Recommendations for successful establishment of *Sphagnum* farming on shallow highly decomposed peat

Amanda Grobe[1], Bärbel Tiemeyer[2], Martha Graf[3]

[1] Institute of Environmental Planning, Leibniz University Hannover, Germany
[2] Thünen Institute of Climate-Smart Agriculture, Braunschweig, Germany
[3] Lower Saxony State Department for Mining, Energy and Geology (LBEG), Hannover, Germany

SUMMARY

Sphagnum farming aims to produce peat moss fibres for horticultural growing media or founder material for bog restoration. The objective of this study was to examine the establishment of *Sphagnum* on cut-over bog with shallow layers (average 78 cm) of highly decomposed "black peat" under different hydrological starting conditions. One of the two study sites in northwestern Germany was established directly after peat extraction, while the other one has been rewetted 7 years prior to its installation. Irrigation ditches were installed on these sites for water management. *Sphagnum* fragments were introduced and covered with straw mulch or geotextile for protection. The establishment of *Sphagnum* and the site conditions, including vascular plant growth, were evaluated to determine the supporting and limiting factors for *Sphagnum* farming under the difficult hydrological conditions of shallow highly decomposed peat (low porosity, low hydraulic conductivity). The cultivation of *Sphagnum* mosses is possible on shallow layers of highly decomposed peat. *Sphagnum* growth in cover and carpet thickness was significantly higher at the site that had previously been rewetted and had a thicker layer of residual peat. The areas covered with a geotextile showed significantly lower percentages of *Sphagnum* cover compared to those covered with straw mulch. While sufficient water quantity and quality are known to be prerequisites for *Sphagnum* farming, a sufficient peat layer thickness seems to be an additional factor for successful *Sphagnum* establishment and growth. Maintaining an optimal water table proved to be a challenge for these shallow layers of highly decomposed peat, as the low hydraulic conductivity of the peat has impeded a complete irrigation of the sites. Furthermore, the irrigation effort might need to be increased to compensate for additional water loss into the subsoil. On such sites with difficult hydrological and soil conditions, a favourable microclimate provided by vascular plants and a rewetted surrounding area can promote successful establishment of *Sphagnum* and can even partially counterbalance effects of a low water table.

KEY WORDS: alternative substrates, biomass, paludiculture, peat moss cultivation, water management

INTRODUCTION

Sphagnum mosses are known to have several remarkable properties for a variety of applications (Pouliot *et al.* 2015, Glatzel & Rochefort 2017, Gaudig *et al.* 2018). *Sphagnum* biomass is a promising alternative to fossil peat. Several horticultural trials have shown that it has nearly identical physical and chemical properties as "white peat" and could thus successfully substitute peat in growing substrates (Emmel 2008, Oberpaur *et al.* 2010, Reinikainen *et al.* 2012, Jobin *et al.* 2014). It is therefore increasingly sought after as raw material and expected to have a future as a renewable, high quality constituent of horticultural growing media (Pouliot *et al.* 2015, Gaudig *et al.* 2014, 2017). Furthermore, fragments of living *Sphagnum* can be used as founder material (also known as donor material) in bog restoration sites to initiate and accelerate the revegetation as well as to restart peat accumulation again (Quinty & Rochefort 2003, Robroek *et al.* 2009, González & Rochefort 2014, Karofeld *et al.* 2016, Caporn *et al.* 2018). Growing *Sphagnum* as founder material for restoration projects is especially important in countries where undisturbed mires are rare and protected. Therefore, founder material is difficult to obtain (Hugron & Rochefort 2018).

Sphagnum farming aims to grow *Sphagnum* mosses for harvesting peat moss biomass (Pouliot *et al.* 2015, Gaudig *et al.* 2014, 2018). The original idea was to grow living biomass as founder material for peatland restoration (Money 1994), but recently interest has shifted towards growing non-decomposed *Sphagnum* fibres as a crop (Pouliot *et al.* 2015, Gaudig *et al.* 2014, 2017). The fibres are

Mires and Peat, Volume 27 (2021), Article 27, 18 pp., http://www.mires-and-peat.net/, ISSN 1819-754X
International Mire Conservation Group and International Peatland Society, DOI: 10.19189/MaP.2020.APG.StA.2022

sustainably produced, in contrast to the conventional extraction of fossil peat from undisturbed mires (Pouliot *et al*. 2015). This type of peatland agriculture is an example of paludiculture, which is defined as the sustainable, productive use of peatlands under wet and therefore peat-preserving conditions (Wichtmann *et al.* 2016). Conventional drainage-based peatland agriculture leads to high greenhouse gas emissions (Waddington & Price 2000, Tiemeyer *et al.* 2020). Paludiculture offers a chance to mitigate these negative environmental impacts (Beyer & Höper 2015, Günther *et al.* 2017), which should be considered urgent due to the current climate change. In addition, paludiculture creates ancillary benefits by improving water quality (Vroom *et al.* 2020) and provides habitat for rare and endangered species (Muster *et al.* 2015, 2020; Dahl *et al*. 2020, Zoch & Reich 2020).

The practical feasibility of *Sphagnum* farming has been demonstrated by pilot studies on former bog grassland (Gaudig *et al.* 2014), floating mats (Blievernicht *et al.* 2011, 2013, Hoshi 2017) and cut-over bogs (Gaudig *et al.* 2017). Starting in 2004, pilot studies in Canada and Germany have been inspired by the Canadian moss layer transfer technique (Quinty & Rochefort 2003). They were mostly conducted on slightly decomposed "white peat" (degree of humification H1–H5 after von Post (1924)) with a peat layer thickness larger than 100 cm. Therefore, the soil properties of these sites (high porosity, high hydraulic conductivity (Liu & Lennartz 2019)) were conducive to maintaining a constant, high water table needed for optimal *Sphagnum* growth (Pouliot *et al.* 2015, Gaudig *et al.* 2014, 2017). One pilot study in northwest Germany has already demonstrated that high *Sphagnum* yields can be achieved on cut-over (milled) bogs with thicker (160–195 cm) residual layers of moderately decomposed peat (Gaudig *et al.* 2017).

However, after industrial peat extraction generally only thin layers of peat remain (Lundin 2017). For example, in northwest Germany, a statutory layer of only 50 cm of residual peat has to remain after peat extraction (NMELF 1981). No large-scale *Sphagnum* farming trials on cut-over sites with shallow layers of residual peat have been carried out so far (Wichmann *et al.* 2017). The remaining "black peat" has a high degree of decomposition (H6–H10 after von Post (1924)) and therefore a low porosity and a very low hydraulic conductivity compared to the only slightly decomposed "white peat" (Baden & Eggelsmann 1963, Caspers 2010, Brust *et al.* 2018). Long-term agricultural drainage may also cause white peat to mineralise and to decrease in porosity as well as hydraulic conductivity (Liu & Lennartz 2019), leaving sites with physical properties similar to cut-over bog. Such peat properties create problems for maintaining a continuously high water table in the *Sphagnum* fields, which is required for optimal *Sphagnum* growth (Hayward & Clymo 1983, Pouliot *et al*. 2015, Gaudig *et al.* 2020). Therefore, knowledge of how to grow *Sphagnum* on highly decomposed peat is important, not only for cut-over bogs, but also for agricultural fields with shallow decomposed peat.

Especially due to the difficult hydrological conditions found on black peat, *Sphagnum* fragments need a protective cover during the establishment phase to improve the microclimate and protect the mosses from desiccation. Quinty & Rochefort (2003) recommend a loose cover of straw mulch to improve the microclimate by keeping higher relative humidity and balancing surface temperatures (lower during daytime and higher at night). Straw mulch has been used most often in *Sphagnum* farming trials so far (Quinty & Rochefort 2003, Pouliot *et al.* 2015, Gaudig *et al.* 2014, 2017, 2018). Besides straw mulch, we also tested geotextile (50 % shade), which had shown promising results in Canada (Campeau & Rochefort 1996).

The objective of this study was to examine the establishment of *Sphagnum* on cut-over bog with shallow layers (average 78 cm) of highly decomposed black peat under different hydrological starting conditions. One of the two study sites was established directly after peat extraction, while the other one has been rewetted 7 years prior to the start of our experiments.

In this article we address the following questions:

1. Is *Sphagnum* farming possible on shallow layers (average 78 cm) of highly decomposed black peat?
2. How do two cultivation sites with different rewetting histories differ regarding *Sphagnum* establishment and growing conditions?
3. Is geotextile a suitable alternative to straw mulch for protection of moss fragments from desiccation during the initial phase in large scale *Sphagnum* farming?
4. What are the supporting and limiting factors for *Sphagnum* farming on shallow layers of black peat?

METHODS

Study sites

Two *Sphagnum* cultivation sites were set up on cut-over bog near Twist in northwestern Germany, at Drenth (52° 41' N, 07° 05' E; Figure 1) and Provinzialmoor: (52° 40' N, 07° 06' E; Figure 2)

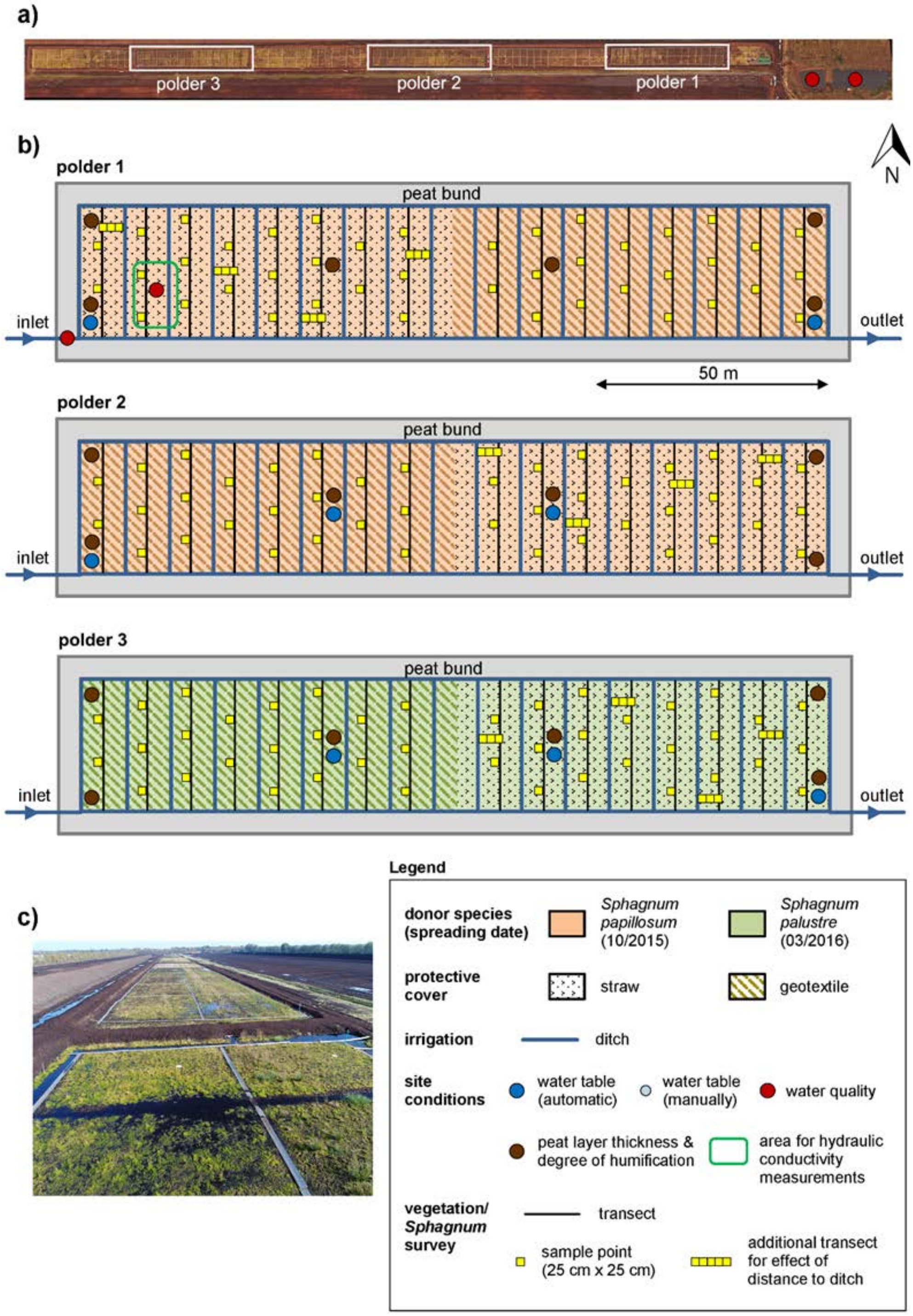

Figure 1. *Sphagnum* cultivation site “Drenth”. a) aerial view of the study site (March 2017); b) study site with sampling locations (vegetation, water, soil); c) cultivation site Drenth with surrounding peat extraction area (October 2017). Photos: Klasmann-Deilmann GmbH.

(Graf *et al*. 2017, Figure 2e). The local climate is oceanic with a mean annual temperature of 9.8 °C and a mean annual precipitation of 758 mm per year (1951–2018, meteorological station Lingen). In the years of experiments annual precipitation was 677 mm (2016), 841 mm (2017) and 561 mm (2018), respectively (DWD 2019).

Prior to the study, peat had been extracted on both locations with the “milled peat” method, leaving a residual peat layer of highly decomposed black peat (30–100 cm thickness). *Sphagnum* farming was tested on these sites for three years (2015–2018).

Each cultivation site had a total area of 5 ha, including infrastructure, peat bunds for causeways and irrigation system as well as the cultivation fields to which *Sphagnum* mosses were introduced (2.5 ha on each cultivation site). In this study we examine data collected only in sections with ditch irrigation and two founder species that were reintroduced in the same way and at the same time on both cultivation sites. Thus, the actual study site Provinzialmoor was 1 ha and the study site Drenth was 1.2 ha in size (Figure 1b and 2c).

Sphagnum mosses were introduced on both cultivation sites using the moss layer transfer technique. Using this technique fragments of *Sphagnum* mosses collected at a founder site were transferred and spread on bare peat surface, which was rewetted in the last step (Quinty & Rochefort 2003). Founder material for the study sites was harvested manually in two near-natural mires 200 km and 60 km from the cultivation sites. In October 2015 and in March 2016, respectively, fragments (5–10 cm, application density 60–80 %) of *Sphagnum papillosum* and *S. palustre* were spread manually on the bare peat.

Each species was spread in a separate section on both sites (Figure 1b and 1d). The two species were chosen because they are widespread and well-suited for the production of growing media (Emmel 2008). While *Sphagnum papillosum* mostly grows in oligotrophic peatlands, *Sphagnum palustre* is common in mesotrophic to eutrophic peatlands (Frahm & Frey 2003, Hoelzer 2010).

Two different types of protective cover were used to cover the *Sphagnum* fragments: (i) parts of the study sites were covered with straw mulch (750–800 kg ha^{-1}, application density 80 %) while (ii) other sections were covered with geotextile (50 % shade, made from UV-stable polypropylene with a weight of 18 g m^{-2}) (Figures 1b and 2c). At Provinzialmoor the geotextile was tested only with *Sphagnum papillosum*, while it was tested with both species at Drenth. The geotextile was removed from the sites about six months after installation.

In order to limit competition from vascular plants, both sites were mown 1–2 times per year with either a handheld petrol strimmer or a single-axle mower with a double-knife cutter bar.

The cultivation site **Drenth** was established on a narrow cut-over bog strip and situated within a current peat extraction area of 50 ha (Figure 1).

To prepare the site for rewetting, polders separated by peat bunds were formed and the area within was levelled with an excavator before *Sphagnum* mosses were introduced. The study site Drenth was made up of three polders of 0.4 ha, for a total area of 1.2 ha. For active water table regulation, ditches about 0.3 m deep and 0.3–0.7 m wide were dug every 10 m, connecting to a perimeter ditch on both sides with a distance of about 23 m. An overflow was installed to prevent flooding. Excess precipitation during the winter months discharged into two retention basins with a total volume 6000 m^3. The water from these basins was pumped into the ditches of the polders with an electrical pump as needed during the summer months. When the water in the retention basins from precipitation ran low, the reservoirs were supplemented with groundwater using another electrical pump.

The cultivation site **Provinzialmoor** was established on a cut-over bog area, which has been rewetted 7 years prior to the installation of the cultivation site. It is surrounded by a rewetted area of around 100 ha (Figure 2). After peat extraction had terminated, several polders separated by peat bunds were formed and rewetted through shallow inundation by excess rainfall in winter. This approach is common in peatland restoration work in Germany (Blankenburg 2004). The rectangularly shaped study site Provinzialmoor was situated within one of these polders and had a total area of 1 ha.

During the experiment set-up, the water table of the inundated polder had to be lowered to make the site accessible. Any vegetation that had already established during the time of rewetting was removed. For irrigation, ditches with varying distances of 40 to 60 m with the same dimensions as at Drenth (0.3 m deep and 0.3–0.7 m wide) were installed at Provinzialmoor. Water inflow was controlled manually with an elbow pipe (KG pipe) that connects the surrounding flooded polders with the cultivation site. An overflow was installed to prevent flooding. When the surrounding polders could not provide sufficient water for irrigating the cultivation site in dry summers, water was pumped from a ditch north of the cultivation site containing drainage water from areas with ongoing peat extraction. Unfortunately, subsurface pipes (drainage distance 30 m) were still draining the cultivation site into this ditch throughout the whole study. These remnants of former peat extraction were only discovered and destroyed after the conclusion of this study.

Survey of site conditions

On both study sites, the thickness of the residual black peat layer was measured using a metal rod with a scale at 18 points at Drenth and at 10 points at Provinzialmoor (Figure 1b and 2c) At the same points, the degree of humification of the peat was determined according to von Post (1924). In addition, two profile pits were dug on both sites down to the mineral soil and described according to the German

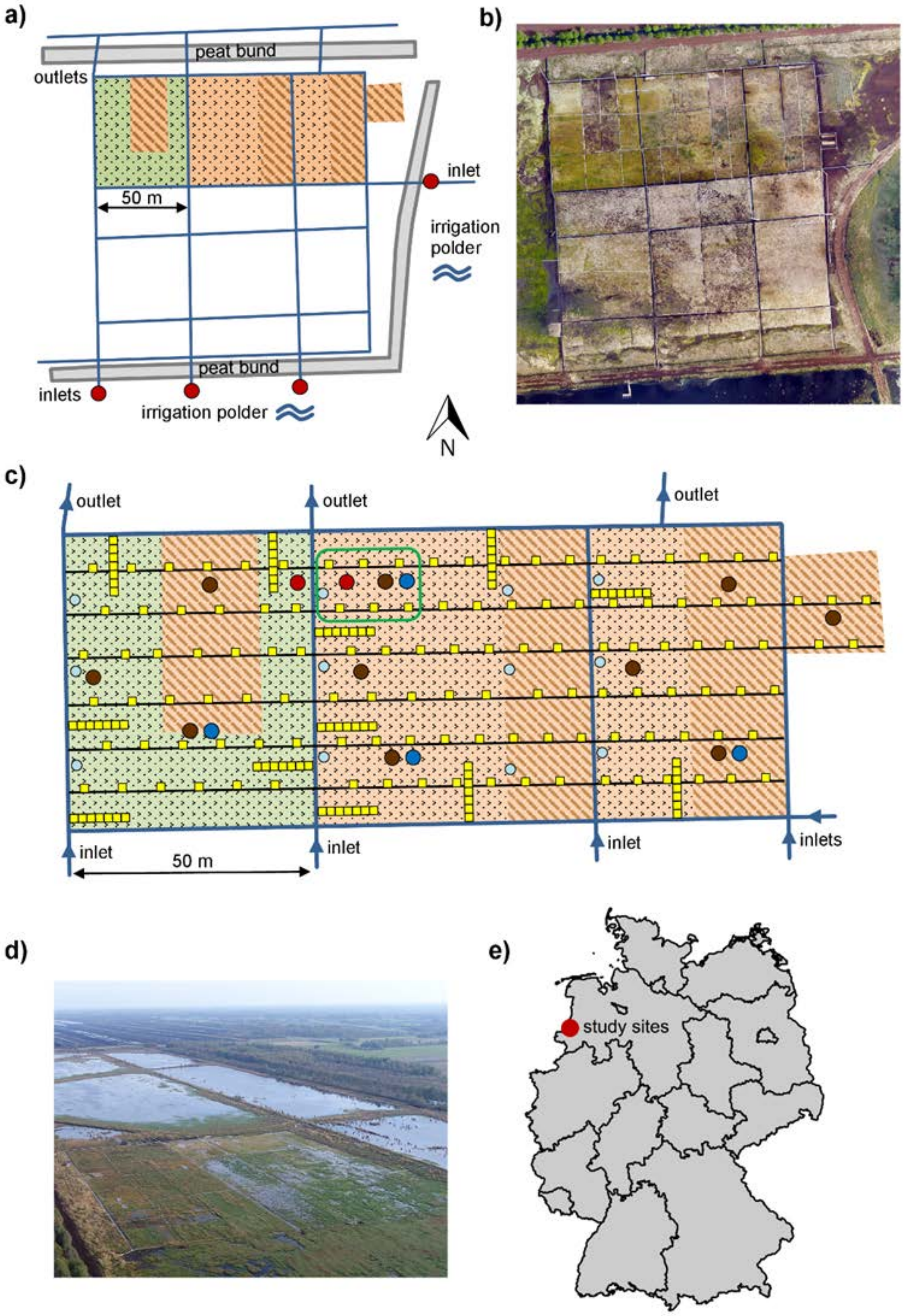

Figure 2. *Sphagnum* cultivation site “Provinzialmoor”. a) schematic plan with irrigation system; b) aerial view (May 2017); c) study site with sampling locations (vegetation, water, soil, legend see Figure 1); d) cultivation site Provinzialmoor with surrounding rewetted polders (October 2017); e) location of “Drenth” and “Provinzialmoor” near Twist in Lower Saxony (Germany). Photos: Klasmann-Deilmann GmbH.

Soil Mapping Manual KA5 (Ad-hoc-AG Boden 2005). A detailed description of the soil properties can be found in Oestmann *et al*. (2021).

The saturated hydraulic conductivity K_s of the peat was measured at the sites via bail tests and evaluated according to Hvorslev (1951) and Surridge *et al*. (2005). In brief, water was manually bailed from 23 and 24 shallow boreholes at Drenth and Provinzialmoor, respectively. The recovery of the water level was recorded at a high temporal resolution using pressure sensors (Mini-Divers) in combination with Baro-Divers for atmospheric pressure correction (Eijkelkamp, Giesbeek). K_s values were calculated following Brand & Premchitt (1980) and Surridge *et al*. (2005). The water table was close to the surface during the experiment, so that the results are valid for depths between about 5 and 30 cm below peat surface.

Starting in January 2016, the water table was measured manually in dipwells (perforated plastic tubes) once a month at 12 evenly distributed locations on the study site Provinzialmoor (Figure 1b and 2c). This approach was changed to automatic hourly recordings using 4 data loggers (Seba Hydrometrie: Dipper PT) in June 2017. At Drenth, the water table measurements at 8 dipwells started in April 2016 (hourly automatic recording).

Samples for water quality analysis were taken from water in selected dipwells filtered through the peat only (Oestmann *et al*. 2021) and from the irrigation water (ditches, water retention ponds and surrounding polders at Provinzialmoor) every two to three weeks from March 2017 until March 2019. In total, 120 samples from Drenth and 232 samples from Provinzialmoor were taken at 4 points at Drenth and 6 points at Provinzialmoor (Figure 1b, 2a and 2c). As summer droughts caused the dipwells to dry out, sampling was only possible to a limited extent during the summer months. Electrical conductivity (EC) and pH values were determined at the sites on the day of sampling with a portable multi variable meter (WTW pH/Cond 3320). In the laboratory, water samples were filtered to 0.45 µm (PES membrane filter, Pall Life Science) and stored frozen (-20 °C) until analysis for nitrate (NO_3), ammonium (NH_4^+), phosphate (PO_4^{3-}) and calcium (Ca^{2+}) by ion chromatography (850 Professional Ion Chromatograph, Metrohm).

Survey of *Sphagnum* establishment

Sphagnum establishment was assessed using a 25 cm × 25 cm sample frame in September 2018 (30 months after the introduction of fragments of *Sphagnum palustre* and 36 months after the introduction of *Sphagnum papillosum*). 247 sample points (Drenth: 126, Provinzialmoor: 121) were distributed systematically along transects 10 m apart (Figure 1b and 2c). In addition, 12 random “ditch transects” on each cultivation site perpendicular to the irrigation ditches were assessed to evaluate the correlation between *Sphagnum* establishment and distance to the irrigation ditch. Along each ditch transect line, 19 sample frames were positioned directly next to one another (228 additional sampling points per study site) (Figure 1b and 2c). Within the frames, the cover of *Sphagnum*, other mosses and vascular plants was estimated according to the scale of Londo (1976). Additionally, *Sphagnum* carpet thickness was measured with a folding stick at five points in each frame when mosses were present. Afterwards, biomass samples were collected over the entire surface within the frame from every fifth sample point of the systematic transects, but not from the additional ditch transects. All material above the peat substrate was collected. In the laboratory, *Sphagnum* fibres were separated from other material (i.e. vascular plants and litter), washed and dried at 80 °C to constant weight (Hendry & Grime 1993). Then the biomass dry weight was measured with a scale of 0.001 g accuracy.

Data analysis

To evaluate differences in *Sphagnum* establishment in cover, carpet thickness and dry mass accumulation between the two study sites, the non-parametric Wilcoxon Rank Sum Test (Mann-Whitney U test) was used (significance level of $P<0.05$). Only data from systematic transects was used. Beforehand, data was tested for normality and homogeneity of variance using the Shapiro-Wilk test and the Levene test, respectively. For better comparison, the data was analysed separately for the two founder species, because they were spread at different times and therefore differed in age at the time of data collection. Because geotextile (protective cover) was not tested with *S. palustre* at Provinzialmoor, only data from sample points with straw coverage were included in this analysis.

The same approach was used to compare the saturated hydraulic conductivity (K_S) and the peat layer thickness at the two sites.

To summarise the effect of different variables on *Sphagnum* establishment, boosted regression trees (BRTs) using the R packages “dismo” (Hijmans *et al.* 2017) and “gbm” (Greenwell *et al.* 2019) and applying approaches described in Bechtold *et al*. (2014) to avoid overfitting (monotonic slopes, dropping of correlated parameters). BRTs were used, because they are able to fit complex nonlinear relationships, use both categorical and non-categorical variables, deal with missing data and aim to improve the performance of a single model by fitting many models and combining them for prediction (Elith *et al.* 2008). The boosted regression tree model was performed with 126 observations of Drenth and 121 of Provinzialmoor and seven predictors, using the Gaussian distribution, with tree complexity = 4, learning rate = 0.002 and bag fraction = 0.5. The final model was fitted with 1650 trees and reached a total explained deviance = 0.52.

Data from all systematically positioned sample points (both founder species, both types of protective cover), but not from the additional ditch transects, were used for the model. The dependence of *Sphagnum* cover (in %, September 2018) on the founder species, age (months after installation), minimum distance to an irrigation ditch (m), type of protective cover (straw *vs*. geotextile), peat layer thickness (cm) and cover of vascular plants (in %, September 2018) as well as the cover of the dominant species *Eriophorum angustifolium* (in %, September 2018) was tested. Due to small-scale spatial heterogeneity, e.g. caused by the distance to the ditches or by uneven surfaces, the water table data was unfortunately not sufficient to assign water levels to each of the 247 sampling locations. Installing and (manually) reading an adequate number of dipwells would have caused too much damage to the sites. The data from the additional ditch transects were used for visualising the effect of distance of growing point to the irrigation ditch, but not for statistical analysis.

All statistical analyses were performed with R software (R version 3.6.0, R Development Core Team 2019). For graphical presentation R package "ggplot2" was used (Wickham 2016).

RESULTS

Site conditions

The thickness of the residual peat layer differed within the sites and between the sites (Figure 3). Peat thickness at Drenth varied between 32 cm and 100 cm with an average of 61 cm and showed a gradient of increasing thickness from east to west. At Provinzialmoor, peat layer thickness was significantly higher with a minimum of 86 cm, a maximum of 100 cm and an average of 95 cm that remained after peat extraction. The average degree of humification of the topsoil - according to von Post (1924) - was similar (H7 to H8) at both sites. In the soil profiles at Drenth medium decomposed fen peat (H5 to H7) was overlain by highly decomposed bog peat (H5 to H8). Between peat and mineral soil, a thin layer of organic sediment was found. At Provinzialmoor 80 cm of medium decomposed bog peat (H5 to H7) over 15 cm highly decomposed fen peat (H8) was mapped. A fossil gley (silty sand) is located below the peat. The slightly lower degree of decomposition at Provinzialmoor was accompanied by lower bulk density, higher porosity and a higher field capacity (details in Oestmann *et al*. 2021).

Saturated hydraulic conductivity (K_s) was significantly lower at Provinzialmoor with a mean ± standard error of (0.10 ± 0.03 m d^{-1}) compared to Drenth (0.18 ± 0.04 m d^{-1}) (Figure 4).

Fluctuations of the water table were high on both sites (Figure 5). At Drenth, the highest water table measured was 15 cm above and it did not drop lower than 55 cm below peat surface. However, in the early phase of peat moss establishment (January 2017) some polders at Drenth were flooded and the water table was up to 28 cm above peat surface for a short

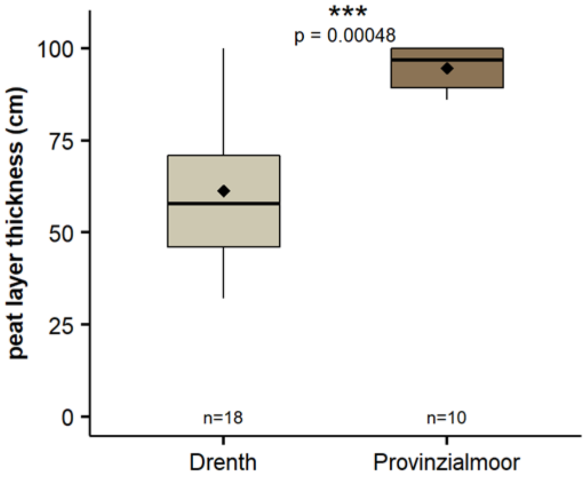

Figure 3. Comparison of the peat layer thickness (cm) at the sites Drenth and Provinzialmoor. Boxplots are showing median (central thick lines), 25 % and 75 % quartile ranges around the median (box length), outliers (circles) and mean values (rhomb); stars indicate the level of significance; n: number of samples.

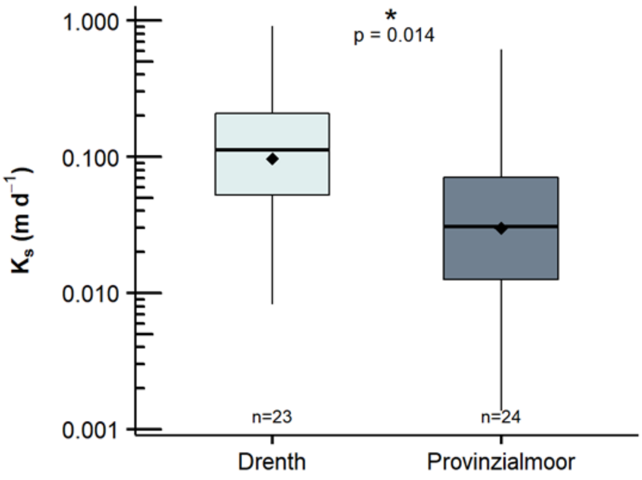

Figure 4. Comparison of the saturated hydraulic conductivity k_s (m d^{-1}) of the peat at the study sites Drenth and Provinzialmoor. Boxplots are showing median (central thick lines), 25 % and 75 % quartile ranges around the median (box length), outliers (circles) and mean values (rhomb); stars indicate the level of significance; n: number of samples.

period of time. Mean annual water table (November to October) of the 8 dipwells ranged from 13 cm below to 0.5 cm above in 2017 and from 15 cm below to 3 cm below in 2018, respectively.

At Provinzialmoor even stronger fluctuations were measured, ranging from 13 cm above and 80 cm below peat surface. Figure 5 shows that the water table was most stable in the winter months of 2017 and 2018. The lowest water table was generally measured during the summer months. Especially in the summer of 2018 the water table at Provinzialmoor was lower than 40 cm below peat surface over a period of four months. Mean annual water table (November to October) of the 4 dipwells thus ranged from 24 cm below to 7 cm below in 2017 and from 33 cm below to 12 cm below in 2018, respectively, and were clearly lower than at Drenth.

At the site Drenth higher values of pH, calcium (Ca) and ammonium (NH_4^+) as well as slightly higher values of electrical conductivity (EC) were measured in the irrigation water compared to Provinzialmoor (Table 1). However, values measured in the dipwells within the peat did not differ much between the sites.

Sphagnum establishment

The percent cover, carpet thickness and dry mass of *Sphagnum* species was significantly higher at Provinzialmoor (rewetted prior to moss introduction) than at Drenth (rewetted after moss introduction) (Figures 6 and 7). For comparability between the cultivation sites, the results are shown separately for the founder species and only variants are compared that have been installed equally on both sites (founder material, timeframe, application density, straw cover).

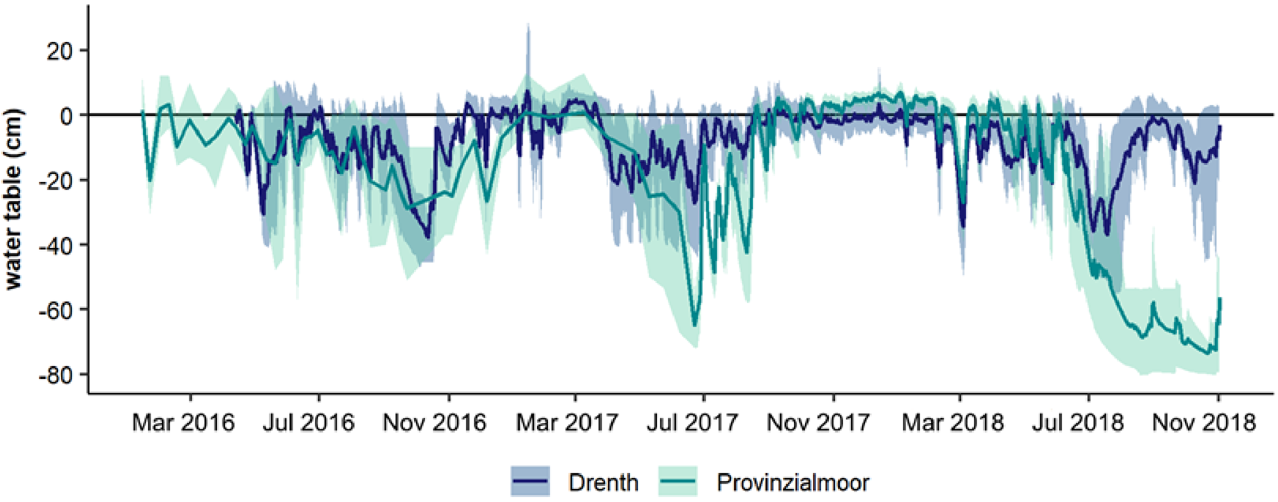

Figure 5. Comparison of the water table (cm) below peat surface of the study sites Drenth and Provinzialmoor between January 2016 and November 2018. The thick line shows the mean value of measured values at each site and the shade shows the range (min to max).

Table 1. Mean values ± standard error (SE) of water quality at the study sites Drenth and Provinzialmoor measured in the irrigation water and dipwells between March 2017 and March 2019 (details in Oestmann *et al.* 2021); EC = electrical conductivity.

site	sample point	pH (-)	EC (μS cm^{-1})	NO_3^- (mg l^{-1})	NH_4^+ (mg l^{-1})	PO_4^{3-} (mg l^{-1})	Ca^{2+} (mg l^{-1})
Drenth	Irrigation water	5.5 ± 0.15	152 ± 7	4.0 ± 0.5	0.8 ± 0.1	0.07 ± 0.014	9.7 ± 1.0
Drenth	Dipwells	4.4 ± 0.06	159 ± 8	4.1 ± 1.3	5.2 ± 0.3	0.01 ± 0.004	2.3 ± 0.5
Provinzialmoor	Irrigation water	4.2 ± 0.03	93 ± 3	0.3 ± 0.02	0.8 ± 0.1	0.02 ± 0.005	0.6 ± 0.1
Provinzialmoor	Dipwells	4.4 ± 0.03	107 ± 3	0.4 ± 0.1	1.9 ± 0.1	0.06 ± 0.017	1.1 ± 0.2

Sphagnum papillosum

After 36 months the mean cover of *Sphagnum papillosum* was 19 % at Drenth and 66 % at Provinzialmoor. A maximum of 100 % cover was reached in some sample plots at both sites (Figure 6). With the exception of the hollow species *Sphagnum cuspidatum*, which had a mean cover of 5 % at Provinzialmoor, other *Sphagnum* species were only present with less than 1 %. The thickness of the existing carpet of *S. papillosum* reached a mean of 1.6 cm at Drenth and 3.5 cm at Provinzialmoor. Maximum values of 5 cm at Drenth and 8.8 cm at Provinzialmoor were measured after 36 months. The mean dry mass accumulation (including initially applied moss material) of *S. papillosum* at Drenth was 22 g m^{-2}, whereas at Provinzialmoor it was significantly higher (349 g m^{-2}) 36 months after the introduction of fragments. The maximum values were 116 g m^{-2} at Drenth and 828 g m^{-2} at Provinzialmoor. The mean cover of vascular plants in plots with *S. papillosum* was 27 % at Drenth and 48 % at Provinzialmoor (8 months after the last mowing).

Sphagnum palustre

After 30 months, *S. palustre* also showed significantly higher values of cover, carpet thickness and dry mass at Provinzialmoor than at Drenth (Figure 7). The mean cover at Drenth was 32 % and 79 % at Provinzialmoor. In some sample plots a maximum cover of 100 % was measured. Whereas *S. cuspidatum* was only present with a few individuals at Drenth, the *Sphagnum* carpet at Provinzialmoor contained on average 11 % of this species. Mean thickness of the existing carpet of *S. palustre* was 1.9 cm at Drenth and 8.4 cm at Provinzialmoor. Maximum values of 8.4 cm at Drenth and 19 cm at Provinzialmoor were measured. Mean dry mass accumulation (including initially applied moss material) of *S. palustre* was 112 g m^{-2} at Drenth and 629 g m^{-2} at Provinzialmoor 30 months after the introduction of fragments. The maximum values measured were 179 g m^{-2} at Drenth and 1000 g m^{-2} at Provinzialmoor. The mean cover of vascular plants was 14 % at Drenth and 52 % at Provinzialmoor (8 months after the last mowing).

Factors affecting *Sphagnum* establishment

The BRT model indicates that the establishment of *Sphagnum* expressed as cover (%) was mainly influenced by minimum distance to an irrigation ditch (m), cover of vascular plants (%), type of protective cover (straw *vs*. geotextile) and peat layer thickness (cm). Since the greatest possible distance from the irrigation ditch at Drenth is 5 m, all data beyond this distance includes only measurements from Provinzialmoor. The factors which were associated with a higher establishment of *Sphagnum* were a short distance to the irrigation ditch, a higher cover of vascular plants, a protective cover of straw and a greater peat layer thickness (Figure 8). Unfortunately, a large part of the data variability could not be explained with the BRT model (total explained deviance 0.52). The calibration of the BRT model showed a Nash-Sutcliffe efficiency of 0.51, while the validation only reached an NSE of 0.40, despite of a bag fraction of 0.5 to avoid overfitting.

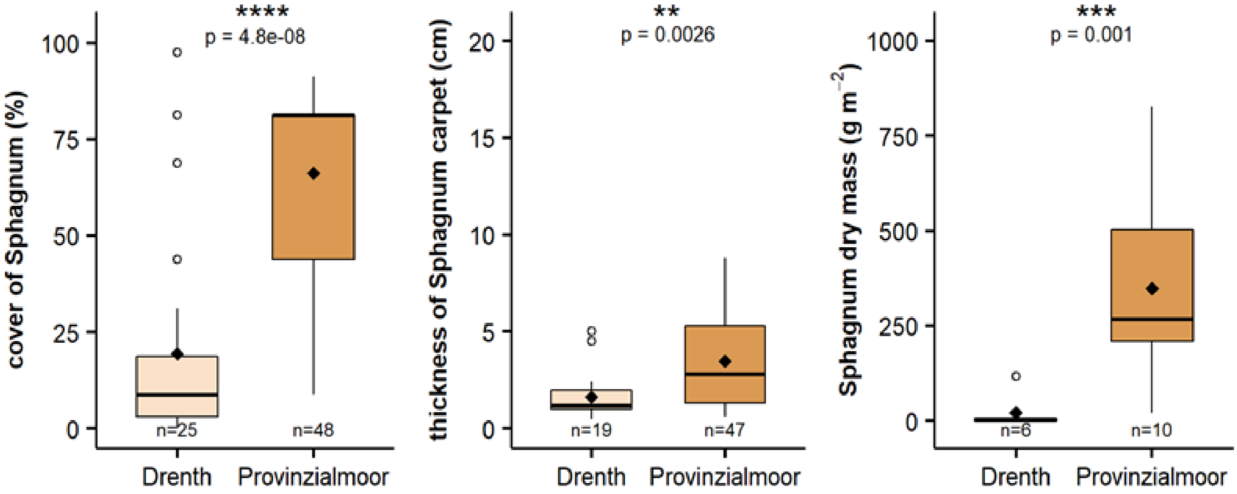

Figure 6. Comparison of the establishment of *Sphagnum papillosum* on the study sites Drenth and Provinzialmoor in cover (%), carpet thickness (cm) and dry mass (g m^{-2}) in September 2018 (including only data from sections where straw was used as protective cover). Carpet thickness includes only measured values where mosses were present. Boxplots are showing median (central thick lines), 25 % and 75 % quartile ranges around the median (box length), outliers (circles) and mean values (rhomb); stars indicate the level of significance; n: number of samples.

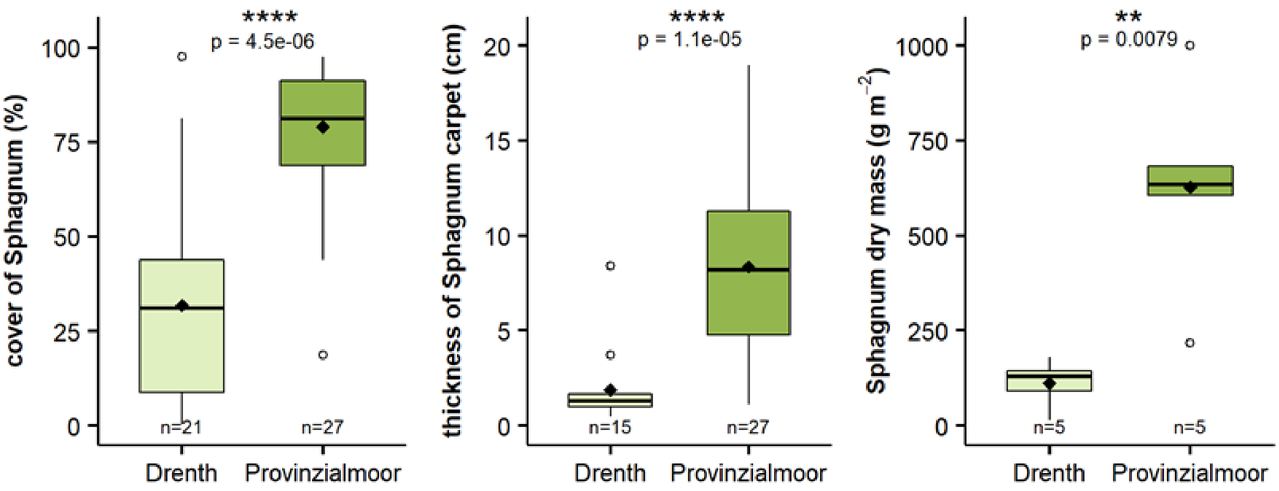

Figure 7. Comparison of the establishment of *Sphagnum palustre* on the study sites Drenth and Provinzialmoor in cover (%), carpet thickness (cm) and dry mass (g m^{-2}) in September 2018 (including only data from sections where straw was used as protective cover). Carpet thickness includes only measured values where mosses were present. Boxplots are showing median (central thick lines), 25 % and 75 % quartile ranges around the median (box length), outliers (circles) and mean values (rhomb); stars indicate the level of significance; n: number of samples.

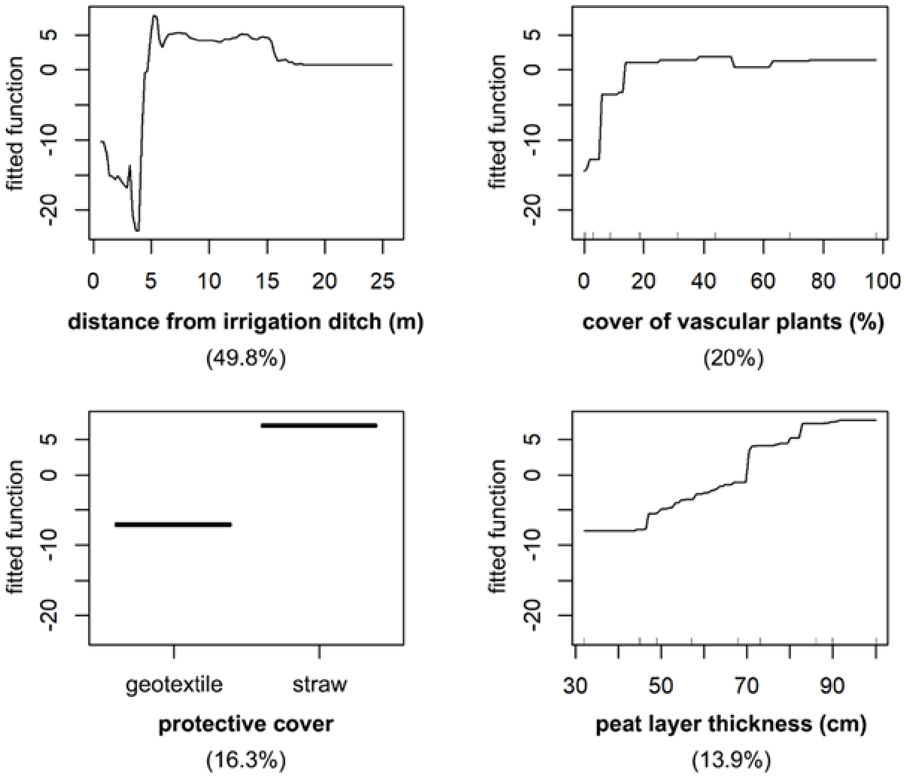

Figure 8. Boosted regression tree partial dependence plot showing the effect of the four most influential predictor variables on the establishment of *Sphagnum* at the two study sites Drenth (126 observations) and Provinzialmoor (121 observations) expressed as cover (%) with the predictor variables being distance from irrigation ditch (m), cover of vascular plants (%), cover of *Eriophorum angustifolium* (%), type of protective cover (straw & geotextile) and peat layer thickness (cm). The fitted function is the difference between the actual y-axis value and the mean response value. The important predictor range is where the fitted function is above zero. The graphs show the effect of a particular variable on the response: positive fitted function values suggest that *Sphagnum* cover responds favourably and low values suggest the opposite. The relative influence for each predictor variable is shown in parentheses below each graph.

Distance to the irrigation ditch

Since the distance of irrigation ditches differed strongly between the study sites the data was evaluated more thoroughly with additional transects. On both sites, the average cover of *Sphagnum* was comparably high around 70 % within 100 cm distance from the irrigation ditch (Figure 9), while at Drenth *Sphagnum* cover decreases with increasing distance. At more than 250 cm distance the cover evens out at an average of around 20 %. In contrast, only slight variations in cover were recorded along the transects at Provinzialmoor (*Sphagnum* cover between 60–78 %).

DISCUSSION

In this study, we could show that *Sphagnum* cultivation is possible on highly decomposed peat. In the first part of the discussion, we will set the results on *Sphagnum* establishment and growth into perspective of previous findings both regarding productivity and water availability. The most striking result was that *Sphagnum* growth was significantly higher at Provinzialmoor than at Drenth despite exhibiting a clearly lower water table especially during the summer months. Therefore, in the second part of the discussion we will focus both on site conditions and management effects that might have caused these results to draw conclusions on how to improve management at similar sites with highly decomposed peat.

Sphagnum establishment and productivity

Sphagnum mosses established successfully on both sites, but the establishment success of both founder species was significantly lower at the site Drenth. Results for cover, carpet thickness and dry mass accumulation (including initially applied moss material) of *S. papillosum* growth at Provinzialmoor are comparable to the results of the first trial of Gaudig *et al.* (2017) on deep black peat in Ramsloh, northwest Germany. Even higher values of cover, carpet thickness and dry mass accumulation on black peat could be accomplished with *S. palustre*. This result agrees with findings from undisturbed mires of North Germany where *S. palustre* was also observed to have a higher natural productivity (250–332 g m^{-2} yr^{-1}) than *S. papillosum* (172–220 g m^{-2} yr^{-1}) (Lütt 1992). The mean value measured in this study for dry mass accumulation (including initially applied moss material) of *S. palustre* (629 g m^{-2} after 30 months) at Provinzialmoor is comparable to its natural productivity. The measured maximum in this study (1000 g m^{-2}) even exceeded natural productivity. However, at the same study site, the mean value of *S. papillosum* was lower than natural productivity (349 g m^{-2} after 36 months) (Lütt 1992). This is comparable to values measured at a *Sphagnum* farming site in Canada over the same time period (Pouliot *et al.* 2015). Values, comparable to natural productivity of *S. papillosum*, were only measured in a few sample plots at Provinzialmoor (maximum value 828 g m^{-2}). At Drenth, neither of the two tested species reached natural productivity rates, not even the maximum values.

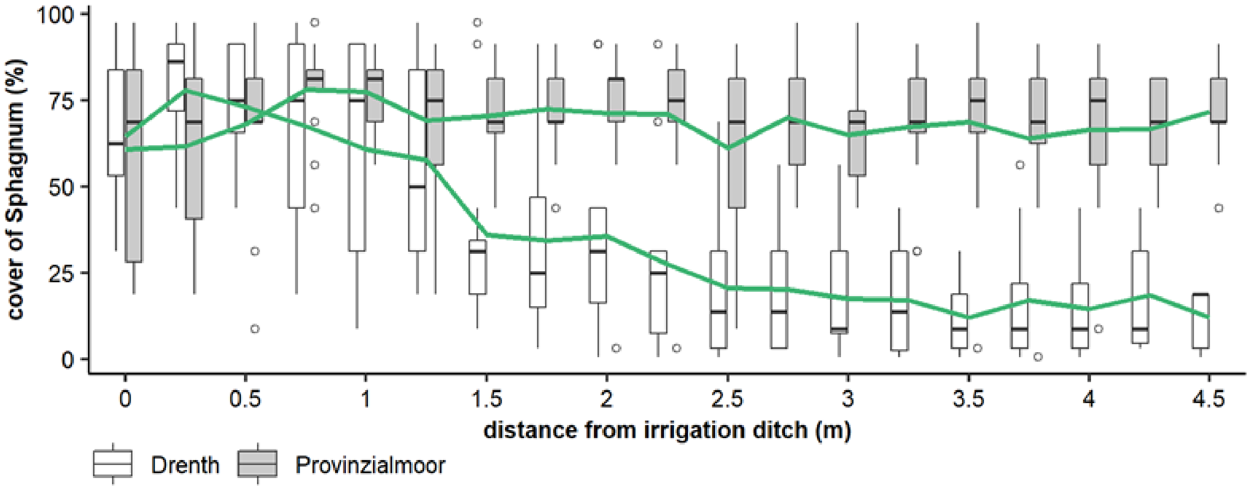

Figure 9. Dependence of *Sphagnum* cover (%) on the distance (m) of the sampling location to the nearest irrigation ditch at the study sites Drenth and Provinzialmoor (including an equal number of samples from both species (*S. palustre* and *S. papillosum*) and only data from sections where straw was used as protective cover). Boxplots are showing median (central thick lines), 25 % and 75 % quartile ranges around the median (box length) and outliers (circles); the green line connects the mean values; n=12 number of samples for each box.

The growth rate of the tested species measured in undisturbed mires of North Germany was 2.8–3.8 cm yr^{-1} for *S. papillosum* and 7.8–10.4 cm yr^{-1} for *S. palustre* (Lütt 1992). This was only achieved in a few sample plots at Provinzialmoor with maximum values of 8.8 cm for *S. papillosum* after 36 months and 19 cm for *S. palustre* after 30 months. *S. palustre* has significantly higher growth rates in length and biomass than *S. papillosum* (Krebs *et al.* 2016, Lütt 1992), which we observed especially at Provinzialmoor, even though this species was introduced six months later than *S. papillosum*. However, it is conceivable that a more favourable water table in sections where *S. palustre* was introduced contributed to the better growth of this species, yet due to lack of detailed data on the water table this is not certain.

Since the productivity of *Sphagnum* measured in some sections of the site Provinzialmoor was comparable to natural productivity, our results confirm that *Sphagnum* farming is possible on shallow layers of highly decomposed black peat. However, we were not able to achieve the high productivity that was measured in *Sphagnum* farming on white peat (Gaudig *et al.* 2014).

Impact of the low water table and water availability

Maintaining a stable water table close to the surface is essential for high *Sphagnum* productivity (Hayward & Clymo 1983, McNeil & Waddington 2003, Gaudig *et al.* 2014, 2020), which could not be achieved during the summer months of our study. The low water table could be explained both by low precipitation and insufficient water supply. The amount of precipitation was particularly low in the summer of the first and throughout the third year (2016: 90 % and 2018: 75 % of the long-term average (DWD 2019)) after the introduction of moss fragments. The year in between (2017) had a very dry spring and a wet autumn. Due to the resulting water deficiency, a closed *Sphagnum* carpet could not develop on either study site after 30 or 36 months, respectively. The establishment of a closed *Sphagnum* carpet is a key element in the early stage of *Sphagnum* farming, because desiccation tolerance increases when a closed carpet with cover of > 90 % has formed (Price *et al.* 2003, Gaudig *et al.* 2017, 2018). A faster development could be achieved by a higher application density of the peat moss fragments (Campeau & Rochefort 1996, Rochefort *et al.* 2003, Gaudig *et al.* 2018) and thus increase the likelihood of successful growth in areas with prolonged droughts, which are likely to become more frequent due to climate change (IPCC 2019).

In undisturbed mires, the productivity of *Sphagnum* mosses naturally decreases temporarily during periods of water deficits (Robroek *et al*. 2009, Rydin & Jeglum 2009). To ensure high productivity of *Sphagnum* throughout the year, water quantity to compensate for very dry summers needs to be carefully considered before planning a cultivation site. At the same time unproductive water loss (leaky ditches, “hidden” drainage pipes, increased evapotranspiration due to an oasis effect) should be given equal attention. Furthermore, evapotranspiration and water loss by horizontal water movement decrease with increasing size of the rewetted area (Brust *et al.* 2018). Water storage, however, should not take place directly on the cultivation site in the winter months with high precipitation, because inundation reduces *Sphagnum* growth by leading to elongation of *Sphagnum* stems without any gain of biomass and might also lead to the dieback of mosses (Rochefort *et al.* 2002, Campeau *et al.* 2004, Brust *et al.* 2018). Inundation might also favour the immigration or establishment of hollow species (e.g. *S. cuspidatum*), which we observed in wet areas of Provinzialmoor. Hollow species under very wet conditions are strong competitors to hummock species, because they are more productive (Gunnarsson 2005, Hájek 2009). However, these species have a greater rate of decomposition (Johnson & Damman 1991) and are therefore not targeted in biomass production for horticultural growing media (Emmel 2008).

Low hydraulic conductivity

Boosted regression trees (BRTs) indicated that a shorter distance from the irrigation ditch resulted in better establishment of *Sphagnum*. These results were confirmed by the analysis of the “ditch transects”, which showed that especially at Drenth irrigation was successful mainly in the vicinity of the irrigation ditch (< 100 cm), while other areas remained dry. Consequently, a large part of the cultivation field could not be supplied with sufficient water, which resulted in the desiccation of mosses. The recovery of photosynthesis and survival of *Sphagnum* mosses decrease with the duration of a desiccation period (Wagner & Titus 1984). Insufficient and more heterogenous distribution of irrigation water therefore led to a lower establishment success at Drenth compared to Provinzialmoor. Surprisingly, the measured values of saturated hydraulic conductivity (K_s) were significantly higher at Drenth than at Provinzialmoor, which should have led to a better distribution of irrigation water at Drenth. Nevertheless, K_s was also low at Drenth and, at both sites, corresponded to typical K_s values of highly decomposed peat (Baden & Eggelsmann 1963), and measurement locations were not evenly distributed over the whole study site. However, the water table was not close to the surface for much of the summer, which increases the importance of the unsaturated hydraulic conductivity for water movement in the peat. Such data could help to explain the apparent discrepancy between the K_s values and *Sphagnum* growth patterns.

Residual peat thickness

The residual peat thickness differed significantly between the sites with a much thinner peat layer at Drenth. BRTs indicated that cover of *Sphagnum* was positively correlated with peat layer thickness. In a modelling study, Dixon *et al.* (2017) have demonstrated that peatlands with shallow peat deposits (less than 50 cm) are least able to buffer prolonged periods of evapotranspiration due to limited water storage and will thus quickly experience drought stress. Therefore, such shallow systems will only be productive during wet periods (Dixon *et al*. 2017). However, Dixon *et al*. (2017) assumed an impermeable layer below the peat, while in the case of our study site, which is underlain by sandy material, water might be additionally lost by seepage, especially when ditches cut into the mineral soil, or *via* the unknown drainage pipes at Provinzialmoor. In order to avoid unnecessary water loss, irrigation ditches should be installed only if at least 50 cm residual peat thickness is present under the ditch bed. If dams are created for the area installation, this peat demand must be included in the calculation of the planned residual peat thickness after peat extraction. Overall, leaving a thicker peat layer after extraction keeps remnant peat conditions favourable, resembling natural peatland properties and facilitating *Sphagnum* farming as well as bog restoration (Lundin 2017).

Microclimate and vascular plants

We observed that a favourable microclimate can promote successful establishment of *Sphagnum*, especially with the difficult hydrological condition of shallow layers of highly decomposed peat and an insufficient availability of irrigation water. The BRTs indicated that the cover of vascular plants positively influenced *Sphagnum* establishment. The cover of vascular plants at Provinzialmoor was higher than at Drenth, which might have contributed to better growth of *Sphagnum* at Provinzialmoor despite the lower water table. Vascular plants improve the microclimate by increasing relative humidity and balancing surface temperatures. Furthermore, they also access deeper soil water with their roots and could, once established, improve the survival and growth of *Sphagnum*, especially in drier climates or when abiotic conditions are sub-optimal (Tuittila *et al.* 2000, Pouliot *et al.* 2011, Guêné-Nanchen *et al.* 2017). However, at the same time, vascular plants might increase evapotranspiration due to their higher leaf area index and deeper roots and could thus contribute to the lower water table at Provinzialmoor. Still, the *Sphagnum* carpet without a cover of vascular plants became pale and brittle over the summer, those protected by vascular plants remained intact and green over the dry period in summer. This was also observed by McNeil & Waddington (2003), who emphasised the importance of stable moisture availability for the growth of *Sphagnum*. In addition, vascular plants provide mechanical support for the mosses (Pedersen 1975, Malmer *et al.* 1994, Pouliot *et al.* 2011). However, vascular plants can reduce *Sphagnum* growth, if their interception of light reduces the photosynthetically active radiation (PAR) by more than 50 % (Clymo & Hayward 1982).

In addition to the presence of vascular plants, the shape and location of a site can also substantially influence evapotranspiration and microclimate (Brust *et al.* 2018). The site Drenth is a long strip and borders on areas with active peat extraction, which are still drained. A drained environment increases the water loss of a wet cultivation area by the advection of drier ambient air, also called the "oasis effect" (Succow & Joosten 2001). In comparison, the site Provinzialmoor has a rectangular shape and is surrounded by rewetted polders. In theory, this should clearly increase humidity and thus favour *Sphagnum* growth, but measurements at both sites did not show differences in humidity near the ground surface (Oestmann *et al.* 2021). However, the situation might have been different in the early phase of the project when the irrigation was not yet fully functional at Drenth.

Geotextile *vs*. straw

Especially in the initial phase of a cultivation site, *Sphagnum* fragments need to be protected from desiccation (Quinty & Rochefort 2003). The geotextile used in this study enabled a more even shading and faster installation in the field compared to the manual spreading of straw mulch. However, this study indicated that geotextiles (50 % shade) are nevertheless not a viable alternative to straw mulch in providing shade and keeping the surface of the peat moist. Even though small-scale trials have shown promising results with geotextile (Klasmann-Deilmann GmbH, personal communication), BRTs indicated that the moss fragments established better when covered with straw (application density 80 %).

While using geotextile, *Sphagnum* establishment was hampered mostly when the geotextile got saturated with water (e.g. through precipitation), creating an impervious layer, which led to anoxic conditions. When wind speed was high, the geotextile flapped and lifted the fragments off the peat. Attempts to equip the large geotextile pieces with space holders failed in our experiments as they tore the fabric. The geotextile therefore failed to provide a suitable microclimate, which is especially important in the initial phase when *Sphagnum* fragments are most vulnerable (Campeau & Rochefort 1996). Even after the removal of the geotextile the mosses did not recover, which led to a low cover of the *Sphagnum* carpet in the parts of the sites where geotextile was used. Additionally, the appropriate disposal of geotextile is expensive as well as the disposal of the sand bags needed to secure it. Straw mulch has the advantage that it does not have to be removed from the site because it decomposes over time. Overall this study confirms that straw mulch is a suitable material to promote establishment of *Sphagnum* fragments if constant water supply cannot be ensured (Quinty & Rochefort 2003, Pouliot *et al*. 2015; Gaudig *et al*. 2018).

Irrigation system in the initial phase

The data on the water table and other site conditions during our monitoring period could not fully explain why *Sphagnum* growth was much lower at the site Drenth. Therefore, both the water quality and the initial phase of the project need to be taken into consideration. While at Provinzialmoor the irrigation polders fell dry in the summer months, at Drenth groundwater was pumped into the retention ponds to maintain a sufficient water supply there. This led to higher concentrations of nutrients in the irrigation water, but not in the dipwells. However, in the initial phase (first six months) the irrigation system at Drenth was not fully functional (e.g. broken pumps) and the fragments were not provided with sufficient water, which could have restricted *Sphagnum* growth during the initial phase or even damaged the *Sphagnum* fragments beyond recovery.

RECOMMENDATIONS FOR *SPHAGNUM* FARMING

From our results we derive the following recommendations for *Sphagnum* farming on shallow layers of highly decomposed black peat:

- Ensure a sufficient quantity and quality of water (rainwater).
- Plan for additional water needs for years with low precipitation and limit water loss. The sites may need continuous irrigation through the vegetation period, especially in the wake of climate change (IPCC 2019).
- When working on cut-over sites, leave a sufficient thickness of the residual peat layer (> 50 cm) and avoid creating ditches, which cut into the underlying mineral soil.
- Avoid flooding (especially when using water with high amounts of nutrients).
- Assure a fully functional irrigation (and monitoring) system before introducing *Sphagnum* fragments.
- Protect mosses from desiccation in the initial phase by covering them with straw, not geotextile.
- Ensure a favourable microclimate (site geometry, rewetted surrounding area and reasonable management of vascular plants).

ACKNOWLEDGEMENTS

The establishment of the cultivation sites and the accompanied research were funded by the Lower Saxony Ministry for Nutrition, Agriculture and Consumer Protection (ML, AZ 105.1-3234/1-13-3) and the German Federal Environmental Foundation (DBU, AZ 33305/01-33/0), whose support is gratefully acknowledged. The permissions granted by the Weser-Ems Office for Regional State Development (State Bog Administration) and the County Emsland facilitated the project. We thank our project partners Klasmann-Deilmann GmbH for the productive cooperation. Dr. Ullrich Dettmann, Mareille Wittnebel and Jan Oestmann provided data regarding soil properties and water quality. Dr. Arndt Piayda has contributed valuable data on hydraulic conductivity. Dr. Michel Bechtold's adaptation of the BRT model considerably improved the data analysis. Prof. Dr. Michael Rode has provided valuable insights and advice. Their contributions are kindly appreciated. We also thank the students who helped in the field and in the laboratory.

AUTHOR CONTRIBUTIONS

AG collected the data and wrote the first draft with contributions from BT. MG designed the experimental sites and planned the study. AG and BT conducted the statistical analyses. All authors contributed to the final version of the manuscript.

REFERENCES

Ad-hoc-AG Boden (2005) *Bodenkundliche Kartieranleitung* (*Soil Mapping Manual*). E. Schweizerbart, Hannover, 438 pp. (in German).

Baden, W., Eggelsmann, R. (1963) Zur Durchlässigkeit der Moorböden (On the hydraulic conductivity of peat soils). *Zeitschrift für Kulturtechnik*, 4, 226–254 (in German).

Bechtold, M., Tiemeyer, B., Laggner, A., Leppelt, T., Frahm, E., Belting, S. (2014) Large-scale regionalization of water table depth in peatlands optimized for greenhouse gas emission upscaling. *Hydrology and Earth System Sciences*, 18, 3319–3339.

Beyer, C., Höper, H. (2015) Greenhouse gas exchange of rewetted bog peat extraction sites and a *Sphagnum* cultivation site in northwest Germany. *Biogeosciences*, 12, 2101–2117.

Blankenburg, J. (2004) Praktische Hinweise zur optimalen Wiedervernässung von Torfabbauflächen (Guidelines for optimal rewetting of peat cut areas). *Geofakten 14*, Niedersächsisches Landesamt für Bodenforschung, Bremen, 11 pp. Online at: http://www.lbeg.niedersachsen.de/download/882, accessed 18 Dec 2018 (in German).

Blievernicht, A., Irrgang, S., Zander, M., Ulrichs, C. (2011) Produktion von Torfmoosen (*Sphagnum* sp.) als Torfersatz im Erwerbsgartenbau (Production of peat moss (*Sphagnum* sp.) as an alternative for peat in professional horticulture). *Gesunde Pflanze*, 4, 125–131 (in German).

Blievernicht, A., Irrgang, S., Zander, M., Ulrichs, C. (2013) *Sphagnum* biomass - the next generation of growing media. *Peatlands International*, 2013-1, 32–35.

Brand, EW., Premchitt, J. (1980) Shape factors of cylindrical piezometers. *Geotechnique*, 30, 4, 369–384.

Brust, K., Krebs, M., Wahren, A., Gaudig, G., Joosten, H. (2018) The water balance of a *Sphagnum* farming site in north-west Germany. *Mires and Peat*, 20, 10, 12 pp.

Campeau, S., Rochefort, L. (1996) *Sphagnum* regeneration on bare peat surfaces: field and greenhouse experiments. *Journal of Applied Ecology*, 33, 599–608.

Campeau, S., Rochefort, L., Price, J.S. (2004) On the use of shallow basins to restore cutover peatlands: Plant establishment. *Restoration Ecology*, 12, 471–482.

Caporn, S.J.M., Rosenburgh, A.E., Keightley, A.T., Hinde, S.L., Riggs, J.L., Buckler, M., Wright, N.A. (2018) *Sphagnum* restoration on degraded blanket and raised bogs in the UK using micropropagated source material: a review of progress. *Mires and Peat*, 20, 09, 17 pp.

Caspers, G (2010) Die Unterscheidung von Torfarten in der bodenkundlichen und geologischen Kartierung (Differentiating different types of peat in pedological and geological mapping). *Telma*, 40, 33–66 (in German).

Clymo, R.S., Hayward, P.M. (1982) The ecology of *Sphagnum*. In: Smith, A.J.E. (ed.) *Bryophyte Ecology*, Chapman & Hall, London, 229–289.

Dahl, M., Krebs, M., Unterseher, M., Urich, T., Gaudig, G. (2020) Temporal dynamics in the taxonomic and functional profile of the Sphagnum-associated fungi (mycobiomes) in a Sphagnum farming field site in Northwestern Germany. *FEMS Microbiology Ecology*, 96, 11, 11 pp.

Dixon, S.J., Kettridge, N., Moore, P.A., Devito, K.J., Tilak, A.S., Petrone, R.M., Mendoza, C.A., Waddington, J.M. (2017) Peat depth as a control on moss water availability under evaporative stress. *Hydrological Processes*, 31, 23, 4107–4121.

DWD (2019) Deutscher Wetterdienst: Mittelwerte der Periode 2016–2018 (German Weather Service: mean values for the period 2016–2018). Online at: https://www.dwd.de/DE/klimaumwelt/cdc/cdc_node.html, accessed 10 Jan 2019 (in German).

Elith, J., Leathwick, J.R., Hastie, T. (2008) A working guide to boosted regression trees. *Journal of Animal Ecology*, 77, 802–813.

Emmel, M. (2008) Growing ornamental plants in *Sphagnum* biomass. *Acta Horticulturae*, 779, 173–178.

Frahm, J-P., Frey, W. (2003) *Moosflora* (*Moss Flora*). Ulmer, Stuttgart, 538 pp.

Gaudig, G., Fengler, F., Krebs, M., Prager, A., Schulz, J., Wichmann, S., Joosten, H. (2014) *Sphagnum* farming in Germany - a review of progress. *Mires and Peat*, 13, 08, 11 pp.

Gaudig, G., Krebs, M., Joosten, H. (2017): *Sphagnum* farming on cut-over bog in NW Germany: Long-term studies on *Sphagnum* growth. *Mires and Peat*, 20, 04, 19 pp.

Gaudig, G., Krebs, M., Prager, A., Wichmann, S. and 30 others (2018) *Sphagnum* farming from species selection to the production of growing media: a review. *Mires and Peat*, 20, 13, 30 pp.

Gaudig, G., Krebs, M., Joosten, H. (2020) *Sphagnum* growth under N saturation: interactive effects of water level and P or K fertilization. *Plant Biology*, 22, 394–403.

Glatzel, S., Rochefort, L. (2017) Growing *Sphagnum*: Foreword. *Mires and Peat*, 20, 00, 3 pp.

González, E., Rochefort, L. (2014) Drivers of success in 53 cutover bogs restored by a moss layer transfer technique. *Ecological Engineering*, 68, 279–290.

Graf, M., Bredemeier, B., Grobe, A., Köbbing, J.F., Lemmer, M., Oestmann, J., Rammes, D., Reich, M., Schmilewski, G., Tiemeyer, B., Zoch, L. (2017) Torfmooskultivierung auf Schwarztorf: ein neues Forschungsprojekt in Niedersachsen (*Sphagnum* farming on highly decomposed peat: a new research project in Lower Saxony). *Telma*, 47, 109–128 (in German).

Greenwell, B., Boehmke, B., Cunningham, J., GBM Developers (2019) R package "gbm": *Generalized Boosted Regression Models*. Version 2.1.5. Online at: https://CRAN.R-project.org/package=gbm

Guêné-Nanchen, M., Pouliot, R., Hugron, S., Rochefort, L. (2017) Effect of repeated mowing to reduce graminoid plant cover on the moss carpet at a *Sphagnum* farm in North America. *Mires and Peat*, 20, 06, 12 pp.

Gunnarsson, U. (2005) Global patterns of *Sphagnum* productivity. *Journal of Bryology*, 27, 269–279.

Günther, A., Jurasinski, G., Albrecht, K., Gaudig, G., Krebs, M., Glatzel, S. (2017) Greenhouse gas balance of an establishing *Sphagnum* culture on a former bog grassland in Germany. *Mires and Peat*, 20, 02, 16 pp.

Hájek, T. (2009) Habitat and species controls on *Sphagnum* production and decomposition in a mountain raised bog. *Boreal Environment Research*, 14, 947–958.

Hayward, P., Clymo, R. (1983) The growth of *Sphagnum*: experiments on, and simulation of, some effects of light flux and water-table depth. *Journal of Ecology*, 71, 845–863.

Hendry, G.A.F., Grime, J.P. (1993) *Methods in Comparative Plant Ecology: a Laboratory Manual*. Chapman and Hall, London, 252 pp.

Hijmans, R.J., Phillips, S., Leathwick, J., Elith, J. (2017) R package "dismo": *Species Distribution Modeling*. Version 1.1-4. Online at: https://CRAN.R-project.org/package=dismo

Hoelzer, A. (2010) *Die Torfmoose Südwestdeutschlands und der Nachbargebiete* (*Sphagnum Mosses of Southwestern Germany and Neighbouring Areas*). Weissdorn-Verlag, Jena, 248 pp. (in German).

Hoshi, Y. (2017) *Sphagnum* growth in floating cultures: Effect of planting design. *Mires and Peat*, 20, 08, 10 pp.

Hugron, S., Rochefort, L. (2018) *Sphagnum* mosses cultivated in outdoor nurseries yield efficient plant material for peatland restoration. *Mires and Peat*, 20, 11, 6 pp.

Hvorslev, M.J. (1951) *Time Lag and Soil Permeability in Ground-Water Observations*. Bulletin No. 36, Waterways Experiment Station, US Army Corps of Engineers, Vicksburg, Mississippi, USA, 55 pp.

IPCC (2019) Special report on climate change, desertification, land degradation, sustainable land management, food security, and greenhouse gas fluxes in terrestrial ecosystems - summary for policymakers [Shukla, P.R., Skea, J., Calvo Buendia, E., Masson-Delmotte, V., Pörtner, H-O., Roberts, D.C., Zhai, P., Slade, R., Connors, S., van Diemen, R., Ferrat, M., Haughey, E., Luz, S., Neogi, S., Pathak, M., Petzold, J., Portugal Pereira, J., Vyas, P., Huntley, E., Kissick, K., Belkacemi, M., Malley, J. (eds.)]. *Climate Change and Land*, 36 pp.

Jobin, P., Caron, J., Rochefort, L. (2014) Developing new potting mixes with *Sphagnum* fibers. *Canadian Journal of Soil Science*, 94, 585–593.

Johnson, L.C., Damman, A.W.H. (1991) Species-controlled *Sphagnum* decay on a South Swedish raised bog. *Oikos*, 61, 234–242.

Karofeld, E., Müür, M., Vellak, K. (2016) Factors affecting re-vegetation dynamics of experimentally restored extracted peatland in Estonia. *Environmental Science and Pollution Research*, 23, 13706–13717.

Krebs, M., Gaudig, G., Joosten, H. (2016) Record growth of *Sphagnum papillosum* in Georgia (Transcaucasus): rain frequency, temperature and microhabitat as key drivers in natural bogs. *Mires and Peat*, 18, 04, 16 pp.

Liu, H., Lennartz B. (2019) Hydraulic properties of peat soils along a bulk density gradient - A meta study. *Hydrological Processes*, 33, 101–114.

Londo, G. (1976) The decimal scale for releves of permanent quadrats. *Vegetatio*, 33, 1, 61–64.

Lundin, L., Nilsson, T., Jordan. S., Lode, E., Strömgren, M. (2017) Impacts of rewetting on peat, hydrology and water chemical composition over 15 years in two finished peat extraction areas in Sweden. *Wetlands Ecology and Management*, 25, 4, 405–419.

Lütt, S. (1992) Produktionsbiologische Untersuchungen zur Sukzession der Torfstichvegetation in Schleswig-Holstein (Succession and productivity of peat pit vegetation in Schleswig-Holstein). *Mitteilungen der Arbeitsgemeinschaft Geobotanik in Schleswig-Holstein und Hamburg*, 43, 250 pp. (in German).

Malmer, N., Svensson, B.M., Wallén, B. (1994) Interactions between *Sphagnum* mosses and field layer vascular plants in the development of peatforming systems. *Folia Geobotanica*, 29, 483–496.

McNeil, P., Waddington, J.M. (2003) Moisture controls on *Sphagnum* growth and CO_2 exchange in a cutover bog. *Journal of Applied Ecology*, 40, 354–367.

Money, R.P. (1994) *Restoration of Lowland Raised Bogs Damaged by Peat Extraction - with Particular Emphasis on Sphagnum Regeneration*. PhD thesis, University of Sheffield, UK, 221 pp.

Muster, C., Gaudig, G., Krebs, M., Joosten, H. (2015) *Sphagnum* farming: the promised land for peat bog species? *Biodiversity and Conservation*, 24, 8, 1989–2009.

Muster, C., Krebs, M., Joosten, H. (2020) Seven years of spider community succession in a *Sphagnum* farm. *Journal of Arachnology*, 48, 119–131.

NMELF (1981) *Niedersächsisches Moorschutzprogramm Teil I* (*Lower Saxony Mire Conservation Programme Part 1*). Niedersächsischer Minister für Ernährung, Landwirtschaft und Forsten (NMELF), Hannover, 37 pp. (in German).

Oberpaur, C., Puebla, V., Vaccarezza, F., Arévalo, M.E. (2010) Preliminary substrate mixtures including peat moss (*Sphagnum magellanicum*) for vegetable crop nurseries. *Ciencia Investigación Agraria*, 37, 123–132.

Oestmann, J., Tiemeyer, B., Düvel, D., Grobe, A., Dettmann, U. (2021) Greenhouse gas balance of *Sphagnum* farming on highly decomposed peat at former peat extraction sites. *Ecosystems*, 22 pp. https://doi.org/ 10.1007/s10021-021-00659-z.

Pedersen, A. (1975) Growth measurements of five *Sphagnum* species in South Norway. *Norwegian Journal of Botany*, 22, 277–284.

Pouliot, R., Rochefort, L., Karofeld, E., Mercier, C. (2011) Initiation of *Sphagnum* moss hummocks in bogs and the presence of vascular plants: Is there a link? *Acta Oecologica*, 37, 346–354.

Pouliot, R., Hugron, S., Rochefort, L. (2015) *Sphagnum* farming: A long-term study on producing peat moss biomass sustainably. *Ecological Engineering*, 74, 135–147.

Price, J.S., Heathwaite, A.L., Baird, A.J. (2003) Hydrological processes in abandoned and restored peatlands: An overview of management approaches. *Wetlands and Ecology Management*, 11, 1–2, 65–83.

Quinty, F., Rochefort, L. (2003) *Peatland Restoration Guide: Second Edition*. Canadian *Sphagnum* Peat Moss Association (St. Albert, AB) & New Brunswick Department of Natural Resources and Energy (Fredericton, NB), Canada, 106 pp. Online at: http://www.gret-perg.ulaval.ca/uploads/tx_centrerecherche/Peatland_Restoration_guide_2ndEd.pdf, accessed 08 May 2018.

R Development Core Team (2019) *R: A Language and Environment for Statistical Computing*. R Foundation for Statistical Computing, Vienna, Austria. Online at: http://www.r-project.org

Reinikainen, O., Korpi, J., Tahvonen, R., Näkkilä, J., Silvan, N., Silvan, K. (2012) Harvesting of *Sphagnum* biomass and its use as a growing medium constituent. Abstract No. 137, *Proceedings of the 14th International Peat Congress*, International Peat Society, Stockholm, Sweden, 6 pp.

Robroek, B.J.M., van Ruijven, J., Schouten, G.C., Breeuwer, A., Crushell, P.H., Berendse, F., Limpens, J. (2009) *Sphagnum* re-introduction in degraded peatlands: The effects of aggregation, species identity and water table. *Basic and Applied Ecology*, 10, 697–706.

Rochefort, L., Campeau, S., Bugnon, J.L. (2002) Does prolonged flooding prevent or enhance regeneration and growth of *Sphagnum*? *Aquatic Botany*, 74, 327–341.

Rochefort, L., Quinty, F., Campeau, S., Johnson, K., Malterer, T. (2003) North American approach to the restoration of *Sphagnum* dominated peatlands. *Wetlands Ecology and Management*, 11, 3–20.

Rydin, H., Jeglum, J.K. (2009) *The Biology of Peatlands*. Second edition, Oxford University Press, 400 pp.

Surridge, B.W.J., Baird, A.J., Heathwaite, A.L. (2005) Evaluating the quality of hydraulic conductivity estimates from piezometer slug tests in peat. *Hydrological Processes*, 19, 6, 1227–1244.

Tiemeyer, B., Freibauer, A., Borraz, E.A., Augustin, J., Bechtold, M., Beetz, S., Beyer, C., Ebli, M., Eickenscheidt, T., Fiedler, S., Förster, C., Gensior, A., Giebels, M., Glatzel, S., Heinichen, J., Hoffmann, M., Höper, H., Jurasinski, G., Laggner, A., Leiber-Sauheitl, K., Brak, M., Drösler, M. (2020) A new methodology for organic soils in national greenhouse gas inventories: Data synthesis, derivation and application. *Ecological Indicators*, 109, 105838, 14 pp.

Tuittila, E.-S., Rita, H., Vasander, H., Laine, J. (2000) Vegetation patterns around *Eriophorum vaginatum* L. tussocks in a cut-away peatland in southern Finland. *Canadian Journal of Botany*, 78, 47–58.

Von Post, L. (1924) Das genetische System der organogenen Bildungen Schwedens (The genetic system of the organogenic formations of Sweden). In: Comité International de Pédologie, IVème commission (commission pour la nomenclature et la classification des sols, commission pour l'Europe, président: B. Frosterus) (ed.) *Mémoires sur la Nomenclature et la Classification des Sols*, Helsingfors/Helsinki, 287–304 (in German).

Waddington, J.M., Price, J.S. (2000) Effect of peatland drainage, harvesting, and restoration on atmospheric water and carbon exchange. *Physical Geography*, 21, 5, 433–451.

Wagner, D.J., Titus, J.E. (1984) Comparative desiccation tolerance of two *Sphagnum* mosses. *Oecologia*, 62, 182–187.

Wichmann, S., Prager, A., Gaudig, G. (2017) Establishing *Sphagnum* cultures on bog grassland, cut-over bogs, and floating mats: procedures, costs and area potential in Germany. *Mires and Peat*, 20, 03, 19 pp.

Wichtmann, W., Schröder, C., Joosten, H. (eds.) (2016) *Paludiculture - Productive Use of Wet Peatlands*. Schweizerbart Science Publishers, Stuttgart, 272 pp.

Wickham, H. (2016) *ggplot2: Elegant Graphics for Data Analysis*. Springer-Verlag, New York, 213 pp.

Zoch, L., Reich, M. (2020) Torfmooskultivierungsflächen als neuer Lebensraum für Moorlibellen (*Sphagnum* cultivation sites provide new habitats for peatland dragonflies). *Libellula*, 39 ,1–2, 27–48 (in German).

Submitted 12 Jun 2020, final revision 30 Jun 2021
Editor: Ab Grootjans

Author for correspondence:
Amanda Grobe, Institute of Environmental Planning, Leibniz University Hannover, Herrenhäuser Straße 2, 30419 Hannover, Germany. Tel: +49 511 762 4054; E-mail: grobe@umwelt.uni-hannover.de