The water balance of a Sphagnum farming site in north-west Germany

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SUMMARY

Sphagnum farming provides a sustainable wet land use alternative for drained peatland agriculture. Since 2011 *Sphagnum* has been cultivated on formerly drained bog grassland at Hankhauser Moor in north-west Germany. The site has been rewetted and is equipped with an automatic irrigation system which controls the inflow and outflow of water. We used measurements and models to determine the amount of irrigation water needed to keep the water table just below the *Sphagnum* surface throughout the year. In winter there was a water surplus, whereas in spring and summer evapotranspiration exceeded precipitation, creating a water deficit. Next to evapotranspiration, horizontal seepage was a major cause of water loss. Modelling indicated that the amount of irrigation required to make up the water deficit in the dry hydrological year 2013 (November 2012 to October 2013) amounted to 359 mm (3,588 m^3 ha^{-1}). To compensate for the average water deficit over the 20-year period 1993–2013, 160 mm of water would be needed annually (*i.e.* 1,600 m^3 ha^{-1} yr^{-1}), but the maximum water deficit accumulated during that period was much higher, at 6,363 m^3 ha^{-1}. In relative terms, both evapotranspiration and seepage losses will decrease with increasing size of the rewetted area because drained surroundings enhance water losses from the wetter Sphagnum farming site, both as evapotranspiration due to advection (oasis effect) and as horizontal seepage due to steepening of hydraulic gradients. For successful Sphagnum farming the water demand must be considered and an appropriate water supply must be guaranteed.

KEY WORDS: irrigation demand, paludiculture, peatland rewetting, *Sphagnum* cultivation, water management

INTRODUCTION

Paludiculture, the cultivation of biomass on wet or rewetted peatlands, provides sustainable land use options for drained peatlands and allows peatlands to be used for agriculture without degrading the peat layer (Wichtmann *et al.* 2016). Sphagnum farming is the commercial production of *Sphagnum* (peatmoss) biomass in paludiculture, *e.g.* for use in horticultural substrates (Gaudig *et al.* 2018). Various field studies have demonstrated the feasibility of Sphagnum farming on rewetted drained bogs that were formerly used as pasture (bog grassland) or for peat extraction (Krebs *et al.* 2012, Gaudig *et al.* 2014, Pouliot *et al.* 2015, Brown *et al.* 2017, Wichmann *et al.* 2017).

Sphagnum depends on water retention and capillary rise, and cannot actively control its own water supply and losses like vascular plants, because it lacks roots, a water transport system in the stems and stomata in the leaves (McCarter & Price 2014). Thus, to achieve high productivity, water supply by precipitation (Hayward & Clymo 1983, Robroek *et al.* 2009, Nijp *et al.* 2014, Krebs *et al.* 2016) combined with capillary movement from the water table must be sufficient to maintain stable moisture conditions and keep the peatmoss optimally wet (Price & Whittington 2010, Brown *et al.* 2017). The highest *Sphagnum* biomass productivity is obtained with a stable water table just a few centimetres below the peatmoss surface (Gaudig *et al.* 2014).

North-west Germany has the largest concentration of bogs in Germany and is, therefore, the area with the highest potential for Sphagnum farming in the country (Trepel *et al.* 2017, Wichmann *et al.* 2017). Under natural conditions atmospheric water supply provides enough water to cover the evaporative demand and all additional losses. In the present widely drained landscape, however, precipitation alone cannot ensure permanently wet conditions, particularly in summer when evapotranspiration commonly exceeds precipitation (Wichtmann *et al.* 2016). Consequently, Sphagnum farming requires a water management system that enables irrigation in periods of water deficit and allows water discharge *via* overflow to avoid flooding in times of water excess (Gaudig *et al.* 2017, Wichmann *et al.* 2017).

In 2011 a Sphagnum farming site was established on 4 ha of bog grassland on the Hankhauser Moor (Lower Saxony, north-west Germany) (Krebs *et al.* 2012, Wichmann *et al.* 2017). This site offered a first opportunity to investigate the water balance of a Sphagnum farming site in Europe. In this article we

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address the following questions:

- How much water is needed to keep the water table just below the *Sphagnum* surface throughout the year?
- In which periods do water excesses and deficits occur?
- What are the main causes of water loss?

METHODS

Study area

The 4 ha Sphagnum farming site (53° 15.80' N, 08° 16.05' E) is situated on the Hankhauser Moor near Rastede in Lower Saxony, north-west Germany (Figure 1a), on a bog underlain by fen peat and sand (Figure 1c). Since 1958 the study area has been used as deeply drained grassland. The uppermost 30–50 cm of strongly degraded peat was removed prior to establishment of the *Sphagnum* lawn (Wichmann *et al.* 2017), exposing a 30 cm *Sphagnum* peat layer (section Cymbifolia) with horizontal and vertical saturated hydraulic conductivity 236 and 113 cm day^{-1}, respectively (Figure 1c, Rosskopf *et al.* 2016). The deeper peat layers have much lower hydraulic conductivity and consist of Cuspidata peat (~ 40 cm thick), Acutifolia peat (~120 cm thick) and strongly decomposed fen peat (Figure 1c). The low permeability of these peat layers, combined with the high groundwater level in the underlying aquifer (LBEG 2015), results in very limited vertical seepage to the mineral subsoil. Groundwater equipotentials (isohypses; LBEG 2015) show that the underground catchment area is 22 km², with groundwater flowing eastward to the study area from a more elevated sandy plain.

The site consists of level *Sphagnum* production fields 10 m wide, narrow ditches (0.5 m wide and deep) for water management, and bunds (1 m high, 15 m wide at the base) built from the topsoil removed during site preparation, which are used as causeways for machinery and cover 55 %, 5 % and 40 % of the site, respectively (Figures 1b–d; Günther *et al.* 2017). Irrigation water is pumped from the adjacent Schanze stream, east of the study area (Figure 1b), which drains the surrounding territory and cuts into the upper aquifer. The Schanze water level is kept low by pumping water into the North Sea, leading to a distinct hydraulic gradient between the water in the peat (and the groundwater) and the stream itself so the site can be drained into the stream by gravity. An elevated area adjacent to the Schanze (around B1 in Figure 1b) prevents the stream from flooding the production fields, and non-return flaps in the outlet tubes prevent uncontrolled entry of water by that route. The surroundings of the Sphagnum farming site are drained and used as fertilised bog grassland.

Water regulation for the Sphagnum farming site is provided by two independent inlet-outlet systems (Figure 1b). A water balance was constructed for the western system, referred to as the Sphagnum farming trial (Figure 1b, d). It consists of three *Sphagnum* production fields (each 10 m wide, 275 m long) and four irrigation ditches, surrounded by a bund. The *Sphagnum* production fields had an average altitude of -0.85 m a.s.l. (± 0.02, SD) and maximum micro-relief differences of 10 cm (Krebs *et al.* unpublished).

The climate of the study region is warm-temperate with mean annual temperature 9.8 °C, average annual precipitation 849 mm yr^{-1}, and most precipitation in summer (1989–2013; climate stations Rastede and Oldenburg, Figure 2). Precipitation is greater than evapotranspiration on an annual basis, but in spring and summer evapotranspiration exceeds precipitation. Precipitation was less than the long-term mean in both study years (762 mm in 2012, 735 mm in 2013).

Study design

Measurements on the study area

Gauges were set up to measure water levels within the peat (phreatic water level, plastic tubes perforated in the upper 50 cm of peat), the ditches and the Schanze (metal rods in the mineral subsoil), and hydraulic heads in the underlying aquifer (piezometers with slotted intakes of length 1 m, from 3.4 to 4.4 m below the peat surface in the sand) (Figure 1b, d). All points and heights were surveyed with differential GPS and expressed in metres above sea level (m a.s.l.). Water levels were measured manually, at least weekly, between August 2011 and October 2013. Water levels were also recorded every ten minutes at gauges F11, O5, B3, and B7 (Figures 1b, d) using automatic data loggers with automatic compensation for barometric fluctuations (pressure transducer, Hydrotechnik HT Type 575). Differences in measured water levels between gauges were analysed with the non-parametric Kruskal Wallis test and a multiple comparison test after Siegel & Castellan (1988, R package pgirmess, Giraudoux 2010). A weather station was installed on the Sphagnum farming trial (Figure 1d). It measured precipitation (Young 52202), temperature and humidity (Galltec C2.4), global radiation (Type 3.5 Indium Sensor Technic), wind speed and direction as well as soil temperature (AD592).

Water balance components

The water balance of the Sphagnum farming site consists of all inflow and loss components, as well as the change in water storage (ΔS) within the peat

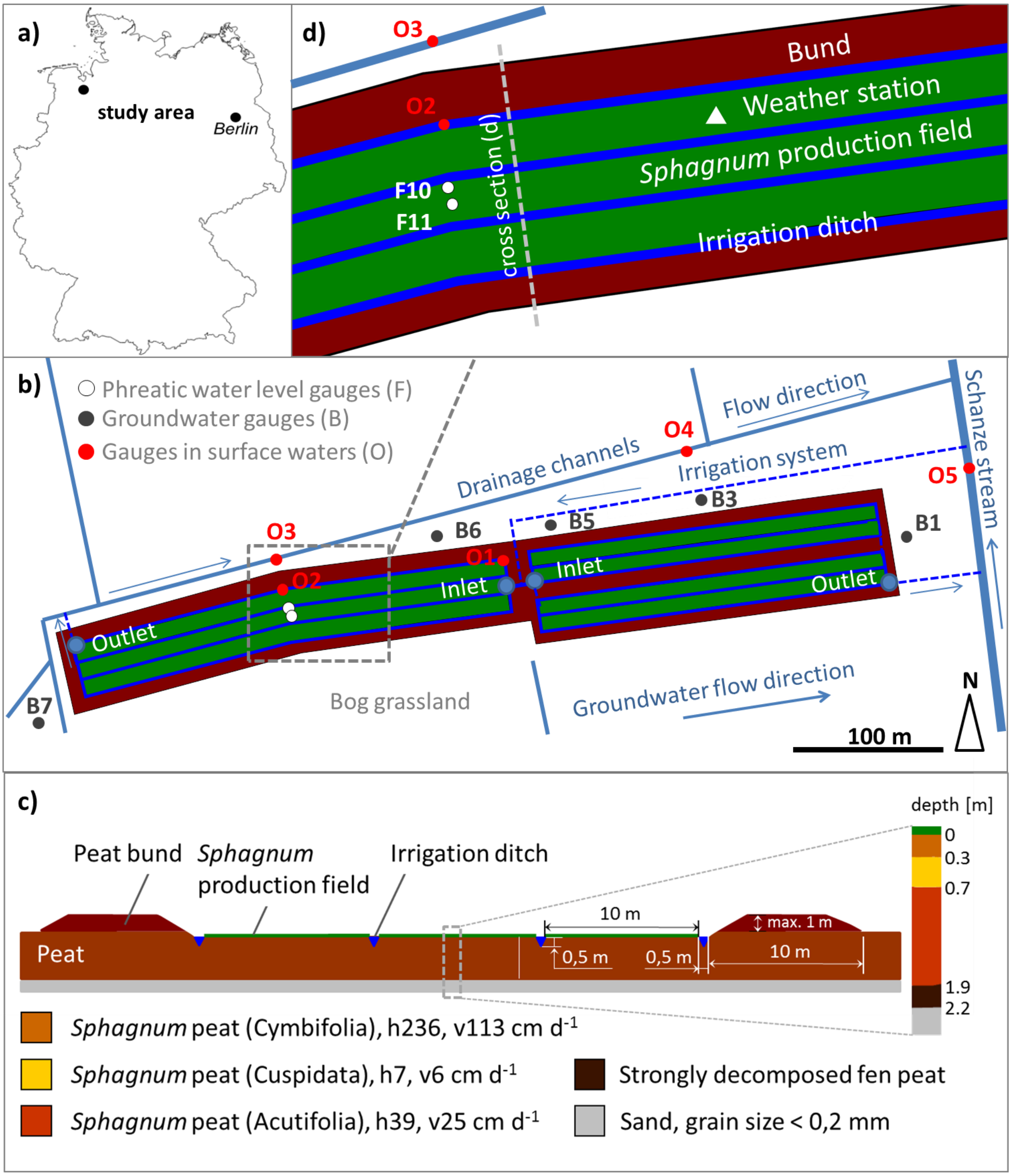

Figure 1. The study area on Hankhauser Moor: a) location in north-west Germany; (b) full extent of the Sphagnum farming site and surrounding bog grassland with irrigation system; (c) cross-section of the Sphagnum farming trial, which consists of three Sphagnum production fields (10 m wide, 275 m long) and four irrigation ditches surrounded by the bund of the western water regulation system, with a profile showing the stratigraphical sequence of peat layers (Krebs *et al*. unpublished data) and their saturated hydraulic conductivities (prefixed h for horizontal and v for vertical, in cm d^{-1}, Rosskopf *et al*. 2016); and d) part of the Sphagnum farming trial. The positions of the weather station (white triangle) and water level gauges (white circles: phreatic, black circles: groundwater, red circles: surface water) are shown.

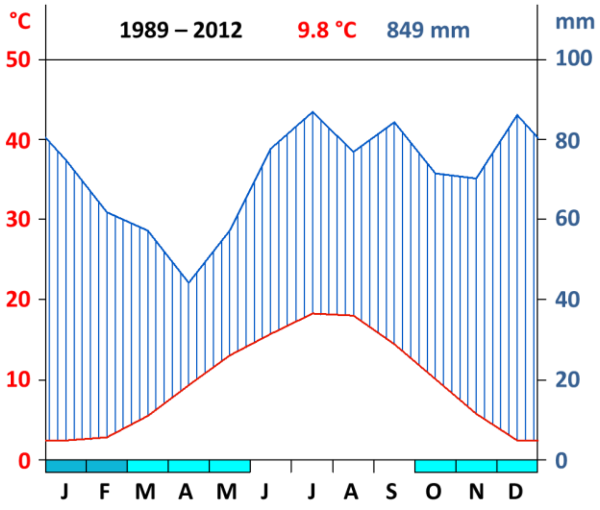

Figure 2. Climate graph (Walter & Lieth 1967) for the meteorological stations Rastede (precipitation, mm) and Oldenburg (temperature, °C), located at distances of 4 km and 11 km, respectively, from the study area. The right-hand vertical axis indicates precipitation in mm *per* calendar month. On the horizontal axis, dark blue panels indicate months when the occurrence of frost is certain, and light blue panels those when it is possible. Data provided by the German Meteorological Service DWD (Deutscher Wetterdienst).

(Figure 3). Water reaches the site as precipitation (P) and inflow (Q_{in}). Water losses include evapotranspiration (ETR), seepage ($Q_{seepage}$) and outflow (Q_{out}):

$$P + Q_{in} = ETR + Q_{seepage} + Q_{out} \pm \Delta S \qquad [1]$$

To construct the water balance for the Sphagnum farming trial (western independent irrigation system), P, Q_{in} and Q_{out} were measured whereas ETR, $Q_{seepage}$ and ΔS were modelled (Table 1).

P was recorded at the weather station from August 2011 to October 2013. The data were checked for plausibility against data from the nearest (Rastede) station operated by the German Meteorological Service DWD (Deutscher Wetterdienst). For long-term water balance simulations we used climate data (1993–2013) from the DWD Bremen station (about 40 km from study area; 53° 2.66' N, 08° 47.89' E).

Inflow to the Sphagnum farming trial was managed by an automatic control system that continuously measured the water level within the trial and, when the water level in the irrigation ditches fell below a predefined level, pumped in water from the Schanze stream. The pump started automatically when the water table dropped 8 cm below the *Sphagnum* surface and stopped at 3 cm below the *Sphagnum* surface. Q_{in} was measured directly by a water meter on the pump, but it was also modelled because water was sometimes pumped by accident when outflow was activated, leading to an over-estimate of the required Q_{in}. Measured Q_{in} was also used to verify modelled water demand.

Outflow was managed manually *via* a discharge pipe in which the water level was measured. Q_{out} was calculated from the water level using the Gauckler-Manning-Strickler formula for flow in partially filled pipes (Bollrich 2007).

As peatland evapotranspiration is a strong function of water table depth, we calculated ETR using the Romanov approach (Edom *et al.* 2010):

$$ETR = \alpha \cdot Rn + C_A \qquad [2]$$

where α is a phreatic water level specific evapotranspiration parameter (Succow & Joosten 2001), Rn is net radiation and C_A is an advective term (Edom 2001). Evaporation (ET) from the ditches was calculated by the Dalton method (DVWK 1996) using wind speed, humidity and water temperature data from the weather station. ETR for the entire Sphagnum farming trial was calculated as the sum of ETR from the three *Sphagnum* production fields (8,125 m²) and ET from the four irrigation ditches (515 m²), and standardised to an area of one hectare.

$Q_{seepage}$, *i.e.* the sum of all underground inflow and outflow (horizontal and vertical), was modelled with the package *Visual MODFLOW* (Version 4.3, Schlumberger Water Services, Waterloo ON, Canada, 2010), using the size and shape of the Sphagnum farming site, peat stratigraphy and soil hydraulic properties (saturated hydraulic conductivity, porosity, bulk density) measured on peat samples from the site (Figure 1c, Rosskopf *et al.* 2016), and assuming a homogeneous aquifer below the peat of thickness 10 m (thickness of top aquifer, NIBIS 2011).

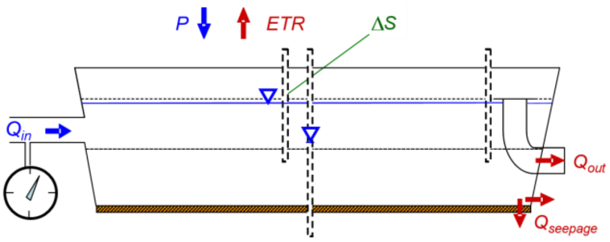

Figure 3. Water balance components. Blue: water inputs (P = precipitation, Q_{in} = inflow); red: water losses (ETR = evapotranspiration, $Q_{seepage}$ = seepage, Q_{out} = outflow); green: plus/minus change in storage (ΔS).

Table 1. Water balance components and measured variables of the Sphagnum farming trial (*cf*. Figures 1, 3).

Water balance component	Abbreviation	Measured variables
Precipitation	P	Direct measurements at the Sphagnum farming trial; missing data were interpolated using data from the Rastede precipitation station operated by the German Meteorological Service DWD.
Evapotranspiration	ETR	Global radiation. Phreatic water level (F).
Change in water storage within peat	ΔS	Phreatic water level (F).
Inflow *via* irrigation system	Q_{in}	Water flow directly metered at pump.
Seepage = net underground inflow (inflow minus outflow)	$Q_{seepage}$	Phreatic water level (F). Surface water level in irrigation ditches, the Schanze stream and the ditch to the North (O). Hydraulic head of groundwater (B).
Outflow from the trial	Q_{out}	Water level in discharge pipes.

Boundary conditions at the eastern and western edges of the model (general head boundary) were set to represent the regional groundwater slope in the underlying aquifer and the groundwater inflow and outflow from east to west. Groundwater recharge was set as upper boundary separately for the Sphagnum farming trial and the surrounding area, due to the differences in ETR. Internal boundaries in the peat layers were ditches (constant water level, reflecting the irrigation) and the surrounding drainage system (Schanze stream and drainage channels, Figure 1b). For the initial conditions a steady state calculation was simulated using the water level measurements from spring 2012. For each month a steady state calculation was done using the measured water levels (constant and general head boundary conditions) and calculated recharge (P - ETR).

Change in water storage (ΔS) in the ditches was determined from the measured change in water level (Δh) and the area of the irrigation ditches (A_1):

$$\Delta S = \Delta h \cdot A_1 \qquad [3]$$

Peat is a porous medium, but only part of the volume is available to store water. Neither the volume occupied by organic matter (substrate volume SV), nor the permanently water-filled fine pores (FP) which cannot be drained by gravity or plant suction, participate in storage changes. Thus, change in water storage was calculated as:

$$\Delta S = \Delta h \cdot A_2 \cdot (1 - (SV + FP)) \qquad [4]$$

where A_2 is the area of the *Sphagnum* production fields.

Water demand

We determined water demand for the hydrological year 2013 (November 2012 to October 2013) by: a) using measured inflow values and b) modelling the water demand required to compensate for water losses by evapotranspiration and seepage as:

$$Water\ demand = \sum(P - ETR - Q_{seepage}) \qquad [5]$$

The measured and modelled results were compared, and measured values were also used to verify the modelled ones. To assess the long-term irrigation demand we undertook a dynamic scenario study to examine the option of using precipitation as the only source of water by storing all excess precipitation in a reservoir for use in times of water demand. For this analysis we used meteorological data from Bremen and assumed constantly high water level in the peatland with steady seepage of 200 mm yr^{-1} (mean model results Visual MODFLOW, Schlumberger Water Services 2010).

RESULTS

Water levels

Between August 2011 and October 2013 the phreatic water levels in the *Sphagnum* production fields were near the peat surface (gauges F10 and F11) and similar at the edge (gauge F10) and the centre (gauge F11, 5 m from the ditch), with an average value of -0.84 m a.s.l., one centimetre above the average altitude of the peat surface and constantly a few centimetres below the *Sphagnum* surface. In the

Sphagnum production fields, water level differences of 20 cm were recorded (range of the whiskers, Figure 4). Water levels in the drainage ditches and the Schanze stream (O5) were considerably lower (Figure 4). The groundwater level was between the level of the phreatic water and that of the drainage ditches, with the mean water level decreasing from B7 to B1 (west to east).

Water balance components

Total precipitation for the hydrological year 2013 (709 mm) was lower than the mean annual precipitation of 849 mm (1989–2013) in Rastede (4 km from the study area). Monthly precipitation (measured) and evapotranspiration (modelled) showed a pronounced annual cycle with evapotranspiration exceeding precipitation between May and August 2013 (Figure 5), leading to a cumulative atmospheric deficit of 280 mm.

During summer, evapotranspiration constituted the largest output flux, whereas during winter the largest output was the outflow *via* ditches (Figure 6). Water losses from evapotranspiration and seepage had to be compensated by irrigation, in particular

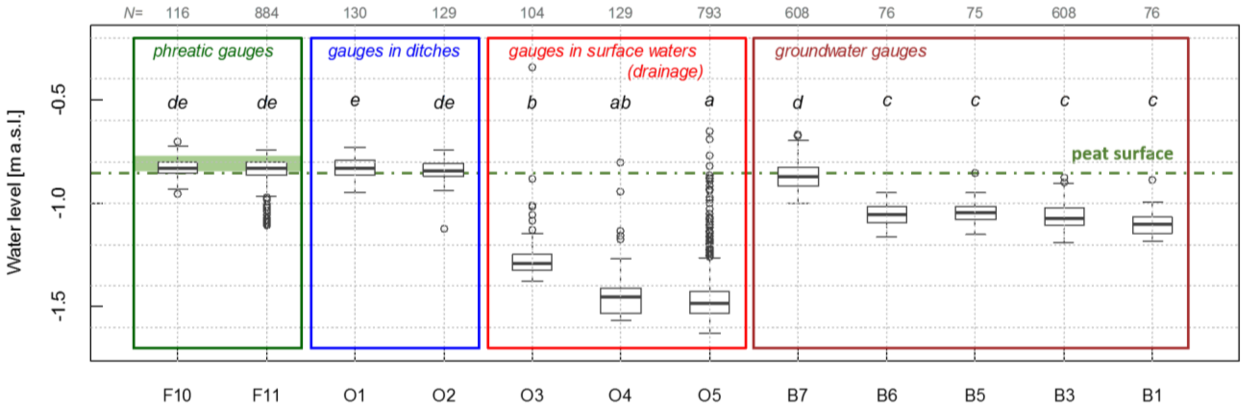

Figure 4. Measured water levels in the study area (Figure 1b, d) for the period August 2011–October 2013, groundwater gauges ordered in groundwater flow direction. The boxplot shows the median (bold line), the upper and lower quartiles (including 50 % of the data and creating the box), the whiskers representing the lowest reading within 1.5 interquartile range (IQR) of the lower quartile and the highest reading within 1.5 IQR of the upper quartile, and the outliers (o), *i.e.* the values outside these ranges. Peat surface (green dotted line) is the mean height in m a.s.l. of the peat surface in the *Sphagnum* production fields of the Sphagnum farming trial (150 observations at the three *Sphagnum* production fields in August 2011, Krebs *et. al.* unpublished data). The solid green box represents the *Sphagnum* lawns on the three *Sphagnum* production fields during the study, thickness 1 cm above peat surface at the beginning of the study and 8 cm at the end of the study (Gaudig & Krebs 2016). Different letters indicate significant differences between measured water levels ($P \leq 0.05$) based on the Kruskal Wallis test and a multiple comparison test after Siegel & Castellan (1988). N = number of measurements.

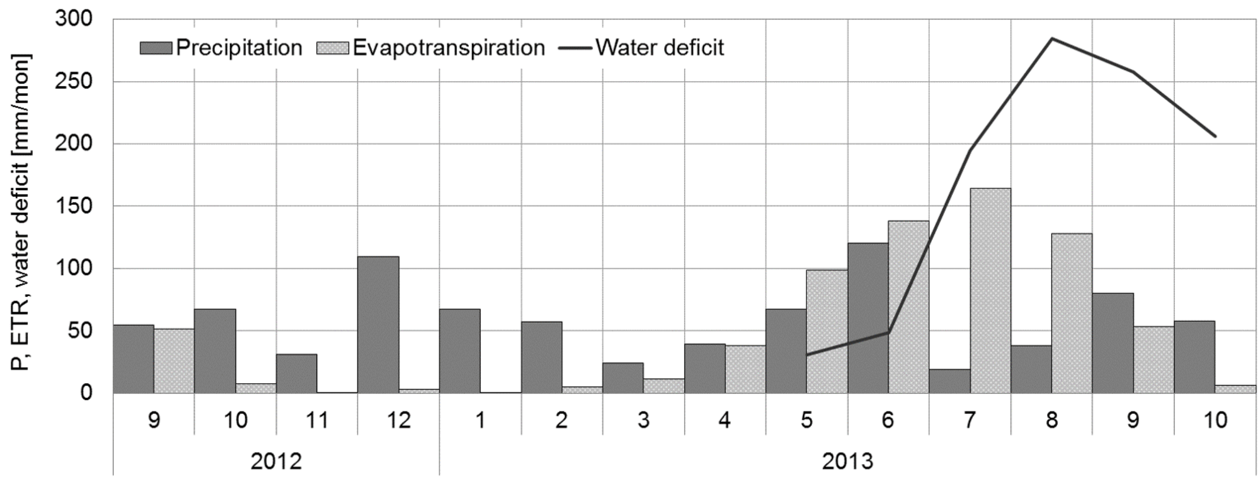

Figure 5. Monthly precipitation (P), evapotranspiration (ETR), and resulting cumulative water deficit from September 2012 to October 2013.

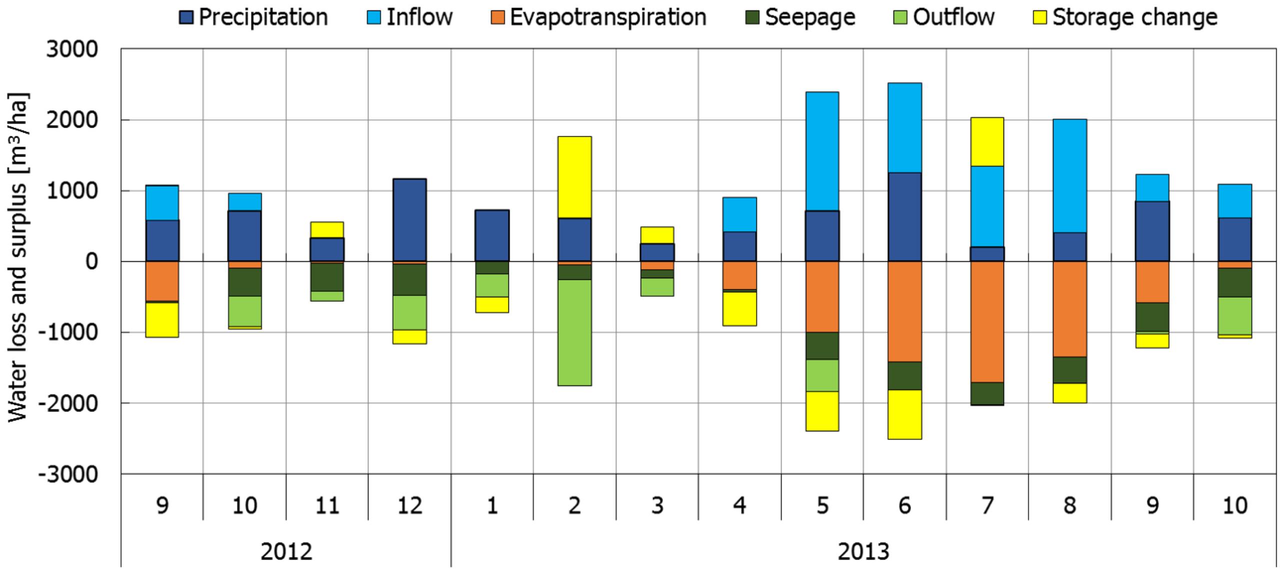

Figure 6. Monthly fluxes for different water balance components (m³ ha^{-1}) and storage change for the period September 2012 to October 2013.

between May and August. For example, in June 2013 the Sphagnum farming trial received 1,181 m³ ha^{-1} of precipitation and required an additional 1,183 m³ ha^{-1} of irrigation water to keep the water table just below the *Sphagnum* surface (Figure 6).

Over the year, 47 % of the incoming water (the sum of precipitation and inflow) was lost as evapotranspiration (Figure 7, Table 2). The remaining water discharged as almost equal amounts of outflow (26 %) and seepage (24 %), while the change in storage accounted for 3 %.

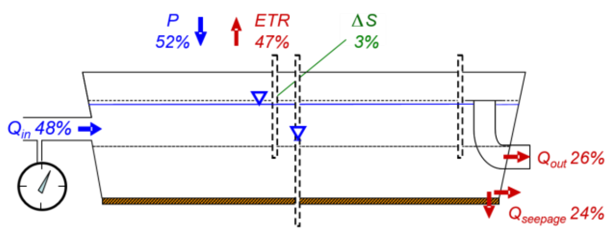

Figure 7. Water balance components of the Sphagnum farming trial (in %) for the hydrological year 2013 (November 2012–October 2013).

Water demand

During the hydrological year 2013 precipitation exceeded water losses in winter (November to February), resulting in 1,890 m³ of outflow. In contrast, the period May to August was characterised by high evapotranspiration (Figure 6). For the whole of the hydrological year 2013 we measured 6,590 m³ of irrigation (Table 2), which differs from the calculated amount of 3,588 m³ due to malfunctioning of the irrigation system (Figure 8).

To place these data in context we calculated average annual water demand using meteorological data for the period 1993–2013. The result, approximately 1,600 m³ ha^{-1} yr^{-1} (Figure 9), was only half of our modelled result for the period November 2012 to October 2013. The 1993–2013 average record showed a similar pattern to that for 2013, with precipitation higher than evapotranspiration in winter and evapotranspiration plus seepage exceeding precipitation from April to August (Figures 8 and 9).

Figure 10 shows the dynamics of water balance components over the period 1993–2013 if all surplus water were to be stored in a reservoir and used for irrigation at times of water deficit. From 1993 until

Table 2. Water balance components of the Sphagnum farming trial for the hydrological year 2013.

units	***P***	***ETR***	Q_{in}	$Q_{seepage}$	Q_{out}	ΔS
m³ ha^{-1} yr^{-1}	7092	-6380	6590	-3414	-3514	-374
mm yr^{-1}	709	-638	659	-341	-351	-37

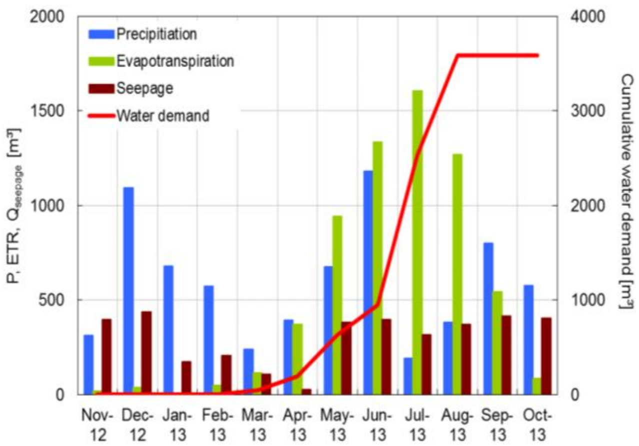

Figure 8. Monthly precipitation, evapotranspiration, seepage, and the cumulative water demand (m³ ha^{-1}) for the Sphagnum farming trial during the hydrological year 2013 (November 2012 to October 2013).

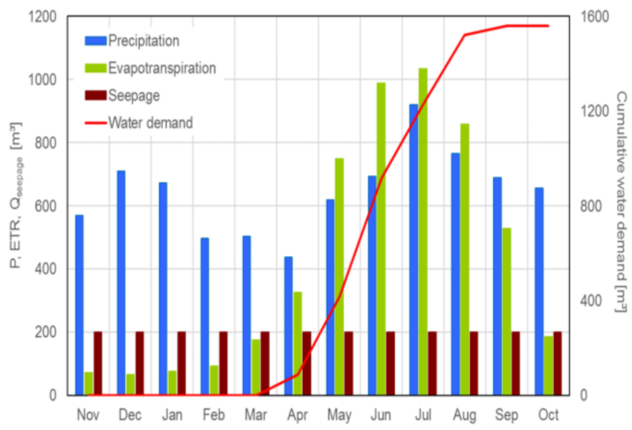

Figure 9. Long-term mean monthly precipitation, evapotranspiration, seepage, and cumulative water demand (m³ ha^{-1}) for the Sphagnum farming site, calculated using precipitation data from Bremen meteorological station (1993–2013, German Meteorological Service DWD).

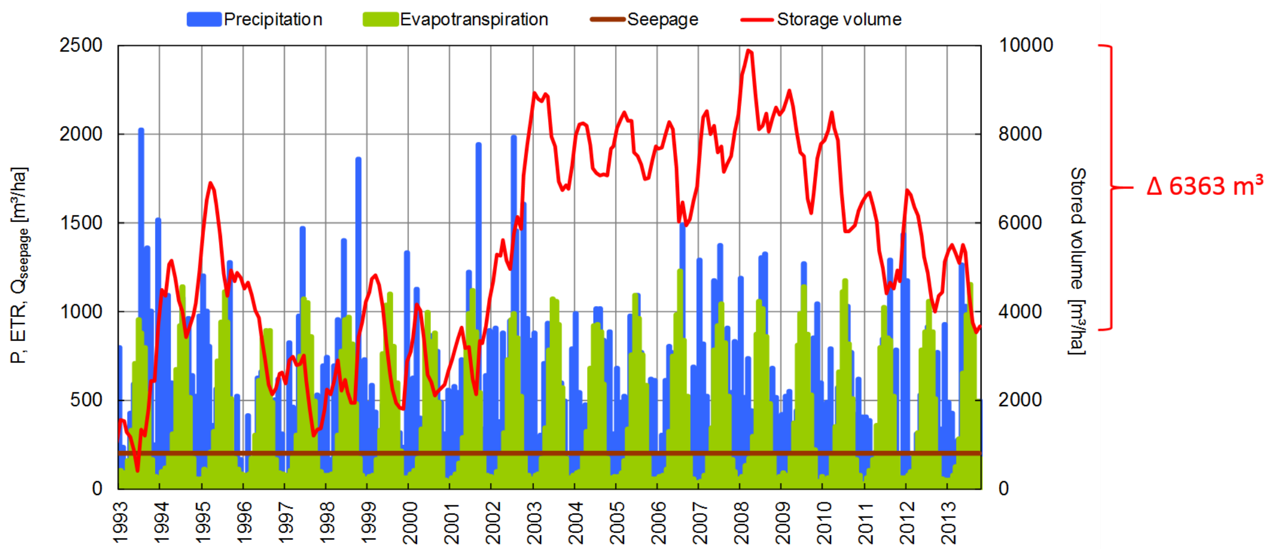

Figure 10. Non-stationary monthly water balance components (precipitation, evapotranspiration, constant seepage) and resulting stored volume for the Sphagnum farming site (in m³ ha^{-1}) over the period 1993–2013, calculated using precipitation data (for Bremen) provided by the German Meteorological Service DWD.

the winter of 1995, the water balance was mainly positive and a water surplus of 6,750 m³ ha^{-1} accumulated. The sum of evapotranspiration and seepage for 1995–1997 exceeded precipitation by approximately 5,500 m³ ha^{-1}, leading to an equivalent decrease in reservoir storage. Following this deficit period, the reservoir filled up and was storing 9,900 m³ ha^{-1} by the winter of 2008. Subsequently, March 2008 to October 2013 was a long-lasting dry period over which 6,363 m³ ha^{-1} of reservoir storage was needed to compensate for the precipitation deficit and seepage losses.

DISCUSSION

Water balance components

In our study the main water balance components are precipitation (influx) and evapotranspiration (outflux). Whereas annual precipitation usually exceeds annual evapotranspiration in north-west Germany, the two fluxes often do not balance at seasonal scale. In summer, evapotranspiration frequently exceeds precipitation, resulting in water deficits. An example is provided by the summer of 2013 (studied here), which was a period of low precipitation, and the same pattern is evident in the long-term mean record. To maintain constantly high water tables just below the *Sphagnum* surface, the Sphagnum farming trial had to be irrigated during periods of water deficit (Figures 4 and 5). The amount of irrigation water provided during the hydrological year 2013 (6,590 m³ ha^{-1}, see Table 2) was unnecessarily high because, in May and October 2013, pumping (in) and outflow were activated simultaneously due to malfunctioning of the irrigation system. Our calculation of water demand (Equation 5) indicated a requirement for only 3,588 m³ ha^{-1} (359 mm) of irrigation water during the dry hydrological year 2013 (Figure 8), which would change the ratio of irrigation water to precipitation ($Q_{in} : P$) from 48:52 to 34:66. A Sphagnum farming site on cut-over bog in Shippagan, New Brunswick (Canada) required about 30 mm $month^{-1}$ of irrigation in the summer of 2015 (Brown 2017) compared to 60 mm $month^{-1}$ (359 mm over six months) during the irrigation period of the hydrological year 2013 in our study (Table 2). However, compared to our site, the Canadian site received ~ 50 % more precipitation and lost only half the evapotranspiration due to lower temperatures.

Evapotranspiration and seepage account for the main water losses (Figure 7). Evapotranspiration is largely determined by depth of the water table below the surface (Lafleur *et al.* 2005, Edom *et al.* 2010). Due to irrigation during periods of water deficit and the fast distribution of water from the ditches through surface peat and later through the grown *Sphagnum* lawn, both of which are characterised by high hydraulic conductivity (Figure 1c), the water table throughout the *Sphagnum* production field was constantly just a few centimetres (mean ~ 5 cm) below the *Sphagnum* surface (Figure 4). Thus, evapotranspiration rates were high and close to the maximum (potential) rate year-round (Kim & Verma 1996, Ketcheson & Price 2011).

In our study evapotranspiration rates are also higher than in natural bogs, where lowering of the water table causes a considerable reduction of evapotranspiration (van der Schaaf 2002). We calculated evapotranspiration rates of 659 mm yr^{-1} for the Sphagnum farming trial using net radiation and water levels, while van der Schaaf (2002) reported substantially lower values of 539–573 mm yr^{-1} under more humid and colder conditions in Ireland. The fraction of total water losses accounted for by seepage (24 %) is considerable compared to the 1 % reported for bogs in Ireland by van der Schaaf (2002). We assume that the horizontal component of seepage is much greater than the vertical one. In particular, in the uppermost 30 cm thick *Sphagnum* peat layer, saturated hydraulic conductivity is high, with a value for the horizontal direction that is almost twice that for the vertical direction (Rosskopf *et al.* 2016, Figure 1c). Saturated hydraulic conductivity is substantially lower in the more strongly decomposed peat layers below, which must lead to very low vertical seepage overall (Baden & Eggelsmann 1963, Rosskopf *et al.* 2016, Figure 1c). This is supported by our observation that the head differences between phreatic and groundwater levels are small in our study area (0.05–0.2 m, Figure 4), resulting in a low hydraulic gradient and limited vertical seepage.

Losses by evapotranspiration and seepage are also high, as our Sphagnum farming site is embedded in a drained landscape where irrigation creates a mounded water table. Thus, evapotranspiration from the *Sphagnum* production fields is increased by advection of drier air from the surroundings (oasis effect; see, *e.g.*, Edom 2001 and Joosten *et al.* 2015). Additionally, horizontal seepage leads to water losses from the irrigation ditches to the bunds and dry surrounding area.

Annual and long-term water demand

Sphagnum farming requires constant water supply to the *Sphagnum* mosses (Gaudig *et al.* 2018), which is dependent on the availability of precipitation or irrigation water as well as the magnitude of water losses. If water availability is insufficient to keep the *Sphagnum* wet, the risk of poor productivity (or even die-back) of the *Sphagnum* mosses during droughts increases (Lütt 1992, Hayward & Clymo 1982). *Sphagnum* is especially sensitive to desiccation from the time when founder material is applied to initiate the production fields until a closed lawn is established (Gaudig *et al.* 2014).

At the Sphagnum farming trial, the calculated annual cumulative demand on irrigation water was 3,588 m³ for the hydrological year 2013 (Figure 8). This is high compared to the mean annual cumulative water demand of 1,600 m³ that we calculated for a 20-year period (Figure 9). However, both results are supported by continuing measurements of irrigation water used at the Sphagnum farming trial, which were 1,540, 1,640 and 3,200 m³ ha^{-1} in 2014, 2015 and 2016, respectively (Krebs *et al*. unpublished data). Thus, large differences in water demand from year to year must be expected for Sphagnum farming sites. Moreover, water demand may exceed the estimates reported here (Figure 10) during long-lasting droughts, resulting in even larger water deficits.

Provision of water from a reservoir

For irrigation of the Sphagnum farming trial we used water from the Schanze stream. If a similar constant water source were not available, a water reservoir which would fill in times of excess atmospheric water and provide water for the *Sphagnum* production fields in times of deficit could be considered as an alternative. The comparison of average and non-stationary long-term data (Figures 9 and 10) shows that the difference between mean annual and maximum cumulative water deficit over the period 1993–2013 (1,600 $m^3\ ha^{-1}\ yr^{-1}$ *versus* 6,363 $m^3\ ha^{-1}$) is substantial. Thus, under the climatic and hydrological conditions of the Sphagnum farming site on Hankhauser Moor, a reservoir with capacity 6,400 $m^3\ ha^{-1}$ would be needed to cover the long-term (1993–2013) water demand if the only source of irrigation water was precipitation falling directly on the site. Depending on its design, water losses from the reservoir itself (seepage and evaporation from the open water body) would have to be added to the water demand for irrigation. Open water evaporation in northern Germany may amount to as much as 700 mm yr^{-1}, meaning that an additional annual loss of approximately 0.7 m^3 *per* square metre of reservoir surface should allowed for when determining the minimum capacity that would be needed in practice.

To minimise the size of reservoir required, the water demand for irrigation should be reduced. At the Sphagnum farming trial losses *via* evapotranspiration are relatively high because the water table is kept just below the *Sphagnum* capitula (Figure 4). Lowering water tables for the entire area of the production fields would reduce evapotranspiration from *Sphagnum* (Boelter 1964, Virta 1966, Nichols & Brown 1980) and irrigation demand, but also *Sphagnum* productivity (Gaudig *et al.* 2014).

Considerations for other sites

This hydrological study has shown that the controlled water management system installed at the Sphagnum farming trial on formerly drained bog grassland at Hankhauser Moor was effective. The water table could be kept close to the surface level of the *Sphagnum* production fields almost constantly, ensuring optimal growth of *Sphagnum* mosses. The approach that we have developed to assess the necessary irrigation volumes is transferable to other sites, although it will always be necessary to consider site-specific characteristics. For example, lower precipitation than at our study area would result in larger water shortages and, consequently, a larger irrigation demand.

Also, boundary conditions significantly influence evapotranspiration and seepage and, thus, the water demand for a site. Drained surroundings like those at our study area enhance evapotranspiration losses from the Sphagnum farming site by advection (oasis effect) and horizontal seepage. In such situations the form and position of the site may substantially influence evapotranspiration, *e.g.* an elongated site lying parallel to the prevailing wind direction will lose less water by the oasis effect than a site with a different orientation. Surroundings (as extensive as possible) with high groundwater levels would reduce water losses by horizontal seepage. Groundwater level strongly influences seepage and thus the water demand. At our study area the groundwater level was close to the phreatic (mire) water level, so the hydraulic gradient driving vertical seepage was low (Figure 4). In sites with significantly lower groundwater levels, water retention will be much more difficult because more water will be lost as seepage into the subsoil unless there is a layer with low hydraulic conductivity beneath the peat.

It is also important to consider the peat layers of the site, as their botanical composition and degree of decomposition profoundly influence hydraulic conductivity and, thus, vertical and horizontal water losses. Former peat extraction sites are often characterised by thin layers of residual peat with elevated degree of decomposition and, thus, reduced hydraulic conductivity. While sparingly permeable surface peat may impede vertical seepage losses, it will also hamper the horizontal water supply to the peatmoss, especially in periods with high evapotranspiration.

Finally, it is important to remember that Sphagnum farming requires not only irrigation, but also outlets to discharge excess surface water and thus prevent long periods of flooding, which would also reduce *Sphagnum* growth.

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REFERENCES

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

Boelter, D.H. (1964) Water storage characteristics of several peats *in situ*. *Soil Science Society of America Journal*, 28, 433–435.

Bollrich, G. (2007) *Technische Hydromechanik 1: Grundlagen (Technical Hydromechanics 1: Basics)*. Huss-Medien, Berlin, 456 pp. (in German).

Brown, C. (2017) *The CO_2 Dynamics and Hydrology of an Experimental Sphagnum Farming Site*. Master Thesis, University of Waterloo, Ontario, Canada, 68 pp.

Brown, C.M., Strack, M. & Price, J.S. (2017) The effects of water management on the CO_2 uptake of *Sphagnum* moss in a reclaimed peatland. *Mires and Peat*, 20(5), 1–15.

DVWK (1996) *Ermittlung der Verdunstung von Land- und Wasserflächen (Determining Evaporation for Land and Water Surfaces)*. Deutscher Verband für Wasserwirtschaft und Kulturbau (DVWK) e.V., Bonn, 238/1996, 134 pp. (in German).

Edom, F. (2001) Moorlandschaften aus hydrologischer Sicht (Mire landscapes from the hydrological point of view). In: Succow, M. & Joosten, H. (eds.) *Landschaftsökologische Moorkunde*. E. Schweizerbart'sche Verlagsbuchhandlung, Stuttgart, 185–228 (in German).

Edom, F., Münch, A., Dittrich, I., Kessler, K. & Peters, R. (2010) Hydromorphological analysis and water balance modelling of ombro- and mesotrophic peatlands. *Advances in Geosciences*, 27, 131–137.

Gaudig, G. & Krebs, M. (2016) Torfmooskulturen als Ersatzlebensraum - Nachhaltige Moornutzung trägt zum Artenschutz bei (*Sphagnum* cultures as surrogate habitat - sustainable peatland utilisation supports species conservation). *Biologie in unserer Zeit*, 46(4), 251–257 (in German).

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(8), 1–11.

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(4), 1–19.

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 (in press).

Giraudoux, P. (2010) pgirmess: Data analysis in ecology. R package version 1.4.9. Online at: http://CRAN.R-project.org/package=pgirmess.

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(2), 1–16.

Hayward, P. & Clymo, R. (1982) Profiles of water content and pore size in *Sphagnum* and peat, and their relation to peat bog ecology. *Proceedings of the Royal Society of London B*, 215, 299–325.

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.

Joosten, H., Brust, K., Couwenberg, J., Gerner, A., Holsten, B., Permien, T., Schäfer, A., Tanneberger, F., Trepel, M. & Wahren, A. (2015) MoorFutures®: Integration of additional ecosystem services (including biodiversity) into carbon credits - standard, methodology and transferability to other regions. BfN, Bundesamt für Naturschutz, Bonn, 120 pp.

Ketcheson, S.J. & Price, J.S. (2011) The impact of peatland restoration on the site hydrology of an abandoned block-cut bog. *Wetlands*, 31, 1263–1274.

Kim, J. & Verma, S.B. (1996) Surface exchange of water vapour between an open *Sphagnum* fen and the atmosphere. *Boundary-Layer Meteorology*, 79, 243–264.

Krebs, M., Gaudig, G. & Joosten, H. (2012) Sphagnum farming on bog grassland in Germany - first results. Abstract No. 294, *Proceedings of the 14th International Peat Congress* (Stockholm, Sweden), International Peat Society, Jyväskylä, 5 pp., access *via* http://www.peatsociety.org.

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(4), 1–16.

Lafleur, P.M., Hember, R.A., Admiral, S.W. & Roulet, N.T. (2005) Annual and seasonal variability in evapotranspiration and water table at a shrub-covered bog in southern Ontario, Canada. *Hydrological Processes*, 19, 3533–3550.

LBEG (2015) Hydrogeologische Übersichtskarte von Niedersachsen (Hydrogeological overview map for Lower Saxony) 1:200,000, Online at: https://www.lbeg.niedersachsen.de/download/102570.

Lütt, S. (1992) *Produktionsbiologische Untersuchungen zur Sukzession der Torfstichvegetation in Schleswig-Holstein* (*Productivity Studies of the Succession of Peat Pit Vegetation in Schleswig-Holstein*). Volume 43, Mitteilungen der Arbeitsgemeinschaft Geobotanik in Schleswig-Holstein und Hamburg, Kiel, 272 pp. (in German).

McCarter, C. & Price, J. (2014) Ecohydrology of

Sphagnum moss hummocks: mechanisms of capitula water supply and simulated effects of evaporation. *Ecohydrology*, 7, 33–44.

NIBIS (2011) NIBIS® map server. Landesamt für Bergbau, Energie und Geologie (LBEG), Hannover. Online at: http://nibis.lbeg.de/cardomap3/

Nichols, D.S. & Brown, J.M. (1980) Evaporation from a *Sphagnum* moss surface. *Journal of Hydrology*, 48, 289–302.

Nijp, J.J., Limpens, J., Metselaar, K., van der Zee, S.E., Berendse, F. & Robroek, B.J. (2014) Can frequent precipitation moderate the impact of drought on peatmoss carbon uptake in northern peatlands? *New Phytologist*, 203, 70–80.

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. & Whittington, P.N. (2010) Water flow in *Sphagnum* hummocks: mesocosm measurements and modeling. *Journal of Hydrology*, 381, 333–340.

Robroek, B.J., Schouten, M.G., Limpens, J., Berendse, F. & Poorter, H. (2009) Interactive effects of water table and precipitation on net CO_2 assimilation of three co-occurring *Sphagnum* mosses differing in distribution above the water table. *Global Change Biology*, 15, 680–691.

Rosskopf, N., Edom, F. & Zeitz, J. (2016) Hydraulische Eigenschaften unterschiedlicher *Sphagnum*-Torfe (Hydraulic properties of different *Sphagnum* peats). *TELMA*, 46, 61–82 (in German).

Siegel, S. & Castellan, N.J.J. (1988) *Nonparametric Statistics for the Behavioral Sciences*. McGrawHill, New York, 399 pp.

Succow, M. & Joosten, H. (2001) *Landschaftsökologische Moorkunde (Landscape Ecology of Peatlands)*. E. Schweizerbart'sche Verlagsbuchhandlung, Stuttgart, 622 pp. (in German).

Trepel, M., Pfadenhauer, J., Zeitz, J. & Jeschke, L. (2017) Germany. In: Joosten, H., Tanneberger, F. & Moen, A. (eds.) *Mires and Peatlands of Europe: Status, Distribution and Conservation.* Schweizerbart Science Publishers, Stuttgart, 413–424.

van der Schaaf, S. (2002) Chapter 4: Bog hydrology. In: Schouten, M.G.C. (ed.) *Conservation and Restoration of Raised Bogs: Geological, Hydrological, and Ecological Studies*. Dúchas - The Heritage Service of the Department of the Environment and Local Government, Dublin, 54–109.

Virta, J. (1966) Measurement of evapotranspiration and computation of water budget in treeless peatlands in the natural state. *Commentationes Physico-Mathematicae, Societas Scientiarum Fennica*, 32(11), 1–70.

Walter, H. & Lieth, H. (1967) *Klimadiagramm-Weltatlas* (*World Atlas of Climate Diagrams*). VEB Gustav Fischer Verlag, Jena, 256 pp. (in German).

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(3), 1–19.

Wichtmann, W., Schröder, C. & Joosten, H. (eds.) (2016) *Paludiculture, Productive Use of Wet Peatlands: Climate Protection, Biodiversity, Regional Economic Benefits*. Schweizerbart Science Publishers, Stuttgart, 272 pp.

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