Comparing Methods for Measuring Water Retention of Peat Near Permanent Wilting Point

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Peat soils shrink and become very hydrophobic when dried. Both properties may cause inaccuracies when applying laboratory methods for soil hydraulic properties that have been developed and tested for mineral soils. This study aimed to compare different methods for the determination of the water retention of peat soils near permanent wilting point (pF 3.5 to 4.2). Three common methods were tested: two pressure apparatus (ceramic plate [Soilmoisture] vs. membrane [Eijkelkamp]) and a dew-point potentiameter (WP4C, Decagon Devices, Inc.), which is based on the equilibrium of soil water potential with air humidity. We used both field-moist peat samples and samples that had been rewetted after oven-drying. We found that there was no systematic difference between the two pressure apparatus. Low moisture variability among replicates and dew-point potentiameter measurements that indicated a drainage to pF 4.2 support the use of pressure apparatus for the determination of water retention near permanent wilting point. Despite a rewetting time of 2 wk including periodic mixing, rewetted oven-dried samples showed lower soil moistures at pF 3.5 and 4.2 than field-moist ones. This severe and long-lasting hysteresis effect was strongest for less decomposed peat samples. Thus, field-moist samples should be used. This makes the classical dew-point potentiameter measurement protocol, which is based on defined water additions to oven-dried samples, unsuitable for peat samples.

Abbreviations: DPP, WP4C dew point potentiameter; PMA, pressure membrane apparatus; PPA, pressure plate apparatus; WRC, water retention characteristics.

Worldwide, many peatlands are drained for economical uses like agriculture or forestry (Tubiello et al., 2016). The altered soil hydrological regimes lead to aerobic conditions and consequentially to increased microbiological activity in the upper part of the soil. While globally the majority of peatlands is still undrained and intact, drainage of peatlands causes hot spots for greenhouse gas emissions from agriculture and land-use, land-use change, and forestry in many locations globally (Tiemeyer et al., 2016; Tubiello et al., 2016). Furthermore, the soil physical properties change because of secondary pedogenetic transformation of the peat (Schwärzel et al., 2002; Dettmann et al., 2014), which superimposes the already complex structure of peat hydraulic properties in undrained peatlands (Weber et al., 2017). Controlled water management optimized to prevent waterlogging and ensure trafficability while reducing peat mineralization, is discussed as a promising path to combine profitable agriculture with reduced emissions (Deru et al., 2014). For this goal, profound knowledge of the soil water retention characteristics (WRC) of peat soils is essential.

Several methods are established to determine WRC for mineral soils. In the range of the permanent wilting point (pF $\approx$ 4.2), Water retention characteristics are most commonly measured under hydrostatic equilibrium with pressure devices, such as the pressure plate apparatus (PPA) and pressure membrane apparatus (PMA;

Core Ideas

- **Properties of peat and mineral soils are very different.**

- **Laboratory methods for hydraulic properties often tested only for mineral soils.**

- **Shrinkage and hydrophobicity of peat may cause inaccuracies.**

- **Pressure plate apparatus provides reliable data despite shrinkage.**

- **Observed long-lasting repellency effects prohibit protocols based on previously dried samples.**

Sreedeep and Singh, 2006; Schelle et al., 2013). Both apparatus measure the gravimetric water content (θ_{grav} [$g^1\ g^{-1}$]) by draining a soil sample with an imposed pressure through a porous drain medium until equilibrium. Comprehensive laboratory testing for mineral soils revealed methodological problems of the pressure apparatus that have been observed in particular for fine-textured mineral soils near wilting point (Solone et al., 2012). These issues comprise the lack of hydrostatic equilibrium because of low soil conductivity, a lost plate-soil contact because of shrinkage, or soil dispersion that causes blocking of pores in the drain medium and thus also incomplete drainage (Bittelli and Flury, 2009). An alternative method is given by the chilled-mirror dew-point potentiameter, which measures the water potential at a given soil moisture based on the equilibrium between soil water potential and air humidity (Gee et al., 1992). Under the assumption that osmotic effects and other potentials are negligible, the water potential can be set equal to the matric potential h and thus be used to calculate the pF = log10 (h) with the matric potential expressed as pressure head in centimeters (cm). The benefit of potentiameter measurements is that one measurement takes only a few minutes, whereas hydraulic equilibrium necessary for pressure apparatus measurements may take several weeks.

The applicability of pressure apparatus and dew-point potentiameter to peat soils is not given without additional testing as their physical and hydraulic properties differ in several aspects from mineral soils that might also cause methodological problems. Peat soils are characterized by a high amount of soil organic matter and by porosities up to 97% (Paavilainen and Päivänen, 1995). Depending on soil moisture, peat soils shrink and swell accompanied by changing pore space geometries. Dry peat soils are highly water repellent, mainly caused by the organic compounds (Doerr et al., 2000). Shrinkage and water repellency enhance hysteresis effects, and can be reversible or irreversible (Schwärzel et al., 2002).

Some studies measured WRC with pressure apparatus on different peat soils up to pF 4.2 (Boelter, 1969; Walczak et al., 2002). However, the contact between drain medium and sample during drainage may get lost because of shrinkage and hydrophobicity. As a result, samples would not be equilibrated. Different drain media in the PPA and PMA can influence the drainage of samples in dependence on changing pore space geometries and on extent of clogging, which can differ between drain media (Gubiani et al., 2013). To our knowledge no study compared the influence of different pressure devices and different drain media for peat soil measurements.

The classical procedure of a measurement sequence with a potentiameter is to prepare a set of samples with defined soil moisture by adding specific amounts of water to oven-dried samples (Decagon Devices Inc., 2015). Applying this procedure to peat soils may lead to enormous uncertainties because of hysteresis, water repellency and irreversible changes in the physical properties of peat soils because of drying. To our knowledge, neither the difference between measurements on originally field-moist and oven-dried peat samples using pressure apparatus or

dew-point potentiameter were compared in any study nor is any data of measurements with a dew-point potentiameter on peat soils published.

The aim of this study was to evaluate common methods to determine WRC of peat soils in the range of the permanent wilting point. We systematically compared the two pressure apparatus, PPA and PMA, and the dew-point potentiameter. Three peat types with different degrees of decomposition were tested, with the target moisture being reached by drainage of field-moist, or by wetting of oven-dried samples. The objective was to determine differences and uncertainties of different measuring techniques and to provide valuable information for deriving reliable WRC for peat soils.

MATERIAL AND METHODS
Peat Sample Description

The experiments in this study were conducted with three different types of peat soils originating from Finland and Germany. The Finish fen peat soil was sampled at grassland near Jokioinen (60.8°N lat., 23.5°E long.) in a depth between 25 and 47 cm. The degree of decomposition was classified as H4 on the von Post scale, which determines the degree of peat decomposition based on the consistency of the plant remains and the soil water color (Von Post and Granlund, 1926). The German site was located in the Donaumoos (48.5°N lat., 10.3°E long.), a fen in the south of Germany. One sample was taken at a grassland site (25 to 70 cm) and classified as H7 on the von Post scale. The second sample from the Donaumoos was amorphous peat (H10) and was sampled at a corn (*Zea mays* L.) field (0 to 30 cm). In the remainder of the paper, the decomposition states will be used as indicator of the sample origins. All investigated peat soils were mainly composed of sedges (*Carex spp.*).

Sample and Device Preparation

The experiments were conducted with either field-moist or oven-dried disturbed samples (80°C for 24 h). Soil aggregates after oven-drying were crushed and grinded by hand if aggregates were obviously too coarse to be rewetted properly. Afterward, oven-dried samples were saturated with tap water and equilibrated for 2 wk. During these 2 wk, soil particles lay in water without ponding and samples were mechanically mixed by hand periodically to foster equilibration. The field-moist samples were taken under wet conditions and could be used without any further treatment.

All samples were measured in the '08.03 Pressure Membrane Apparatus' (PMA) (Eijkelkamp, Giesbeek, The Netherlands) and the 'Pressure Plate Apparatus' (PPA) (Soilmoisture Equipment Corp., Santa Barbara, CA, USA) with three replicates each. For the measurements with the PMA the samples were packed in plastic cylinders with a diameter of 3.5 cm and a height of 1 cm. The samples were then placed on two sheets of nylon cloth and two sheets of cellophane, which have been saturated with tap water, by avoiding any air inclusion. Samples for the PPA measure-
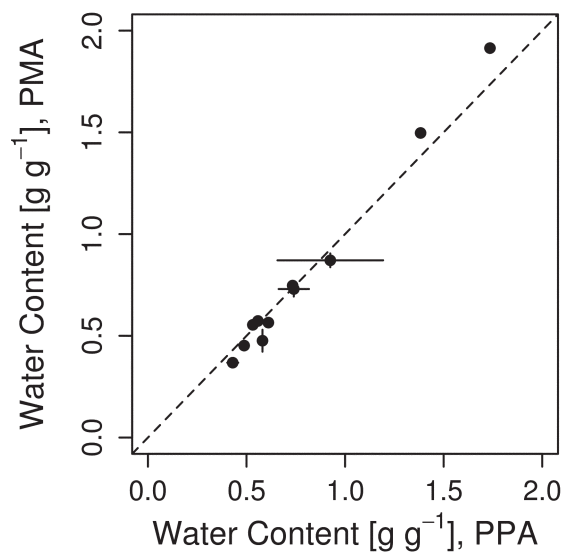
Fig. 1. Average gravimetric water contents (dots) with the corresponding standard deviation among replicates (lines) of all peat samples (three peat types and two pressure levels for both dried/rewetted and field-moist samples) measured by the Pressure Membrane Apparatus (PMA) and the Pressure Plate Apparatus (PPA). Dashed line represents the 1:1 line.

Fig. 2. Dew-point potentiameter (DPP) measurements plotted against Pressure Plate Apparatus (PPA) and Pressure Membrane Apparatus (PMA) measurements at defined pF values of 3.5 and pF 4.2 (pF: = log10(h), where h is the suction head, expressed in cm). The defined pF values are shown for the DPP as dotted lines. Bottom and top of the box are the lower and upper quartiles and the line in the middle of the box is the median. Whiskers indicate the minimum and maximum excluding dots that show values with a distance to the box that is larger than 1.5 times the interquartile range.

ments were packed in metal cylinders (diameter = 2.6 cm; height = 1 cm) and placed on a saturated porous ceramic plate.

Measurements

Measurements were taken at pF 3.5 and pF 4.2, corresponding to suctions of approximately 0.3 and 1.5 MPa, respectively. The pF unit is defined by pF: = log10(h) where h is the suction head, expressed in centimeters (cm), and is a convenient unit to express suctions that span orders of magnitude. We assumed equilibration when water drainage through the outlet had ceased for at least 4 d. The equilibration time for the samples at pF 3.5 was about 3 wk, and for the pF 4.2 samples 4 wk. During this time, the pressure was controlled every day and adjusted a few times because of slight loss of pressure. Directly after opening the PMA and PPA, samples were weighted and a subsample of each PMA and PPA sample was measured in the WP4C dew-point potentiameter (DPP) (Decagon Devices, Inc., Pullman, WA) and again weighted. The DPP was calibrated with a certified 0.5 mol kg^{-1} KCl salt solution. To avoid any staining of the mirror, the DPP sample cups were filled less than half. At the end of the experiment, samples were dried for 24 h at 80°C for the determination of θ_{grav}.

RESULTS AND DISCUSSION
Pressure Membrane Apparatus and Pressure Plate Apparatus comparison

Figure 1 shows the gravimetric water contents after equilibration at pF 3.5 and 4.2 for all peat samples. There are three key observations. (i) The error bars, which indicate the standard deviations between the replicate measurements, are generally small (with one exception being the field-moist H4 peat sample at a pressure of pF 4.2), indicating a good reproducibility of the mea-
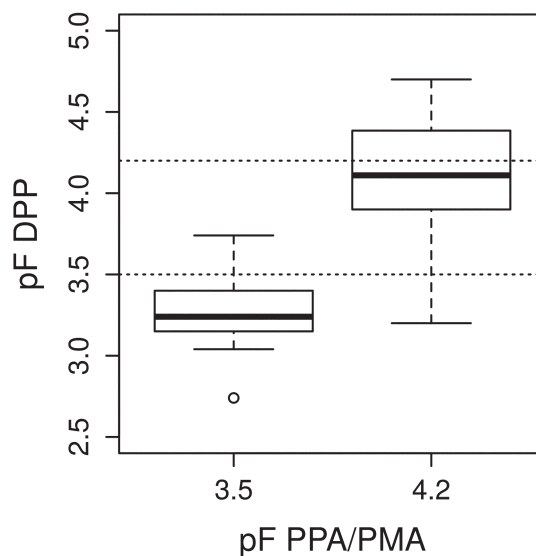
surements. Actually, the deviations measured by the PMA appear smaller compared with the PPA. (ii) The gravimetric water contents from PMA and PPA agree well, indicated by a coefficient of determination of $r^2 = 0.98$. (iii) For most of the wetter samples, there is a tendency to slightly higher water contents for the PMA measurements as compared with the PPA, whereas the contrary is observed for the samples with the lowest water contents. This trend is strongly affected by the two wettest soil samples. We can only speculate about possible reasons. One hypothesis would be a delayed and thus incomplete equilibration on the PMA due to smearing of the pores.

We did not observe any visual contact loss between samples and porous media because of the shrinkage of the peat samples at the end of all pressure apparatus experiments.

Pressure Devices and Dew-Point Potentiameter Comparison

The DPP measurements on samples reclaimed from the pressure devices at pF 3.5 and pF 4.2 are shown as boxplots in Fig. 2. Because PMA and PPA agreed well (coefficient of determination of $r^2 = 0.98$, see section Pressure Membrane Apparatus and Pressure Plate Apparatus Comparison above), we did not differentiate both devices when comparing the applied pF values with the DPP measurements.

The DPP measurements show a high variability for the two applied pressure levels. Furthermore, at pF 3.5, the DPP values were significantly lower than the established pressures at the pressure devices (student's t test: p-value$_{PPA, \text{ field moist}}$ = 0.013, p-value$_{PPA, \text{ rewetted}}$ = 0.013, p-value$_{PMA, \text{ field moist}}$ = 0.023, p-value$_{PMA, \text{ rewetted}}$ = 0.009). At pF 4.2, the mean of the DPP

measurements is in good agreement with the established pressure (p-value$_{PPA, \text{field moist}}$ = 0.1023, p-value$_{PPA, \text{rewetted}}$ = 0.833, p-value$_{PMA, \text{field moist}}$ = 0.159, p-value$_{PMA, \text{rewetted}}$ = 0.006).

Values higher than the applied pressures may indicate evaporative water loss from the surface layer of the samples during the transfer from pressure devices to DPP and the following DPP measurements. As we processed the samples immediately, we consider this uncertainty as inevitable and thus part of the DPP method. Values lower than the applied pressure are difficult to explain as samples seemed to be well equilibrated in the pressure devices. The fact that values of pF 4.2 were reached in average supports our observation that contact loss of peat samples in pressure apparatus are not as problematic as one might think from the shrinkage and hydrophobicity characteristics of peat.

Incomplete equilibration has been observed for fine-textured soils in Bittelli and Flury (2009) and Solone et al. (2012). Their results showed DPP pF values that were systematically lower than the applied pressures and deviations increased with increasing pressure, being highest for pF 4.2. So, for the high pressure in our study (pF 4.2), for which a systematic difference would be expected to be highest, we can conclude that peat samples equilibrated to the applied pressure in 3 to 4 wk (= until water outflow ceased for 4 d). We cannot explain why DPP measurements were on average lower for samples drained at pF 3.5, because we waited for equilibrium using the same rule (ceased outflow for at least 4 d) as for pF 4.2. For lower pressures, in fact, equilibrium should be reached faster because of higher hydraulic conductivities.

Field-Moist and Rewetted Samples Comparison

In Fig. 3, the gravimetric water contents are plotted against the two pressure levels established with the pressure devices. Results clearly show that $\theta_{\text{grav,field moist}}$ was higher than $\theta_{\text{grav,rewetted}}$ for all peat samples at the pressure range of this study.

The differences between $\theta_{\text{grav,field moist}}$ and $\theta_{\text{grav,rewetted}}$ are stronger for lower suctions (pF 3.5) and become less pronounced for stronger decomposed peat soil. For the least decomposed peat (H4), $\theta_{\text{grav,field moist}}$ was almost four times higher than $\theta_{\text{grav,rewetted}}$ at pF 3.5 and about two times higher at pF 4.2. For

the H7 peat soil, $\theta_{\text{grav,field moist}}$ was still about two times higher than $\theta_{\text{grav,rewetted}}$ at pF 3.5 but the difference decreased considerably toward pF 4.2. The H10 soil showed still systematic, but relatively small deviations between $\theta_{\text{grav,field moist}}$ and $\theta_{\text{grav,rewetted}}$. Also, variability between field moist replicates was highest for the least decomposed peat, whereas it was generally small for the crushed dried and rewetted samples.

The comparison of the field-moist and rewetted samples clearly reveals that the oven-drying of peat samples can cause extreme hysteresis effects. This can be attributed to the high hydrophobicity of dry organic material and irreversible changes in the soil matrix. This makes dried and rewetted samples unusable for the determination of field-relevant hydraulic properties. We emphasize that the magnitude of the hysteresis effect shown in Fig. 3 will probably depend on the choice of the drying temperature. Our choice (80°C) was a trade-off between incomplete drying and microbial alteration during longer drying periods expected at low temperatures (e.g., room temperature) and complete drying and charring occurring at high temperatures (e.g., 105°C, the standard drying temperature for moisture determination; see O'Kelly 2014, and references therein).

CONCLUSIONS

In this study, different methods were compared with determine water retention of peat samples near permanent wilting point. Although there is no reference method providing the true value for peat soils, first conclusions about the suitability of the tested methods can be drawn from our results.

The two investigated pressure apparatus showed consistent results without any substantial differences. Loss of contact between sample and drain media seemed not to be an issue for neither apparatus, as indicated by the good reproducibility of the samples' water contents within and between the two systems. We can recommend both apparatus for the determination of accurate WRC near permanent wilting point.

Measurements with the DPP showed some interesting results. First, the measured water potentials after equilibration in the PPA varied considerably. Second, the water potential in the
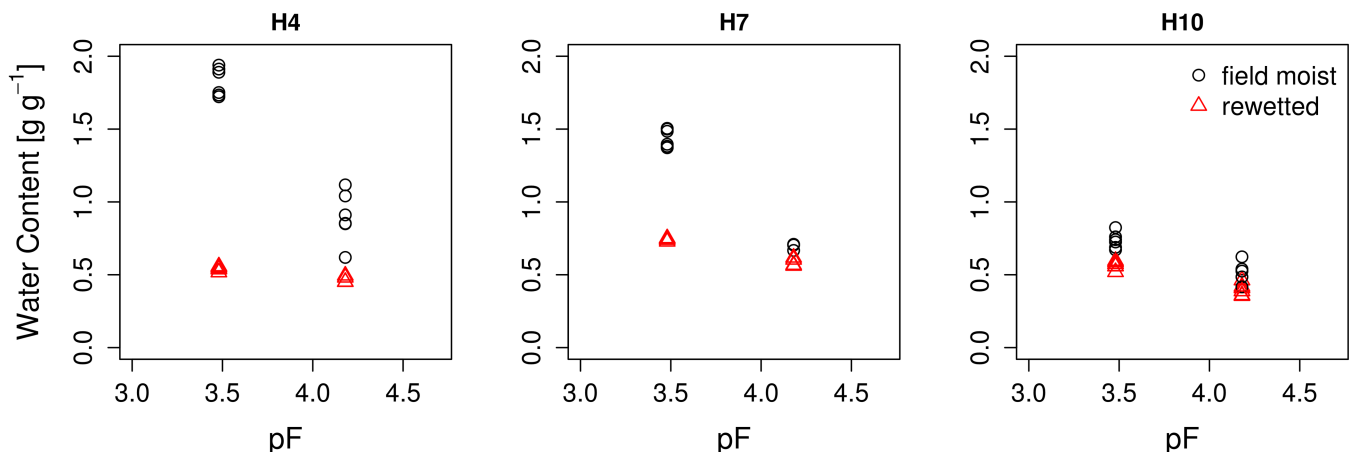

Fig. 3. Gravimetric water contents of rewetted and field-moist peat samples plotted against pF values applied at the pressure device from slightly decomposed (H4) to completely decomposed peat (H10). pF: = log10(h), where *h* is the suction head, expressed in centimeters (cm).

samples that were equilibrated at pF 3.5 was in most samples significantly higher (= lower pF) than expected. This was not the case for the pF 4.2 samples, and we do not know the cause. Third, drying at 80°C leads to an irreversible change of the WRC of the peat soil. Water contents at a given pF in dried and re-wetted samples are much lower than in natural ones. This effect was strongest for the least decomposed material. As a consequence, we conclude that the classical procedure of a DPP measurement for mineral soil, that is, to dry samples and to add specific amounts of water to the dry samples to establish defined soil moisture, cannot be applied to peat samples.

ACKNOWLEDGMENTS

REFERENCES

Bittelli, M., and M. Flury. 2009. Errors in water retention curves determined with pressure plates. Soil Sci. Soc. Am. J. 73:1453–1460. doi:10.2136/sssaj2008.0082

Boelter, D.H. 1969. Physical properties of peats as related to degree of decomposition. Proceedings. Soil Sci. Soc. Am. J. 33:606–609. doi:10.2136/sssaj1969.03615995003300040033x

Decagon Devices, Inc. 2015. WP4C- Dew Point PotentiaMeter, Operator's manual. Decagon Devices, Inc., Pullman, WA.

Deru, J., F. Lenssinck, I. Hoving, J. van den Akker, J. Bloem, and N. van Eekeren. 2014. Effect of submerged drains in peat meadows on soil quality and ecosystem services. Lois Bolk Institute, The Netherlands.

Dettmann, U., M. Bechtold, E. Frahm, and B. Tiemeyer. 2014. On the applicability of unimodal and bimodal van Genuchten–Mualem based models to peat and other organic soils under evaporation conditions. J. Hydrol. 515:103–115. doi:10.1016/j.jhydrol.2014.04.047

Doerr, S.H., R.A. Shakesby, and R.P.D. Walsh. 2000. Soil water repellency: Its causes, characteristics and hydro-geomorphological significance. Earth Sci. Rev. 51:33–65. doi:10.1016/S0012-8252(00)00011-8

Gee, G.W., Campbell, M.D., Campbell, G.S., and J.H. Campbell. 1992. Rapid measurement of low soil water potentials using a water activity meter. Soil Sci. Soc. Am. J. 56:1068-1070. doi:10.2136/sssaj1992.03615995005600040010x

Gubiani, P.I., J.M. Reichert, C. Campbell, D.J. Reinert, and N.S. Gelain. 2013. Assessing errors and accuracy in dew-point potentiameter and pressure plate extractor measurements. Soil Sci. Soc. Am. J. 77:19–24. doi:10.2136/sssaj2012.0024

O'Kelly, B.C. 2014. Water content determinations for peat and other organic soils using the Oven-Drying Method. Dry. Technol. 32:631–643. doi:10.1080/07373937.2013.849728

Paavilainen, E., and J. Päivänen. 1995. Peatland forestry: Ecology and principles. Springer, New York, MD. doi:10.1007/978-3-662-03125-4

Schelle, H., L. Heise, K. Jänicke, and W. Durner. 2013. Water retention characteristics of soils over the whole moisture range: A comparison of laboratory methods. Eur. J. Soil Sci. 64:814–821. doi:10.1111/ejss.12108

Schwärzel, K., M. Renger, R. Sauerbrey, and G. Wessolek. 2002. Soil physical characteristics of peat soils. J. Plant Nutr. Soil Sci. 165:479–486. doi:10.1002/1522-2624(200208)165:4<479::AID-JPLN479>3.0.CO;2-8

Solone, R., M. Bittelli, F. Tomei, and F. Morari. 2012. Errors in water retention curves determined with preassure plates: Effects on the soil water balance. J. Hydrol. 470-471:65–74. doi:10.1016/j.jhydrol.2012.08.017

Sreedeep, S., and D.N. Singh. 2006. Methodology for determination of osmotic suction of soils. Geotech. Geol. Eng. 24:1469–1479. doi:10.1007/s10706-005-1882-7

Tiemeyer, B., E. Albiac Borraz, J. Augustin, M. Bechtold, S. Beetz, C. Beyer, M. Drösler, M. Ebli, T. Eickenscheidt, S. Fiedler, C. Förster, A. Freibauer, M. Giebels, S. Glatzel, J. Heinichen, M. Hoffmann, H. Höper, G. Jurasinski, K. Leiber-Sauheitl, M. Peichl-Brak, N. Roßkopf, M. Sommer, and J. Zeitz. 2016. High emissions of greenhouse gases from grasslands on peat and other organic soils. Glob. Change Biol. 22:4134–4149. doi:10.1111/gcb.13303

Tubiello, F.N., R. Biancalani, M. Salvatore, S. Rossi, and G. Conchedda. 2016. A Worldwide assessment of greenhouse gas emissions from drained organic soils. Sustainability 8:371. doi:10.3390/su8040371

Von Post, L., and E. Granlund. 1926. Södra Sveriges Torvtillgångar I (Peat resources in southern Sweden I). Sver. Geol. Unders. C 335(19):1–128.

Walczak, R., E. Rovdan, and B. Witkowska-Walczak. 2002. Water retention characteristics of peat and sand mixtures. Int. Agrophys. 16:161–165.

Weber, T.K.D., S.C. Iden, and W. Durner. 2017. A pore-size classification for peat bogs derived from unsaturated hydraulic properties. Hydrol. Earth Syst. Sci. doi:10.5194/hess-21-6185-2017