Physical growing media characteristics of *Sphagnum* biomass dominated by *Sphagnum fuscum* (Schimp.) Klinggr.

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SUMMARY

The surface biomass of moss dominated by *Sphagnum fuscum* (Schimp.) Klinggr. (Rusty Bog-moss) was harvested from a sparsely drained raised bog. Physical properties of the *Sphagnum* moss were determined and compared with those of weakly and moderately decomposed peats. Water retention curves (WRC) and saturated hydraulic conductivities (K_s) are reported for samples of *Sphagnum* moss with natural structure, as well as for samples that were cut to selected fibre lengths or compacted to different bulk densities. The gravimetric water retention results indicate that, on a dry mass basis, *Sphagnum* moss can hold more water than both types of peat under equal matric potentials. On a volumetric basis, the water retention of *Sphagnum* moss can be linearly increased by compacting at a gravimetric water content of 2 (g water / g dry mass). The bimodal water retention curve of *Sphagnum* moss appears to be a consequence of the natural double porosity of the moss matrix. The 6-parameter form of the double-porosity van Genuchten equation is used to describe the volumetric water retention of the moss as its bulk density increases. Our results provide considerable insight into the physical growing media properties of *Sphagnum* moss biomass.

KEY WORDS: bog biomass, *Sphagnum* fibre, peat substitute, renewable growing media

INTRODUCTION

Sphagnum mosses are the primary peat-forming plants in northern peatlands (Kuhry & Vitt 1996). In Finland, *Sphagnum fuscum* (Schimp.) Klinggr. (Rusty Bog-moss) is the dominant species in ombrotrophic bogs (Laine *et al*. 2009). Being circumboreal and abundant in Fennoscandia (Laine *et al*. 2009), *S. fuscum* commonly thrives on mires and peatlands, which cover over 9 million hectares, *i.e*. one third of Finland's surface area (Marttila 2011). Despite these enormous natural resources, the horticultural use of *Sphagnum* mosses has not yet been closely examined, unlike that of peat. In Finland, few vegetable-growing trials have been conducted, and only small volumes of *Sphagnum* moss biomass have been available for use as a constituent of growing media (Reinikainen *et al*. 2012). However, there appears to be a consensus that *Sphagnum* moss offers a renewable alternative to peat in many horticultural applications (Whinam & Buxton 1997, Gaudig & Joosten 2002, Emmel 2008, Silvan 2010, Diaz & Silva 2012, Reinikainen *et al*. 2012, Jobin *et al*. 2014, Aubé *et al*. 2015, Pouliot *et al*. 2015). Much of the *Sphagnum* moss on the global market is harvested from natural bogs in Australia, Chile, China and the USA (Buxton *et al*. 1996, Whinam & Buxton 1997, Diaz & Silva 2012). *Sphagnum* fibres are mainly used as floral moss in orchid propagation and decoration, and on green roofs. To date, the lack of effective harvesting methods and suitable amphibious machinery has restricted the availability of Finnish *Sphagnum* moss (Reinikainen *et al*. 2012).

The first experiments on using *Sphagnum* moss as a growing medium for plants have yielded promising results (Emmel 2008, Oberpaur *et al*. 2010, Blievernicht *et al*. 2012, Reinikainen *et al*. 2012). Gaudig *et al*. (2008) demonstrated that the physical and chemical features of *Sphagnum magellanicum* Brid. are close to those of weakly decomposed peat. Successful plant growth trials were reported by Emmel (2008) and Reinikainen *et al*. (2012). The first of these authors grew *Tagetes patula* L. in growing media with different volumes of weakly decomposed peat replaced by *S. magellanicum* fibres without negative effect, and demonstrated an increase in the fresh weight of *Brassica napus* var. *chinensis* (L.) O.E. Schulz when it was grown in media with added *S. magellanicum*. Reinikainen *et al*. (2012) completed vegetable growth trials on *S. magellanicum*, *Sphagnum riparium* Ångstr. and

S. fuscum, as well as on a mixture of all three species, again with promising results. In line with the earlier statement of Jobin *et al*. (2014) about the capability of *Sphagnum* moss fibre to replace perlite in growing media, Aubé *et al*. (2015) reported that the moss had aeration properties comparable to those of perlite and discussed the true potential of moss to replace peat in horticultural applications.

Water holding capacity and pore size distribution are key properties of a horticultural growing medium. The water retention curve (WRC) depicts the functional relationship between water content (θ) and matric water suction (ψ), *i.e*. negative of matric water potential) under equilibrium conditions (Dane & Topp 2002). WRCs are usually referred to as drying curves. A drying WRC indicates the amount of water in a porous medium at equilibrium with increasing levels of suction. If the total porosity is known, the WRC can also be used to estimate the percentage of air-filled pores as a function of water content and allows predictions of the pore size distribution in a medium by expressing how much water is bound to the medium at a given pore-size-dependent strength (differential water capacity). The water retention properties of living *S. papillosum* and *S. capillifolium* were reviewed by Hayward & Clymo (1982), whereas an overview of water flow and retention in hummocks (*S. rubellum* Wils.) was provided by Price & Whittington (2010). WRCs are frequently used in soilless culture when estimating the availability of water to plants and for irrigation management. The WRC is the primary hydraulic property required for modelling water flow in soilless media (Raviv & Lieth 2008). WRC determination has been methodologically summarised by Dane & Topp (2002).

Water is retained in the tubular and angular pore spaces between the particles of growing media by capillarity, as well as in films on the particle surfaces by adsorption. In growing media, permanent wilting occurs at a suction head of around 3000 hPa (pF 3; pF is the logarithm of the suction head in cm of water/hPa) (Heiskanen 1993, Caron *et al.* 1998). In greenhouse and nursery production, yield drops can be expected at a matric suction of 50–100 hPa (pF 1.7–2) and even 30 hPa (pF 1.5) for coarser growing media (Lemay *et al.* 2012). The commonly accepted suction ranges in growing media are 10–50 hPa (easily available water) and 10–100 hPa (available water) (De Boodt *et al.* 1974). In this article, the latter range is adopted for ‘readily available water’ and indicates the suction range within which water availability is not limiting for plant growth, distinguishing it from higher suctions with ‘less readily available water’ (decreasing availability range) or ‘unavailable water’.

The aim of this study was to investigate the physical properties of *Sphagnum* moss biomass in the context of its use in growing media. While seeking to improve our understanding of the water retention properties of *Sphagnum* mosses in general, we determined complete water retention curves for Rusty Bog-moss at different levels of compaction.

METHODS

Collection of study materials

Sphagnum moss biomass was collected in September 2013 from sparsely drained (almost natural) raised bog at Neva-Lyly, Karvia, central Finland (62° 19.13' N, 22° 84.26' E), which lies in the transition between the southern-boreal and middle-boreal coniferous forest zones. Long-term (1983–2013) annual mean temperature at the site was 3.8 °C, annual mean precipitation was 612 mm, and the accumulative temperature sum (> +5 °C) was 1156 degree-days. The harvesting site was on the edge of a large raised bog with characteristics of both poor minerotrophy (lawns) and ombrotrophy (hummocks). The mire (vegetation) type of the harvesting site was low sedge *Sphagnum papillosum* Lindb. fen with large *S. fuscum* hummocks (Laine *et al*. 2009). The site displayed the typical surface patterning of boreal raised bog, with microtopographical elements ranging from relatively wet lawns to dry hummocks (Figure 1). The uppermost ~ 1.5 m of the peat deposit consisted of weakly decomposed *Sphagnum-Carex* peat with a surface layer of live *S. fuscum* (50 % cover), *S. magellanicum* (20 %), *S. papillosum* (10 %), *Sphagnum balticum* (Russ.) C. Jens. (10 %) and *S. rubellum* (10 %).

The Neva-Lyly site was chosen for its *Sphagnum* species composition and hydrology, which make it a representative example of slightly disturbed mires in Finland. These mires are appropriate sites for large-scale commercial harvesting of *Sphagnum* and it is, therefore, important to determine the growing medium properties of their *Sphagnum* moss material. Our research plan was based on the assumption that *Sphagnum* moss was most likely to be used in future as mixtures of the upper biomass layer. The moist moss material was harvested in parallelogram-shaped bales (approximate height 30 cm, width 25 cm, depth 25 cm) using a chainsaw. The bales were air-dried on growing tables under greenhouse conditions (no artificial lighting or air humidity control) and stored for 18 months in plastic cases in a greenhouse corridor. Weakly and moderately decomposed

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Figure 1. Neva-Lyly, a typical sparsely drained raised bog in Finland. An intact *Sphagnum* surface can be seen on the left, and a surface harvested three years previously on the right.

Sphagnum peats of Finnish origin without wetting agents, liming or fertilisers were used for comparison with the *Sphagnum* moss. Based on their stage of humification according to the von Post scale (H; von Post 1922) we refer to these as light (H2) and dark (H5) peat, respectively.

Experiment 1: The effects of fibre length and re-packing on water retention and hydraulic conductivity

Sphagnum moss was tested in the laboratory to establish its water retention curve (WRC) and saturated hydraulic conductivity (K_s) using samples with undisturbed (natural) structure as well as samples prepared by loosely re-packing pre-cut *Sphagnum* fibres (lengths 5 and 40 mm). Loosely packed light and dark peat served as additional control treatments. Three replicates of all experimental treatments were tested.

Sphagnum moss samples with natural structure were taken at an approximate depth of 10 cm (bale surface to upper face of sample), from the middle of the bale. Before sampling of the natural *Sphagnum* moss structure, the uppermost ~ 8 cm of the bale was removed by cutting horizontally. Samples were taken along the vertical orientation of fibres by gently pressing the sharp edge of a 200 cm^3 stainless steel soil sample cylinder against the moss fibres. As the edge delivered pressure to the fibres, these were rotationally cut from under the cylinder edge with a surgical blade. When the cylinder was deep enough to allow ~ 2 cm of fibres to protrude from its dull-edged end, the contained fibres that were still attached to the bale were cut with a knife approximately 2 cm below the sharp-edged end of the cylinder (Figure 2). The top and bottom of the sample were levelled using a knife.

To achieve sufficient precision for testing the effects of fibre length and re-packing of moss, fibres were cut to a target length using scissors. To facilitate re-packing, the growing media materials were first saturated with water and gently mixed on a clean plastic surface, taking care not to physically damage them. Nylon meshes were attached to the bottom sharp-edged ends of the soil sample cylinders with rubber bands. The cylinders were then loosely filled, with the mesh side held against a rigid plastic tray, by gradually adding one gram of the sample material at a time. No hand compaction or shaking was performed. The material was levelled by drawing a ruler across the upper edge of the cylinder. Our method differed from EN 13041 (the European standard; SFS-EN 13041) procedures by using 72.1 mm diameter cylinders instead of the standard 100 mm ones, so that we could fit all 15 cylinders into our equipment for measuring matric potentials at the same time. Also, the experimental materials were saturated prior to packing them into the cylinders and they were not compacted using another cylinder full of the same material.

Experiment 2: The effects of manipulating bulk density on the water retention and hydraulic conductivity of re-packed *Sphagnum* moss.

The effect of compacting to different bulk densities on water retention and K_s was examined with a series of gradually increasing bulk densities (40, 50, 60, 70 and 80 g dm^{-3}) in samples prepared as above but using *Sphagnum* moss cut to a 20 mm fibre length. All treatments had three replicates.

Figure 2. Cutting of the attaching fibres after driving a soil sample cylinder into a *Sphagnum* bale.

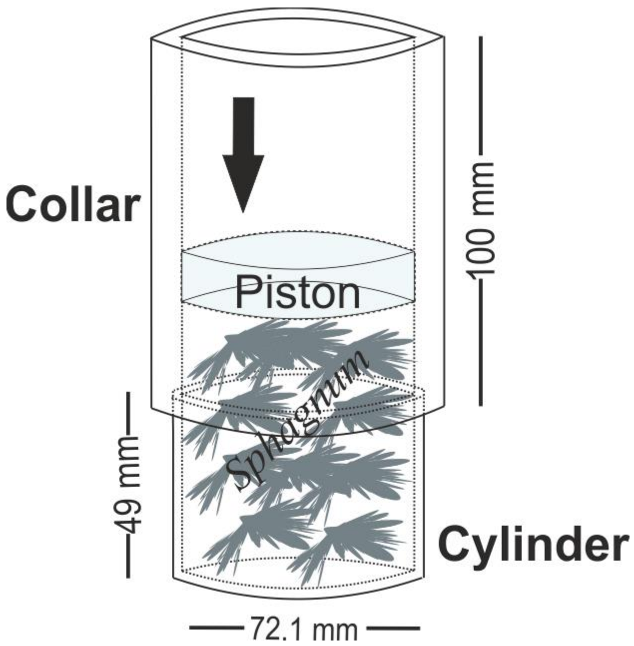

Figure 3. A schematic illustration of the cylinder, collar and piston. This set-up was used to compact *Sphagnum* in the soil sample cylinders to the required bulk density.

Different bulk densities in the cylinders were produced by oven drying (50 °C, 48 h) *Sphagnum* moss and weighing the amounts needed for each cylinder into separate re-sealable plastic bags (1 dm^3). We assumed that a short period of oven drying at low temperature would not significantly affect the physical structure of the *Sphagnum* moss, as *Sphagnum* hummocks in nature commonly desiccate as the atmospheric demand exceeds the upward transportation of water (Ingram 1978). Boiled and cooled tap water was then added to each bag (containing the material for one replicate) in a gravimetric ratio of one part *Sphagnum* moss to two parts water. The bags were equilibrated for seven days at room temperature during which they were frequently turned. This controlled rewetting appeared to restore the elasticity of the *Sphagnum* moss. To facilitate compression of the moss to the required bulk densities, a 100-mm-high non-deforming rubber collar with a similar inner radius to the soil sample cylinder was mounted on the cylinder (Figure 3), and a nylon mesh was attached to the bottom of the cylinder. The contents of a rewetting bag were then poured evenly into the collar. The compressing force was applied with a single slow and continuous press of a tightly fitting hand piston. The piston was kept in place for five minutes before removing it with the collar.

Measurements

Water retention curve (WRC)

The sample cylinders were saturated with pre-boiled and cooled tap water for 24 h in a plastic box in which the water level was kept at a height of 2.5 cm. During this time the tops of the cylinders were covered with a tray. The cylinders were then transferred to a sandbox (08.01 Sandbox Eijkelkamp) and water retention measurements at pF 0, 0.4, 1, 1.5, 1.8 and 2 (0, 2.5, 10, 30, 60 and 100 cm water column) were carried out as described by Dane & Topp (2002). The water retention capacity at pF 3 (1000 cm water column) was determined with a ceramic plate extractor (1500, Soilmoisture Equipment Corp.). Water content at pF 4.2 and 5.6 was determined as described by Dane & Topp (2002): approximately 1 g of air-dried sample material was placed in a desiccator containing saturated salt solution producing a known relative humidity (RH) and weighed after eight weeks (equilibrium was assumed). Saturated $(NH_4)_2C_2O_4$ with RH 99.0 % corresponded to pF 4.2, and saturated NaCl with RH 75.8 % corresponded to pF 5.6.

The volumetric water content (θ) was calculated using the equation:

$$\theta = \frac{V_w}{V_f} \qquad [1]$$

where V_f is the total volume of growing medium and V_w is the volume of water. Due to entrapped air and water draining as samples are moved, the water content determined at saturation (pF 0) in a sandbox can be somewhat imprecise. For this reason we estimated the total porosities from the determined particle and bulk densities, assuming no closed pores were present in the growing media, as suggested by Raviv & Lieth (2008). The total pore volume (ε_t) was calculated as:

$$\varepsilon_t = \left[1 - \left(\frac{BD}{DS}\right)\right] x100 \qquad [2]$$

where *BD* is the bulk density of the sample (g cm^{-3}) and *DS* is the density of solids (g cm^{-3}).

Based on the assumption of a bimodal pore-size distribution in *Sphagnum* moss (discussed later), a non-linear double-porosity model was fitted to the volumetric water content data. The double van Genuchten equation (van Genuchten 1980) is given by:

$$\theta = \left(\theta_{r_1} + \frac{\theta_{s_1} - \theta_{r_1}}{(1+|\alpha_1 \Psi|^{n_1})^{m_1}}\right) + \left(\theta_{r_2} + \frac{\theta_{s_2} - \theta_{r_2}}{(1+|\alpha_2 \Psi|^{n_2})^{m_2}}\right) \qquad [3]$$

where θ is the volumetric water content, ψ is the matric water suction, θ_s is the saturated water content, θ_r is the residual water content, α is the inverse of air entry suction and n is a pore-size distribution index. The use of the double van Genuchten function to model water retention has been discussed by Othmer *et al*. (1991) and Ross & Smettem (1993). Furthermore, Weber *et al*. (2017) discovered the trimodal pore-size distribution of *Sphagnum* moss and peat by using the triple van Genuchten equation. Here, the double van Genuchten equation was estimated with the Mualem (1976) constraint ($m = 1 - 1/n$) and by setting the residual water contents (θ_{r1}, θ_{r2}) to zero. These constraints led to a simple form of double equation with six adjustable parameters, including three parameters for the hydraulic properties of each individual pore matrix (explained later).

Saturated hydraulic conductivity (K_s)

After full saturation (pF 0) of the samples in a sand box, the cylinders were immediately tested for saturated hydraulic conductivity (K_s, cm h^{-1}) with a permeameter (09.02 Laboratory Permeameter, Eijkelkamp), using a constant head method. The hydraulic gradient (ΔH, cm) was measured individually for each sample. The flux density of water (J) was measured and K_s was derived using Darcy's law:

$$J = -K_s \frac{\Delta H}{\Delta s} \qquad [4]$$

where ΔH is the hydraulic head, Δs the sample length and $\frac{\Delta H}{\Delta s}$ the hydraulic-head gradient as given in Dane & Topp (2002).

Particle density, bulk density and specific surface area

Particle density was determined using the pycnometer method with deionised water as described by Dane & Topp (2002) (four replicates). The pycnometers were placed on an electric plate and the suspension was carefully boiled for 40 minutes to remove the air inside. The bulk densities of the samples in the soil sample cylinders were determined after water retention trials by dividing the dry mass by the cylinder volume. Consolidation and shrinkage were not considered. Specific surface area was determined using the water vapour sorption method and the BET equation presented by Brunauer *et al*. (1938):

$$\frac{p/p_0}{v(1-p/p_0)} = \frac{C-1}{v_m C}\, p/p_0 + \frac{1}{v_m C} \qquad [5]$$

where p and p_0 are the equilibrium and saturated pressures of adsorbates, v is the quantity of adsorbed gas and v_m is the monolayer adsorbed gas quantity. C is a BET constant:

$$C = exp\left(\frac{Q_1 - Q_v}{RT}\right) \qquad [6]$$

where Q_1 is the heat of adsorption for the first layer and Q_v is that for next and higher layers and equal to the heat of condensation. Following the procedures described by Niskanen & Mäntylahti (1987), approximately 1 g of air-dried material was accurately weighed (AND HM-202, A&D USA) into lidded crucibles. A 60-day equilibration period was completed in four desiccators containing different solutions with known relative partial pressure of water vapour p/p_0 (H_2SO_4 solution 0.10, saturated $KC_2H_3O_2$ 0.2, saturated $CaCl_2 \cdot 6H_2O$ 0.323, saturated $Zn(NO_3)_2 \cdot 6\,H_2O$ 0.42).

Microscopy observations

The desiccation of a *Sphagnum* branch was observed under a microscope (VMS-005-LCD, Veho, Southampton, UK). The stages of the drying process and the matric potentials corresponding to these stages were estimated by observing the tops of the *Sphagnum* moss samples with a bulk density of 50 g dm^{-3} during the water retention measurements (Experiment 2).

Statistical analyses

The water retention data were analysed by one-way analysis of variance (ANOVA) comparing both the volumetric and the gravimetric water contents of *Sphagnum* moss (natural, 5 mm and 40 mm), light peat and dark peat, at pF 1, 1.5, 1.8, 2, 3 and 4.2. The total porosities and K_s were similarly compared for Experiment 1. Furthermore, ANOVA was used to compare water retention at the different bulk densities tested in Experiment 2. The *p*-value required for a significant difference was set at < 0.05. Multiple comparisons of means were carried out using Tukey's (HSD) tests. SPSS 23 statistical software was used for the analyses (SPSS Inc., IL, USA), and curve fitting was implemented with the Excel solver function. The solver was used to vary a group of adjustable cells containing the function parameters until the sum of the squared deviations between the estimated and measured water contents over all ψ reached its minimum value.

RESULTS

Water retention curve and saturated hydraulic conductivity in natural and loosely packed moss (Experiment 1)

The volumetric water retention of *Sphagnum* moss at matric water suctions below 100 hPa (pF < 2) was generally lower than that of light and dark peat, excluding the suctions very close to saturation (Figure 4). From this point of view, the water retention of *Sphagnum* moss appears minor compared to both peat materials. *Sphagnum* moss with natural structure generally retained more water than loosely packed mosses. It also retained less water than the peats, except at pF 3, where the water retention was slightly higher than in light peat. Dark peat retained more water than light peat at all matric water suctions. The differences ($p < 0.05$) between the peats and between the peats and *Sphagnum* moss were significant up to pF 3 (Figure 5).

The total porosity of *Sphagnum* moss ranged from 97.4 % to 97.8 % with no significant differences. The total porosity of light peat (± SD) averaged 94.6 ± 0.23 % and differed significantly from that of dark peat (87.7 ± 0.10) %. The hydraulic conductivities (K_s) in *Sphagnum* were 2671 (± 1037), 1584 (± 784) and 1024 (± 719) cm h^{-1} for the samples with natural structure, 40 mm fibre length and 5 mm fibre length, respectively. There were no significant differences in K_s between the *Sphagnum* samples ($p = 0.134$), but K_s differed significantly ($p < 0.05$) between light and dark peat and averaged 350 (± 181) and 87 (± 44) cm h^{-1}, respectively.

The volumetric water retention curves are converted to their mass-based equivalents in Figure 6. From these curves it is evident that, on a dry matter basis, the water retention capacity of natural *Sphagnum* moss greatly exceeds that of light peat and

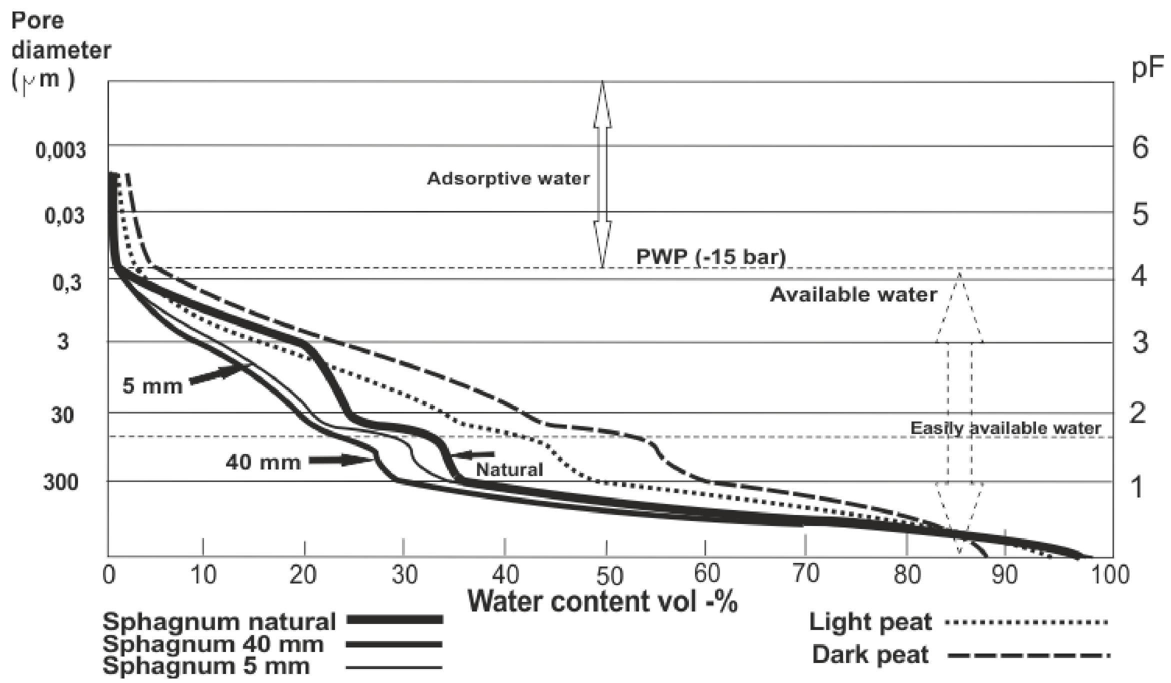

Figure 4. Volumetric water retention curves for *Sphagnum* moss, light peat and dark peat. *Sphagnum* moss was examined at fibre lengths of 5 and 40 mm and with a natural structure.

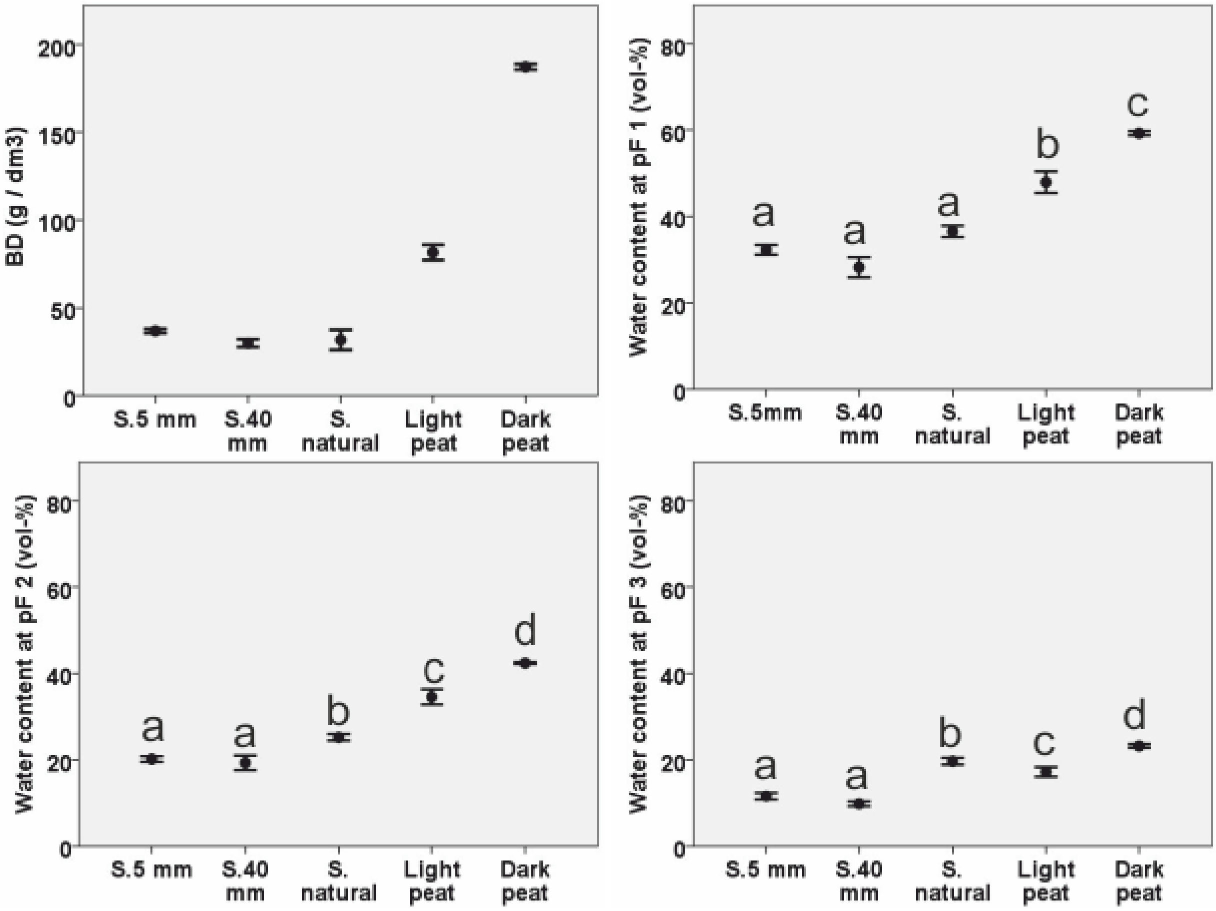

Figure 5. Bulk densities (*BD*) and volumetric water retention of experimental materials under differing matric potentials (pF1, pF2 and pF3). Means ± standard deviation (SD) are presented (n = 3). A different letter above the data point indicates a significant difference ($p < 0.05$). 'S.' on the x-axis denotes *Sphagnum* moss.

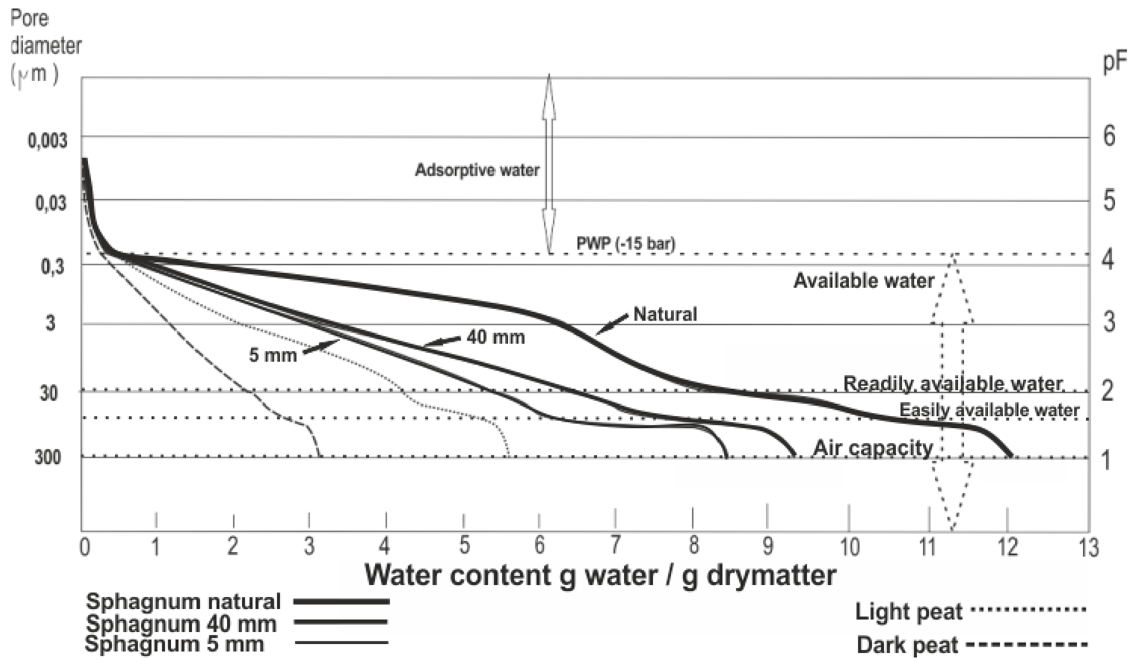

Figure 6. Gravimetric water retention curves for *Sphagnum* and peat samples. *Sphagnum* was examined at fibre lengths of 5 and 40 mm and with natural structure.

dark peat due to the large differences in bulk density between the three materials.

Effect of increasing bulk density on the water retention curve and saturated hydraulic conductivity of *Sphagnum* moss (Experiment 2)

Compacting the *Sphagnum* from a bulk density (*BD*) of 40 g dm^{-1} to 80 g dm^{-1} resulted in a severe reduction in its air capacity, *i.e*. in the difference between the total pore volume and the volume of water-occupied pores at pF 1. Increasing the bulk density increased the plant-available water in the growing medium and reduced its total porosity (Figure 7). Figure 8 depicts the volumetric water retention values as a function of bulk density. Concurrently, the saturated hydraulic conductivity (K_s) decreased steadily from 634 (± 123) cm h^{-1} to 93 (± 56) cm h^{-1} as the bulk density increased from 40 g dm^{-1} to 80 g dm^{-1}.

Bimodal function for the water retention curves of *Sphagnum* moss at different bulk densities

The curve estimated using the double van Genuchten (DvG) equation provided a good fit to the data at all bulk densities. The goodness of fit was quantified in terms of the root mean square error (RMSE), defined as:

$$RMSE = \sqrt{\frac{1}{N}\sum\left(\theta_{measured} - \theta_{fitted}\right)^2} \qquad [7]$$

Table 1 summarises the results of fitting the DvG equation and presents the estimated DvG parameters for different bulk densities. Averaged experimental data for different bulk densities with the fitted DvG curves are presented in Figure 9. The shapes of the pore size distribution functions clearly reveal bimodal pore distributions in the *Sphagnum* moss. Increasing the bulk density reduced the volume of large pores in the growing media. This can be seen from the increasing value of the estimated DvG parameter θ_{s2} at the expense of θ_{s1}.

Particle density and specific surface area

The particle densities of *Sphagnum*, light peat and dark peat averaged 1.410 (± 0.074), 1.519 (± 0.068) and 1.523 (± 0.078) g cm^{-3}, respectively; while the specific surface areas of *Sphagnum*, light and dark peat averaged 314, 310 and 257 m^2 g^{-1}, respectively.

Microscopy observations

The *Sphagnum* branch observed under a microscope appeared to undergo desiccation in two stages (Figure 10). The photographs illustrate capillary water flow from spaces outside the *Sphagnum* fibre (a to c) followed by water flow from pores inside the *Sphagnum* fibre (d to f). Figure 10d presents a situation where the suction force has exceeded the water retention energies of a few hyaline cells, which have thus emptied. This can be discerned from the changed appearance (more defined and transparent) of the cells inside the black square.

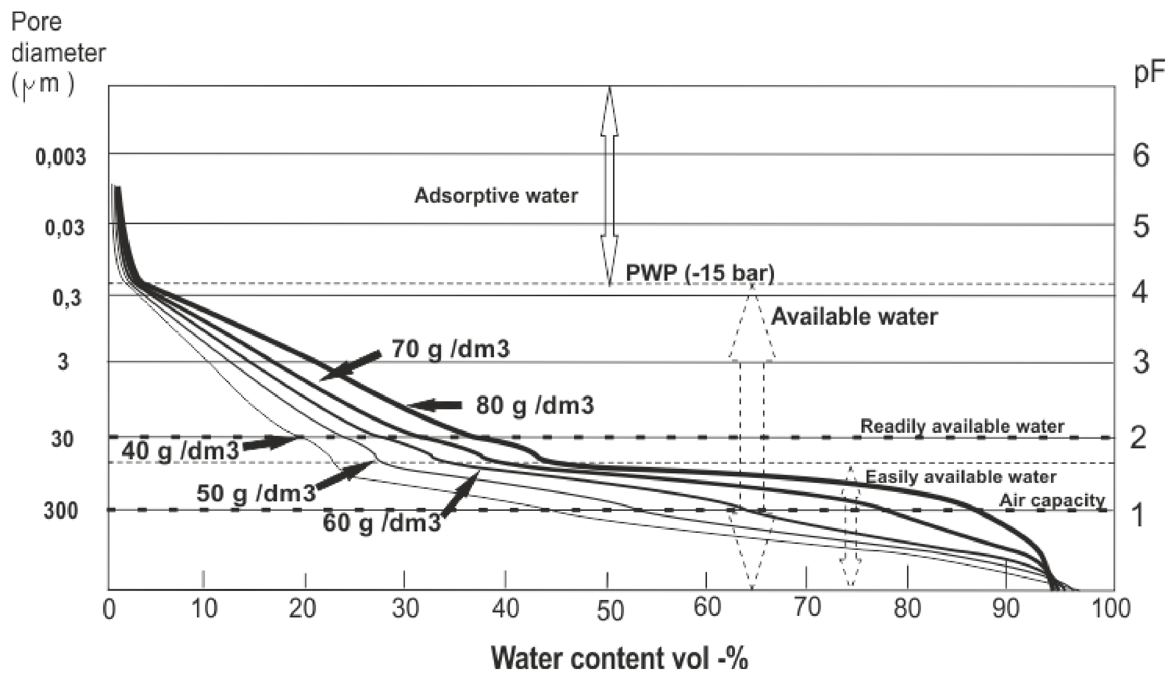

Figure 7. Water retention curves for compacted *Sphagnum* samples. The bulk densities ranged from 40 to 80 g dm^{-3}.

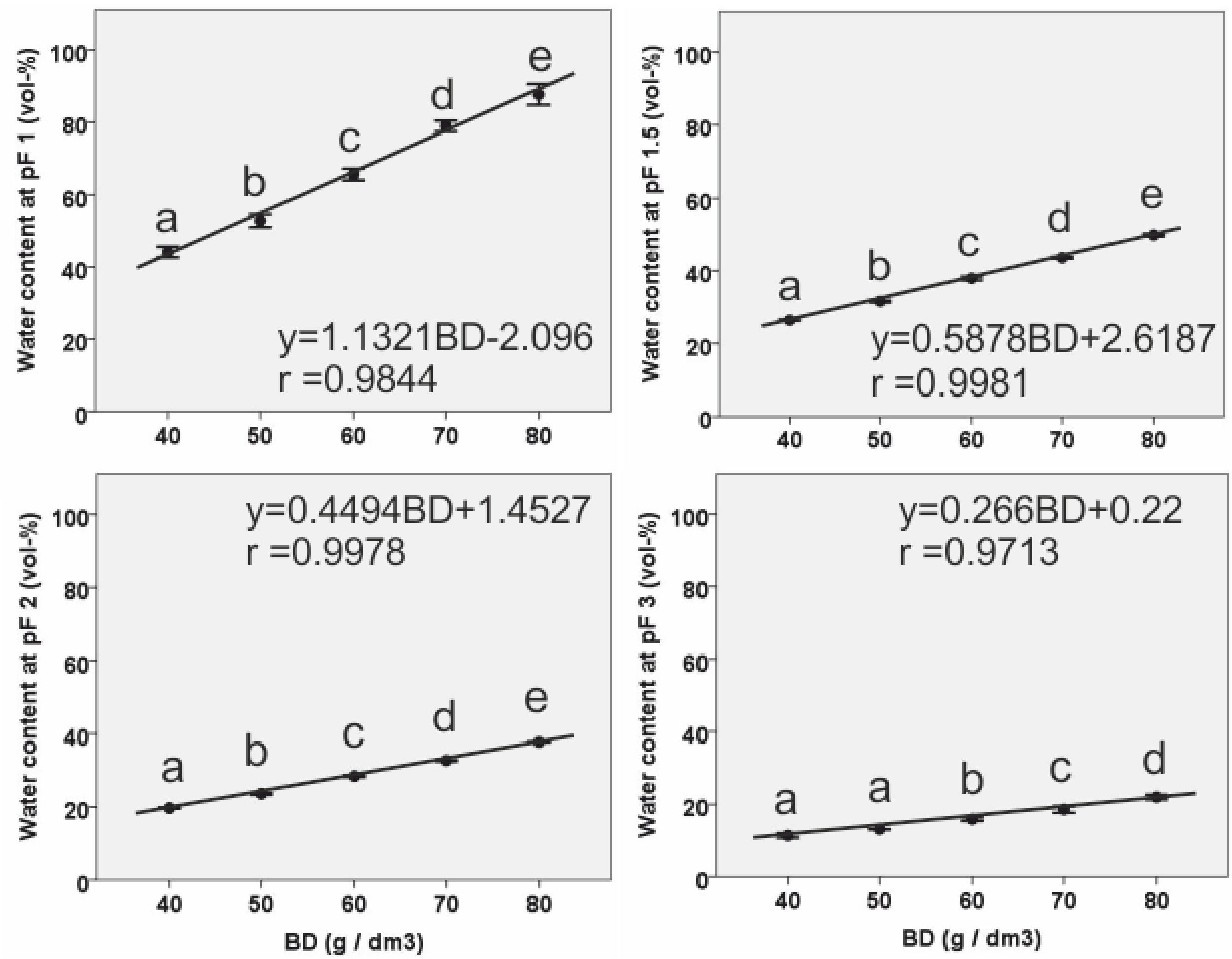

Figure 8. Volumetric water content of *Sphagnum* samples (*BD* 40 to 80 g dm^{-3}) at pF 1, 1.5, 2 and 3. Means ± standard deviation (SD) are presented (n = 3). Significant ($p < 0.05$) differences in water content between different bulk densities are indicated by different letters above the data points.

Table 1. Variation in hydraulic conductivity (K_s) and in double van Genuchten (DvG) WRC function parameters (θ_{s1}, θ_{s2}, α_1, α_2, n_1, n_2) (Equation 3) with bulk density (*BD*). The r and RMSE columns present the fitting values for the equation; r is the linear correlation between the measured data points and estimated points (n = 8). Bulk densities, K_s values, estimated parameters and fitting values are averages (n = 3). The standard deviation is given in parentheses.

BD (g dm^{-3})	K_s (cm h^{-1})	θ_{s1}	θ_{s2}	α_1 (hPa^{-1})	α_2 (hPa^{-1})	n_1	n_2	r	RMSE
39.98 (0.56)	634 (123)	0.828 (0.048)	0.143 (0.050)	0.382 (0.099)	0.00105 (0.0005)	1.793 (0.224)	1.847 (0.13)	0.9998	0.0081 (0.0044)
49.92 (0.25)	393 (154)	0.816 (0.034)	0.148 (0.035)	0.310 (0.035)	0.00093 (0.0004)	1.660 (0.106)	1.836 (0.13)	0.9996	0.0118 (0.0051)
59.69 (0.39)	286 (160)	0.753 (0.006)	0.196 (0.007)	0.176 (0.008)	0.00104 (0.0002)	1.750 (0.030)	1.774 (0.04)	0.9992	0.0179 (0.0025)
69.46 (0.10)	155 (86)	0.604 (0.001)	0.334 (0.006)	0.081 (0.004)	0.00205 (0.0004)	2.794 (0.132)	1.691 (0.04)	0.9994	0.0158 (0.0037)
79.83 (0.75)	93 (56)	0.539 (0.009)	0.397 (0.005)	0.061 (0.007)	0.00204 (0.0001)	3.449 (0.412)	1.693 (0.01)	0.9994	0.0158 (0.0019)

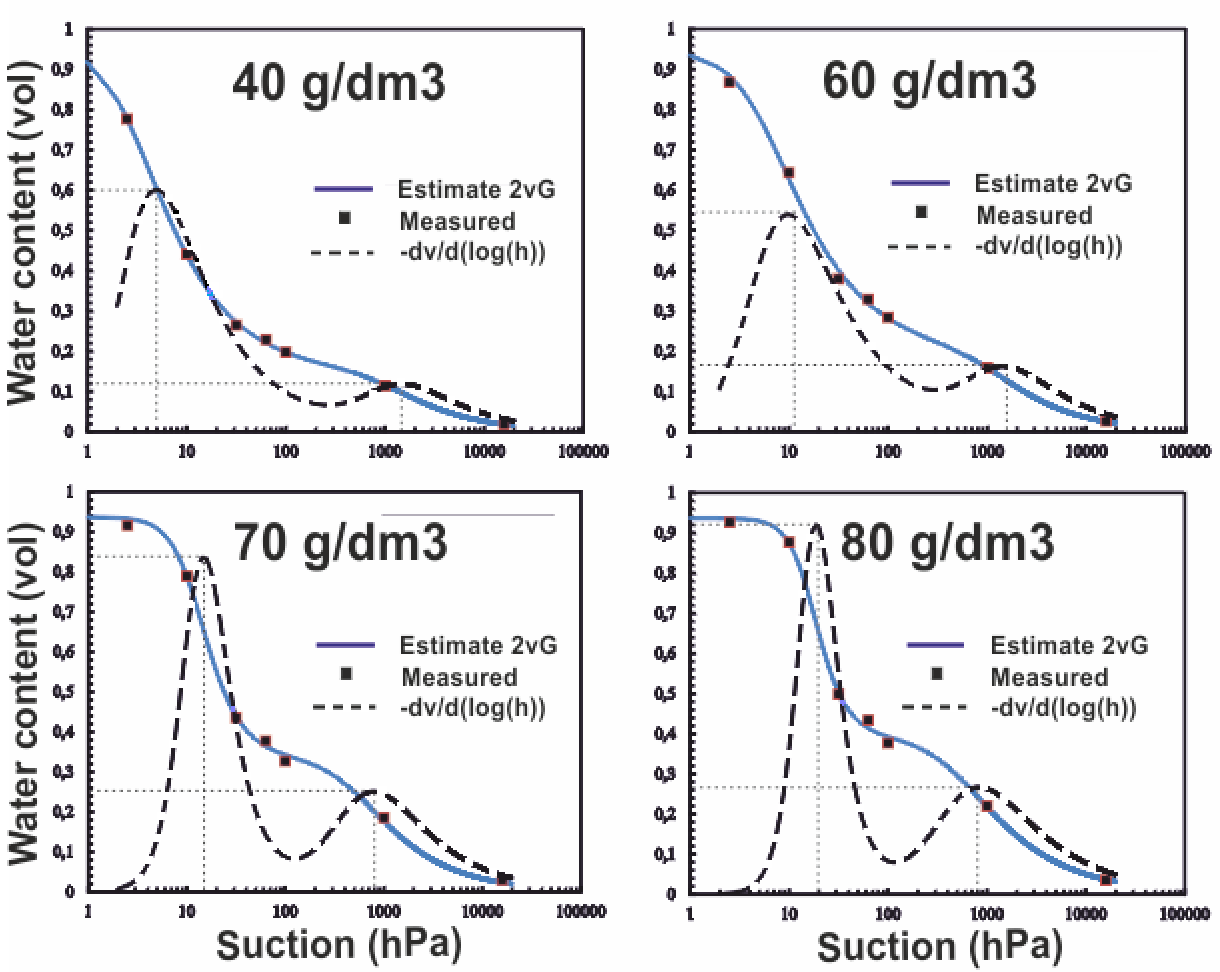

Figure 9. The fitted double van Genuchten models (solid blue curves) with measured experimental values (points) and the pore size distribution functions (-dv/d(log h); dashed black curves) for four different bulk densities. Two points of inflection in the WRC function, *i.e.* points where the curvature of the function changes its sign, indicate the presence of two distinctive pore size ranges in *Sphagnum*. The matric water suction corresponding to the modal pore sizes of the two ranges can be estimated from the positions of the maxima of the pore size distribution curve on the x-axis (dotted lines).

DISCUSSION

The *Sphagnum* biomass dominated by *S. fuscum* (Rusty Bog-moss) is characterised by highly valued physical growing media properties, namely: low bulk density, high free air space and high water holding capacity. Horticultural growing media are often chosen for either aeration or water retention (Raviv & Lieth 2008, Michel 2010). *Sphagnum* moss has favourable attributes for both and, thus, great potential for use as a growing medium or as a base material for growing media mixtures.

We found that the gravimetric water retention capacity for *Sphagnum* moss was higher than for the two investigated peats, and that its volumetric water holding responses to compaction were linear between pF 1 and pF 3 (matric water suction 10–1000 hPa). This indicates that *Sphagnum* moss can be used in peat-based growing media either to increase air-filled porosity (previously termed ‘air capacity’) or to increase water retention, depending on the bulk density. However, it is uncertain whether the total gas exchange in peat-based mixtures can be described in terms of air-filled porosity alone. This was discussed by Caron *et al.* (2005, 2010), who showed that oversized *Sphagnum* particles are potentially disadvantageous to gas exchange in growing media because they may increase total porosity but simultaneously hamper aeration by creating isolated or poorly interconnected air pockets. The effects of *Sphagnum* fragment size, bulk density and matric potential on growing medium ventilation remain a

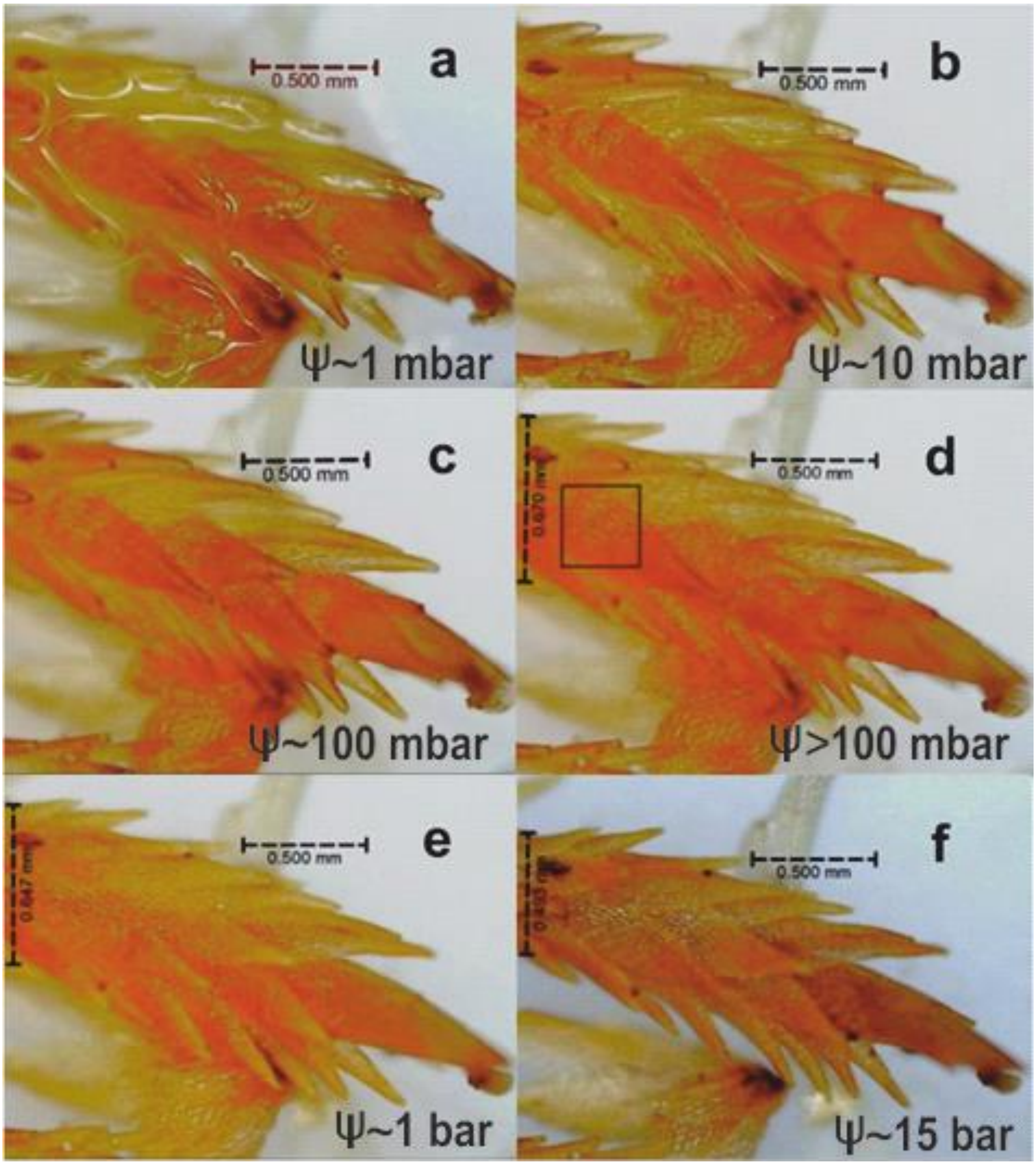

Figure 10. Microscopy observations of a *Sphagnum* branch subjected to increasing matric water suctions ψ, *i.e*. undergoing desiccation from a saturated state (a) to the permanent wilting point (f). The unit used here for the matric water suction (mbar) is equivalent to 1 cm (height of the water column). The black square in (d) indicates part of a branch leaf where hyaline cells have been emptied of water and become transparent.

topic for future research. However, in the context of plant production applications, one noteworthy point indicated by our findings is the possibility that the storage of plant-available water in light peat could be matched by using compacted *Sphagnum* moss containing a smaller amount of dry matter. The use of compacted *Sphagnum* moss could be beneficial in manually irrigated commercial set-ups, where maintenance costs correlate strongly with watering frequency.

Bimodal porosity and *Sphagnum* water retention

This study suggests that the bimodal water retention of *Sphagnum* moss can be regarded as the sum of water retention in its two pore matrices. As the double van Genuchten model was fitted to water retention data, the obtained parameters θ_{s1} and θ_{s2} (Table 1) indicated the saturated water content of each pore system, *i.e*. the volumes of the matrices of larger and smaller pores, respectively, when saturated. Furthermore, the pore size distributions in the two pore matrices were revealed by the -d/dv(log h) function (Figure 9). At this point, we assume the primary pore matrix to be comprised of elongated and different-sized hyaline cells (Laine *et al*. 2009, page 61) along with other smaller-diameter pores inside the *Sphagnum* moss fibres, and the secondary pore matrix to consist of the large pores between *Sphagnum* moss fibres. This is in line with the recent findings of Weber *et al*. (2017), who discovered a trimodal pore size distribution in *Sphagnum* by modelling its unsaturated hydraulic properties. Furthermore, Weber *et al*. (2017) divided the secondary matrix into two parts which they referred to as inter- and intra-plant pores. Our data suggest that the secondary matrix of *Sphagnum* moss consists of pores which empty, at the latest, at a matric water suction of 100 hPa. The diameter of pores ($2r$, µm) corresponding to the matric water suction ψ (cm water column) can be approximated using the capillary equation after McLay *et al.* (1992):

$$2\,r = \frac{3000}{\psi} \qquad [8]$$

Hence, the secondary matrix in *Sphagnum* moss can be thought of as consisting of pores with $2r > 30$ µm, while the primary pores are smaller. It should be noted that the capillary equation (like the related models of water flow) assumes the matric potential to arise from capillary forces only, in capillaries that are either full of water or empty. Thus, it relies on a simplified representation of the pore space, as a bundle of cylindrical capillaries. Figure 10 clearly shows the irregularity of pore geometry in the outer (secondary) matrix, and an actual case where reducing matric potential by a certain amount did not empty the whole pore space at once. Our microscope observations revealed an effective corner flow network (see Hoogland *et al.* 2016) in the secondary matrix of drying *Sphagnum* until the matric suction value reached 100 hPa (pF 2), thus determining a similar suction range of 'readily available water' to that in growing media as conventionally understood in horticulture. However, it seems that most of the water in *Sphagnum* growing media is exploitable by plant roots under severe drought conditions (Kämäräinen, unpublished). When the residual liquid-phase water (trapped mostly in hyaline cells) is released, it can be assumed to move towards regions of lower chemical potential (*e.g.* plant root hairs) mostly *via* water films at significantly slower rates than in straight capillary tubes. This concept was described by Tuller & Or (2001) who proved the dominance of film flow over capillary flow in full pores and corners of different types of mineral soil particles at matric suctions between 1 and 3 bar (15,000–45,000 hPa). The corner and film flow concept, presented by Tuller & Or (2001) and recently extended by Hoogland *et al.* (2016), together with the irregular geometry of the secondary pore matrix in *Sphagnum*, seems to explain the rapid decrease in K with increasing matric suction, as presented by Price *et al.* (2008) among others.

According to Hayward & Clymo (1982), the water in a living *Sphagnum* moss carpet moves upwards through the extremely effective capillary system of the secondary pore matrix formed by the overlapping hanging branches against the stem, then water from the secondary pores enters the primary matrix of hyaline cells. We confirmed this through microscopy (Figure 10) and propose that the primary pore matrix of *Sphagnum* moss is dependent on the secondary one in terms of water supply. The inability of the stem tissue of *Sphagnum* moss to perform a water-conducting function was noted by Cavers (1911) and confirmed by Hayward & Clymo (1982). This was perceived to apply to *S. fuscum* stems in our microscopy observations.

***Sphagnum* drying process**

To better comprehend the WRCs presented here, the water release from an individual branch structure can be broken down into two consecutive stages:

(1) When the matric water suction is close to 1 hPa the *Sphagnum* moss particles are fully enclosed in water films. Water is present between the particle structures and between individual particles (Figure 10a). As the matric water suction approaches 10 hPa (pF1), the surrounding water has mostly drained. Visible films of capillary water remain at the angles of fibres and in the smaller-diameter spaces of the secondary matrix (Figure 10b). This leaf–water interaction is regarded as a mechanism that enables efficient capillary water movement in the living *Sphagnum* carpet (Hayward & Clymo 1982): as the matric potential in *Sphagnum* decreases, the increasing hydrostatic suction between the partly overlapping leaves pulls them together, thus creating smaller pores with increasing water

retention in the thinning water film around the plant structure. At matric water suctions approaching 100 hPa (pF2), the secondary matrix has been mostly drained of visible water. Thin water films remain around the plant material, keeping the primary matrix filled. This can be seen from the swollen form of the *Sphagnum* structure and the dark appearance of its hyaline cells (Figure 10c).

(2) As drying continues, the surrounding water films are eventually withdrawn and the hyaline cells start to release their contents to the surrounding secondary matrix (Figure 10d). The hyaline cells appear more defined and transparent when emptied (Figure 10e). According to Hayward & Clymo (1982), they empty at a matric water suction of approximately 1000 hPa (pF3). Such previous estimates agree well with our determination of average pore size in the primary matrix of *Sphagnum* moss. As desiccation continues, the rest of the water is drawn out from the smallest primary pores. The second stage of drying appears to contribute to the lighter appearance of dry *Sphagnum* (Figure 10f), described as "white and papery" by Hayward & Clymo (1982). Drying-induced shrinkage of the moss seems to take place as the primary matrix empties.

The hyaline cell wall structure of *Sphagnum* is known to be durable and can remain preserved far into the decomposition process (Puustjärvi 1973). The progress of peat formation is described by Nieminen & Reinikainen (2011), who report that recognisable cell structures gradually scatter and finally disappear between the decomposition stages H5 and H7 (von Post 1922). We observed substantially greater gravimetric (mass-based) water retention in *Sphagnum* moss than in peats. Thus, we conclude that this physical phenomenon is a consequence of the interaction between undamaged primary and secondary pore matrices explained above. The mass-based water retention potential becomes inevitably smaller as these pore matrices become damaged during the decomposition process.

Effect of compaction on water retention

The effects of compaction on the behaviour of water in *Sphagnum* moss growing media are most logically understood by focusing on the changes in pore sizes and the volumetric relationships between primary and secondary pore matrices. As the dry bulk density increases from 40 to 80 g dm^{-3}, the volume of primary (within plants) pores *per* unit volume of the growing medium simultaneously doubles. If this assumption is valid, the volume of water retained by the corresponding pore sizes in the growing medium should also double. This was confirmed by the measured volumetric water contents of the samples at a matric water suction of 1000 hPa (pF 3) (Figure 8). However, the pore size distribution functions for bulk densities in the range 40–80 g dm^{-3} (Figure 9) indicated an apparently illogical decrease in the suction corresponding to the average pore size, from 1289 to 834 hPa. This would suggest an increase in the average pore diameter in the primary matrix from 2.3 to 3.6 µm. Nonetheless, we propose that compacting from 40 to 80 g dm^{-3} does not severely alter the sizes of existing primary pores within plants. The detected change seems to result from modification of the overlap between the pore sizes of the two matrices by compaction, *i.e*. compaction causes the smallest of the secondary pores to be interpreted as large primary ones. The greater than two-fold increase (from 0.143 to 0.397, Table 1) in the DvG factor θ_{s2} (reflecting the volume of the small-scale primary pore system) can be similarly explained. Concurrently with these compaction-induced changes in the primary matrix, the average pore size in the secondary matrix diminished as expected: the average matric water suction at bulk densities in the range 40–80 g dm^{-3} was 5–19 hPa. This corresponds to a change in the average diameter of secondary pores from 600 to 157 µm.

We conclude that the quantity of primary pores in *Sphagnum* moss growing media is defined by the amount and quality of *Sphagnum* moss used, whereas the size and number of secondary pores can be adjusted by compaction. The six-parameter form of the double van Genuchten equation served the purpose of this study well. However, the systematic change in some of its parameters resulting from progressive compaction suggests that it may be possible to elaborate a common WRC equation for all bulk densities. Further research is needed to obtain a general water retention model that takes into account the effects of compaction on both pore matrices.

Effect of fibre length on water retention

Our gravimetric water retention measurements at low bulk densities (Figure 6) suggest that, at similar matric water suctions, longer moss fibres can hold more water than the same dry weight of shorter fibres. However, significant differences between cut samples (5 mm and 40 mm) were not detected in volumetric water retention trials (Figure 5). This can be explained by the greater average bulk density of 5 mm samples (+8 g dm^{-3}). In other words, similar testing at equivalent low bulk densities would probably yield slightly greater water retention for

40 mm than for 5 mm *Sphagnum* moss fibre at matric water suctions of less than 15 bar. The more detailed effects of *Sphagnum* fibre length and orientation on water retention and distribution in the growing medium remain topics for future research.

Saturated hydraulic conductivity (K_s)

Through its growth pattern, *Sphagnum* moss creates long and vertically-oriented macropores in hummocks. This explains the high saturated hydraulic conductivity (K_s) of our *Sphagnum* moss samples with natural structure (average value ~ 7×10^{-3} m s^{-1}). This is even higher than the K_s in the topmost layer of living *S. rubellum* (> 10^{-3} m s^{-1}) reported by Price & Whittington (2010). Cutting and mixing of the *Sphagnum* fibres resulted in lower K_s values. Altering fibre orientation and size seems to reduce K_s when compared to the natural structure. However, the generally high K_s of *Sphagnum* indicates that the pore connectivity and, thus, gas diffusion are efficient (Caron & Nkongolo 2004). The collapse of macropores in the decomposing *Sphagnum* structure was discussed by Johnson *et al*. (1990) and by Wallén & Malmer (1992), and explains our result that K_s was higher in *Sphagnum* moss than in peat. In our trials, K_s decreased predictably with compaction. The strong decrease in K_s with increasing bulk density can be explained by the increased volume of dead-end pores (primary matrix) blocking the flow and by the compaction-induced reduction in the average diameter of secondary pores. The compacted samples differed from the samples of natural structure in terms of fibre orientation and size. Along with the degree of compaction, these attributes are linked to hydraulic conductivity in growing media (Caron *et al.* 2010).

Our results provide considerable insight into the physical properties of *Sphagnum* moss biomass as a constituent of growing media. They may be more generally extrapolated to growing media based on other *Sphagnum* species, although with some caution. Our material mainly contained the hummock species *Sphagnum fuscum*, which is smaller in size than some lawn and hollow species (*e.g. S. magellanicum*) (Schipperges & Rydin 1998) and has a greater capitula density (Gunnarsson & Rydin 2000). These properties have been shown to result in a higher water retention capacity among *Sphagnum* species (Luken 1985). Further research is needed to evaluate the effects of different *Sphagnum* species on the water retention properties of growing media. Furthermore, we believe that reporting the properties of *Sphagnum* moss growing media in terms of both volume and dry mass would make the special features of this porous and elastic material more comprehensible.

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