.org/10.2136/sssaj2014.11.0438n

Davis, S. H., Vertessy, R. A., Dunkerley, D. L., & Mein, R. G. (1996). The influence of scale on the measurement of saturated hydraulic conductivity in a forest soil. In Paper presented at the Hydrology and Water Resources Symposium 1996: Water and the environment.

Dettmann, U., Bechtold, M., Frahm, E., & Tiemeyer, B. (2014). On the applicability of unimodal and bimodal van Genuchten-Mualem based models to peat and other organic soils under evaporation conditions. *Journal of Hydrology*, *515*, 103–115. https://doi.org/10.1016/j.jhydrol.2014.04.047

Dunne, K. A., & Willmott, C. J. (1996). Global distribution of plant-extractable water capacity of soil. *International Journal of Climatology*, *16*(8), 841–859. https://doi.org/10.1002/(sici)1097-0088(199608)16:8<841::aid-joc60>3.0.co;2-8

Elliott, J., & Price, J. (2020). Comparison of soil hydraulic properties estimated from steady-state experiments and transient field observations through simulating soil moisture in regenerated sphagnum moss. *Journal of Hydrology*, *582*, 124489. https://doi.org/10.1016/j.jhydrol.2019.124489

Gauthier, T. J., McCarter, C. P. R., & Price, J. S. (2018). The effect of compression on sphagnum hydrophysical properties: Implications for increasing hydrological connectivity in restored cutover peatlands. *Ecohydrology*, *11*(8), e2020. https://doi.org/10.1002/eco.2020

Gnatowski, T., Szatyłowicz, J., Brandyk, T., & Kechavarzi, C. (2010). Hydraulic properties of fen peat soils in Poland. *Geoderma*, *154*, 188–195. https://doi.org/10.1016/j.geoderma.2009.02.021

Golubev, V., & Whittington, P. (2018). Effects of volume change on the unsaturated hydraulic conductivity of sphagnum moss. *Journal of Hydrology*, *559*, 884–894. https://doi.org/10.1016/j.jhydrol.2018.02.083

Greenup, A. L., Bradford, M. A., McNamara, N. P., Ineson, P., & Lee, J. A. (2000). The role of eriophorum vaginatum in CH4 flux from an ombrotrophic peatland. *Plant and Soil*, *227*(1), 265–272. https://doi.org/10.1023/A:1026573727311

Hallema, D. W., Périard, Y., Lafond, J. A., Gumiere, S. J., & Caron, J. (2015). Characterization of water retention curves for a series of cultivated histosols. *Vadose Zone Journal*, *14*(6), vzj2014. https://doi.org/10.0148/vzj2014.10.0148

Heikkilä, R., Ratamäki, O., & Lindholm, T. (2012). Recent debate on peat exploitation in Finland. In Paper presented at the Proceedings of the 14th International Peat Congress.

Heinemeyer, A., Berry, R., & Sloan, T. J. (2019). Assessing soil compaction and micro-topography impacts of alternative heather cutting as compared to burning as part of grouse moor management on blanket bog. *PeerJ*, *7*, e7298. https://doi.org/10.7717/peerj.7298

Heliotis, F. D. (1989). Water storage capacity of wetland used for wastewater treatment. *Journal of Environmental Engineering*, *115*(4), 822–834. https://doi.org/10.1061/(asce)0733-9372(1989)115:4(822)

Holden, J., Chapman, P. J., & Labadz, J. C. (2004). Artificial drainage of peatlands: Hydrological and hydrochemical process and wetland restoration. *Progress in Physical Geography*, *28*(1), 95–123. https://doi.org/10.1191/0309133304pp403ra

Holden, J., Chapman, P. J., Lane, S. N., & Brookes, C. (2006). Chapter 22 impacts of artificial drainage of peatlands on runoff production and water quality. *Developments in Earth Surface Processes*, *9*, 501–528. https://doi.org/10.1016/S0928-2025(06)09022-5

Indoria, A. K., Sharma, K. L., & Reddy, K. S. (2020). Chapter 18—Hydraulic properties of soil under warming climate. In M. N. V. Prasad, & M. Pietrzykowski (Eds.), Climate change and soil interactions, (pp. 473–508). Elsevier. https://doi.org/10.1016/B978-0-12-818032-7.00018-7

Ise, T., Dunn, A. L., Wofsy, S. C., & Moorcroft, P. R. (2008). High sensitivity of peat decomposition to climate change through water-table feedback. *Nature Geoscience*, *1*(11), 763–766. https://doi.org/10.1038/ngeo331

Jaros, A., Rossi, P. M., Ronkanen, A., & Kløve, B. (2019). Parameterisation of an integrated groundwater-surface water model for hydrological analysis of boreal aapa mire wetlands. *Journal of Hydrology*, *575*, 175–191. https://doi.org/10.1016/j.jhydrol.2019.04.094

Kechavarzi, C., Dawson, Q., & Leeds-Harrison, P. B. (2010). Physical properties of low-lying agricultural peat soils in England. *Geoderma*, *154*(3), 196–202. https://doi.org/10.1016/j.geoderma.2009.08.018

Könönen, M., Jauhiainen, J., Laiho, R., Kusin, K., & Vasander, H. (2015). Physical and chemical properties of tropical peat under stabilised land uses. *Mires & Peat*, *16*(8), 1–13.

Krimly, T., Angenendt, E., Bahrs, E., & Dabbert, S. (2016). Global warming potential and abatement costs of different peatland management options: A case study for the pre-Alpine hill and moorland in Germany. *Agricultural Systems*, *145*, 1–12. https://doi.org/10.1016/j.agsy.2016.02.009

Laiho, R. (2006). Decomposition in peatlands: Reconciling seemingly contrasting results on the impacts of lowered water levels. *Soil Biology and Biochemistry*, *38*(8), 2011–2024. https://doi.org/10.1016/j.soilbio.2006.02.017

Lennartz, B., & Liu, H. (2019). Hydraulic functions of peat soils and ecosystem service. *Frontiers in Environmental Science*, *7*, 92. Retrieved from https://www.frontiersin.org/article/10.3389/fenvs.2019.00092

Letts, M. G., Roulet, N. T., Comer, N. T., Skarupa, M. R., & Verseghy, D. L. (2000). Parametrization of peatland hydraulic properties for the Canadian land surface scheme. *Atmosphere-Ocean*, *38*(1), 141–160. https://doi.org/10.1080/07055900.2000.9649643

Lewis, C., Albertson, J., Xu, X., & Kiely, G. (2012). Spatial variability of hydraulic conductivity and bulk density along a blanket peatland hillslope. *Hydrological Processes*, *26*(10), 1527–1537. https://doi.org/10.1002/hyp.8252

Liu, H., & Lennartz, B. (2019). Hydraulic properties of peat soils along a bulk density gradient—A meta study. *Hydrological Processes*, *33*(1), 101–114. https://doi.org/10.1002/hyp.13314

Liu, H., Zak, D., Rezanezhad, F., & Lennartz, B. (2019). Soil degradation determines release of nitrous oxide and dissolved organic carbon from peatlands. *Environmental Research Letters*, *14*(9), 094009. https://doi.org/10.1088/1748-9326/ab3947

McCarter, C. P. R., Ketcheson, S., Weber, T. K. D., Whittington, P., Scarlett, S., & Price, J. (2017). Modified technique for measuring unsaturated hydraulic conductivity in sphagnum moss and peat. *Soil Science Society of America Journal*, *81*(4), 747–757. https://doi.org/10.2136/sssaj2017.01.0006

McCarter, C. P. R., & Price, J. S. (2014). Ecohydrology of sphagnum moss hummocks: Mechanisms of capitula water supply and simulated effects of evaporation. *Ecohydrology*, *7*(1), 33–44. https://doi.org/10.1002/eco.1313

Menberu, M. W., Haghighi, A. T., Ronkanen, A., Marttila, H., & Kløve, B. (2018). Effects of drainage and subsequent restoration on peatland hydrological processes at catchment scale. *Water Resources Research*, *54*(7), 4479–4497. https://doi.org/10.1029/2017WR022362

Menberu, M. W., Marttila, H., Tahvanainen, T., Kotiaho, J. S., Hokkanen, R., Kløve, B., & Ronkanen, A. (2017). Changes in pore water quality after peatland restoration: Assessment of a large-scale, replicated before-after-control-impact study in Finland. *Water Resources Research*, *53*, 8327–8343. https://doi.org/10.1002/2017WR020630

Menberu, M. W., Tahvanainen, T., Marttila, H., Irannezhad, M., Ronkanen, A., Penttinen, J., & Kløve, B. (2016). Water-table-dependent hydrological changes following peatland forestry drainage and restoration: Analysis of restoration success. *Water Resources Research*, *52*(5), 3742–3760. https://doi.org/10.1002/2015WR018578

Mezbahuddin, M., Grant, R. F., & Flanagan, L. B. (2016). Modeling hydrological controls on variations in peat water content, water table depth, and surface energy exchange of a boreal western Canadian fen peatland. *Journal of Geophysical Research: Biogeosciences*, *121*(8), 2216–2242. https://doi.org/10.1002/2016JG003501

Minkkinen, K., & Laine, J. (1998). Effect of forest drainage on the peat bulk density of pine mires in Finland. *Canadian Journal of Forest Research*, *28*(2), 178–186. https://doi.org/10.1139/x97-206

Montzka, C., Herbst, M., Weihermüller, L., Verhoef, A., & Vereecken, H. (2017). A global data set of soil hydraulic properties and sub-grid variability of soil water retention and hydraulic conductivity curves. *Earth System Science Data*, *9*(2), 529–543. https://doi.org/10.5194/essd-9-529-2017

Morris, P. J., Baird, A. J., & Belyea, L. R. (2015). Bridging the gap between models and measurements of peat hydraulic conductivity. *Water Resources Research*, *51*(7), 5353–5364. https://doi.org/10.1002/2015WR017264

Mualem, Y. (1976). A new model for predicting the hydraulic conductivity of unsaturated porous media. *Water Resources Research*, *12*(3), 513–522. https://doi.org/10.1029/WR012i003p00513

Mustamo, P., Hyvärinen, M., Ronkanen, A., & Kløve, B. (2016). Physical properties of peat soils under different land use options. *Soil Use & Management*, *32*(3), 400–410. https://doi.org/10.1111/sum.12272

Mustamo, P., Ronkanen, A., Berglund, Ö., Berglund, K., & Kløve, B. (2019). Thermal conductivity of unfrozen and partially frozen managed peat soils. *Soil and Tillage Research*, *191*, 245–255. https://doi.org/10.1016/j.still.2019.02.017

Ng, C. W. W., & Shi, Q. (1998). Influence of rainfall intensity and duration on slope stability in unsaturated soils. *The Quarterly Journal of Engineering Geology and Hydrogeology*, *31*(2), 105–113. https://doi.org/10.1144/gsl.qjeg.1998.031.p2.04

Oleszczuk, R., Gnatowski, T., Brandyk, T., Szatylowicz, J., Okruszko, T., Maltby, E., et al. (2007). Calibration of TDR for moisture content monitoring in moorsh layers. In T. Okruszko, E. Maltby, J. Szatylowicz, D. Swiatek, & W. Kotowski (Eds.), *Wetlands monitoring, modelling and management*, (pp. 121–124).

Päivänen, J. (1973). *Hydraulic conductivity and water retention in peat soils*. Suomen metsätieteellinen seura.

Pan, T., Hou, S., Liu, Y., & Tan, Q. (2019). Comparison of three models fitting the soil water retention curves in a degraded alpine meadow region. *Scientific Reports*, *9*(1), 18407. https://doi.org/10.1038/s41598-019-54449-8

Parent, L. E., & Ilnicki, P. (2002). *Organic soils and peat materials for sustainable agriculture*. CRC Press.

Peltola, A., Ihalainen, A., & Ylitalo, E. (2014). *Metsätilastollinen vuosikirja 2014* [finnish statistical yearbook of forestry]. Suomen Virallinen Tilasto: Maa-, Metsä-Ja Kalatalous.

Peverill, K. I., Sparrow, L. A., & Reuter, D. J. (1999). *Soil analysis: An interpretation manual*. CSIRO publishing.

Price, J. S., & Schlotzhauer, S. M. (1999). Importance of shrinkage and compression in determining water storage changes in peat: The case of a mined peatland. *Hydrological Processes*, *13*(16), 2591–2601. https://doi.org/10.1002/(SICI)1099-1085(199911)13:163.0.CO;2-E

Price, J. S., Whittington, P. N., Elrick, D. E., Strack, M., Brunet, N., & Faux, E. (2008). A method to determine unsaturated hydraulic conductivity in living and undecomposed sphagnum moss. *Soil Science Society of America Journal*, *72*(2), 487–491. https://doi.org/10.2136/sssaj2007.0111N

Rezanezhad, F., Quinton, W. L., Price, J. S., Elliot, T. R., Elrick, D., & Shook, K. R. (2010). Influence of pore size and geometry on peat unsaturated hydraulic conductivity computed from 3D computed tomography image analysis. *Hydrological Processes*, *24*(21), 2983–2994. https://doi.org/10.1002/hyp.7709

Ronkanen, A., & Kløve, B. (2005). Hydraulic soil properties of peatlands treating municipal wastewater and peat harvesting runoff. *Suo*, *56*(2), 43–56.

Rothwell, R. L., Silins, U., & Hillman, G. R. (1996). The effects of drainage on substrate water content at several forested Alberta peatlands. *Canadian Journal of Forest Research*, *26*(1), 53–62. https://doi.org/10.1139/x26-006

Roy, D., Jia, X., Steele, D. D., & Lin, D. (2018). Development and comparison of soil water release curves for three soils in the red river valley. *Soil Science Society of America Journal*, *82*(3), 568–577. https://doi.org/10.2136/sssaj2017.09.0324

10.1029/2020WR028624

Schulze-Makuch, D., Carlson, D. A., Cherkauer, D. S., & Malik, P. (1999). Scale dependency of hydraulic conductivity in heterogeneous media. *Groundwater*, *37*(6), 904–919. https://doi.org/10.1111/j.1745-6584.1999.tb01190.x

Schwärzel, K., Renger, M., Sauerbrey, R., & Wessolek, G. (2002). Soil physical characteristics of peat soils. *Journal of Plant Nutrition and Soil Science*, *165*(4), 479–486. https://doi.org/10.1002/1522-2624(200208)165:43.0.CO;2-8

Schwarzel, K., Simunek, J., Stoffregen, H., Wessolek, G., & Genuchten, van, M. T. (2006). Estimation of the unsaturated hydraulic conductivity of peat soils: Laboratory versus field data. *Vadose Zone Journal*, *5*(2), 628–640. https://doi.org/10.2136/vzj2005.0061

Silins, U., & Rothwell, R. L. (1998). Forest peatland drainage and subsidence affect soil water retention and transport properties in an Alberta peatland. *Soil Science Society of America Journal*, *62*(4), 1048–1056. https://doi.org/10.2136/sssaj1998.03615995006200040028x

Simhayov, R. B., Weber, T. K. D., & Price, J. S. (2018). Saturated and unsaturated salt transport in peat from a constructed fen. *Soil*, *4*(1), 63–81. https://doi.org/10.5194/soil-4-63-2018

Strack, M. (2008). In M. Strack (Ed.), Peatlands and climate change. IPS, International Peat Society.

Tfaily, M. M., Cooper, W. T., Kostka, J. E., Chanton, P. R., Schadt, C. W., Hanson, P. J., et al. (2014). Organic matter transformation in the peat column at marcell experimental forest: Humification and vertical stratification. *Journal of Geophysical Research: Biogeosciences*, *119*(4), 661–675. https://doi.org/10.1002/2013JG002492

Turunen, J. (2008). Development of Finnish peatland area and carbon storage 1950-2000. *Boreal Environment Research*, *13*(4).

van Genuchten, M. T. (1980). A closed-form equation for predicting the hydraulic conductivity of unsaturated soils. *Soil Science Society of America Journal*, *44*(5), 892–898. https://doi.org/10.2136/sssaj1980.03615995004400050002x

Van Genuchten, M. T., & Nielsen, D. (1985). On describing and predicting the hydraulic properties. *Annales Geophysicae*, *3*(5), 615–628.

Wallor, E., Rosskopf, N., & Zeitz, J. (2018). Hydraulic properties of drained and cultivated fen soils part I—Horizon-based evaluation of van genuchten parameters considering the state of moorsh-forming process. *Geoderma*, *313*, 69–81. https://doi.org/10.1016/j.geoderma.2017.10.026

Waskom, M., Botvinnik, O., O'Kane, D., Hobson, P., Lukauskas, S., Gemperline, D. C., et al. (2017). *Mwaskom/seaborn V0.8.1*. https://doi.org/10.5281/zenodo.883859

Weber, T. K. D., Iden, S. C., & Durner, W. (2017a). Unsaturated hydraulic properties of sphagnum moss and peat reveal trimodal pore-size distributions. *Water Resources Research*, *53*(1), 415–434. https://doi.org/10.1002/2016WR019707

Weber, T. K. D., Iden, S. C., & Durner, W. (2017b). A pore-size classification for peat bogs derived from unsaturated hydraulic properties. *Hydrology and Earth System Sciences*, *21*(12), 6185–6200. https://doi.org/10.5194/hess-21-6185-2017

Weiss, R., Alm, J., Laiho, R., & Laine, J. (1998). Modeling moisture retention in peat soils. *Soil Science Society of America Journal*, *62*(2), 305–313. https://doi.org/10.2136/sssaj1998.03615995006200020002x

Wells, E. D., & Williams, B. L. (1996). Effects of drainage, tilling and PK-fertilization on bulk density, total N, P, K, ca and fe and net N-mineralization in two peatland forestry sites in newfoundland, canada. *Forest Ecology and Management*, *84*(1), 97–108. https://doi.org/10.1016/0378-1127(96)03741-3