Paludiculture on former bog grassland: Profitability of Sphagnum farming in North West Germany

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SUMMARY

Sphagnum farming provides an alternative to detrimental peatland drainage in two ways. Firstly, *Sphagnum* mosses are cultivated on rewetted peatlands. Secondly, *Sphagnum* biomass is a high-quality growing media constituent suitable for replacing peat in horticulture. This study investigated the shift from drained bog grassland to a wet Sphagnum farming site from the micro-economic perspective. Based on five years of field experience, we calculated costs and revenues of Sphagnum farming for a total cultivation time of 20 years. Sensitivity analysis encompassed costs, yields, prices and the effect of public non-market payments. We found that cultivated *Sphagnum* biomass could not compete with peat at current market prices, whereas its use for orchid cultivation was economically viable in the case of medium to high *Sphagnum* productivity. Selling *Sphagnum* shoots as founder or "seeding" material was profitable even in pessimistic scenarios with high costs and low yields. Cost-covering prices for *Sphagnum* biomass substituting peat seem achievable, if end consumers pay a surcharge of 10 % for plants cultivated without using peat (peat free). A commercial-scale implementation, an increasing market demand for renewables, and setting climate targets for the agricultural and horticultural sectors will accelerate the development of Sphagnum farming as a profitable alternative to drainage-based peatland agriculture and peat extraction.

KEY WORDS: break-even price, net present value, peatland agriculture, sustainable growing media

INTRODUCTION

Drainage has commonly been a pre-requisite for the productive use of peatlands, thereby turning unnoticed ecosystem services into major disservices. Nowadays, it is widely acknowledged that draining peatlands for agriculture and peat extraction results in land degradation, soil loss and high greenhouse gas (GHG) emissions; and that sustainable peatland management can be achieved only with high water tables (FAO 2014). The Paris Agreement on limiting global warming to well below 2 °C compared with pre-industrial times (UN 2015) was especially effective in raising general awareness of the ambivalent role of peatlands in contributing to either climate cooling or climate warming. Peatlands are the largest terrestrial organic carbon store, while covering less than 3 % of the global land area (Crump 2017). In contrast to the usually short-term storage of carbon in living biomass, peatlands provide long-term storage for the carbon captured by biomass over hundreds and thousands of years. Drainage turns peatlands into major sources of GHG emissions, releasing CO_2 and N_2O from the aerated peat layer and CH_4 from the drainage ditches (Joosten *et al*. 2016). Drained peatlands cover only 0.4 % of the global land area but are responsible for 5 % of all anthropogenic GHG emissions globally (Joosten 2015). Bringing the water level near to the surface (rewetting) is the most effective measure to preserve the carbon stock, re-initiate a wide range of important ecosystem services and enhance biodiversity (Bonn *et al.* 2016), but usually involves the abandonment of land use.

Paludiculture (*palus*: swamp, *cultura*: cultivation) is agriculture or forestry on wet peatlands and thus offers sustainable land use options for degraded peatlands after rewetting (Wichtmann *et al.* 2016). On rewetted bogs, *Sphagnum* mosses are promising plant species for paludiculture. The cultivation of *Sphagnum* ('Sphagnum farming') produces a renewable growing media constituent that is a suitable substitute for slightly decomposed *Sphagnum* peat ('white peat') in professional horticulture (Gaudig *et al.* 2018). During the last two decades, Sphagnum farming pilot sites have been established on: (a) cut-over bog (Pouliot *et al*. 2015, Gaudig *et al.* 2017, Graf *et al.* 2017), (b) artificial floating mats (Blievernicht *et al.* 2011, 2012) and (c) former bog grassland (see below). Wichmann *et* *al.* (2017) compared the procedures and the costs of establishing commercial *Sphagnum* cultures on these three types of production sites. However, a comprehensive economic evaluation of Sphagnum farming was not possible at that time, due to the lack of field data on management and harvest.

In this article we present the first profitability assessment for Sphagnum farming. Our calculations are based on the first five years of field experience on former bog grassland in North West Germany and anticipate costs and revenues for a total cultivation time of 20 years. While qualitative competitiveness with peat has been shown for *Sphagnum* biomass as a growing media constituent (e.g. Emmel 2008, Oberpaur *et al.* 2010), we examine its current competitiveness in terms of price and discuss market prospects.

METHODS

Study area

The pilot site is located near Rastede in Lower Saxony, North West Germany (53° 15.80' N, 08° 16.05' E). The main land uses in the study area are dairy farming and, to a lesser extent, suckler cow husbandry. Drainage and agricultural use of peatlands has been causing subsidence by compression, shrinkage and oxidation (Eggelsmann 1986). The surface of the peatland 'Hankhauser Moor' now lies up to 1 m below sea level and drainage water has to be pumped out to the North Sea (Hofer & Pautz GbR 2005). The pilot site was used as bog grassland until 2010. Starting up Sphagnum farming involved creating an even surface (for optimal water management), relocating degraded topsoil to create causeways, removing existing drainage pipes and installing infrastructure for water management (e.g. pumps, irrigation ditches and outflows) (see Wichmann *et al.* 2017). The field trial was established in 2011 (Figure 1a) on a 4 ha site with a net area of 2 ha of *Sphagnum* production fields, the remaining area being occupied by infrastructure like causeways and ditches (Wichmann *et al.* 2017). In 2016, the first harvest (Figure 1b) provided *Sphagnum* shoots as founder material for extension of the Sphagnum farming trial to about 14 ha (net: 5.6 ha) (Figure 1c). On the harvested production fields, the lower part of the *Sphagnum* lawn remained to allow *Sphagnum* regrowth and repeated harvests (cf. Krebs *et al.* 2018). Site conditions (e.g. climate, hydrology and nutrients) are described in Brust *et al.* (2018) and Temmink *et al.* (2017).

Cost data and calculation

The considered costs of Sphagnum farming encompass establishment, management, harvest, transport and the processing of *Sphagnum* biomass to create a marketable product. The practical work was conducted by a regional company whose business involves extracting peat and producing growing media for professional horticulture (Torfwerk Moorkultur Ramsloh). We compiled data on labour and machinery use (daily time sheets), standard costing rates (accounting records of the peat company) and payments for materials and contractors (e.g. invoices for irrigation pumps and installation work) covering the period from establishment to first harvest (2011–2016). We assumed regrowth of the residual *Sphagnum* layer after harvesting by cutting (cf. Krebs *et al.* 2018) and used the data from the first rotation period to anticipate costs for a total cultivation time of 20 years including four harvests (Figure 2). Opportunity costs of conventional grassland use were excluded from the calculations because the profit foregone would be highly dependent on European Union (EU) agricultural subsidies, whose continuation for another 20 years cannot be assumed because this would conflict with the EU's climate objectives.

Establishment costs accrue only once at the beginning of the cultivation time ($t = 0$) and include site preparation, investment for water management and spreading of *Sphagnum* shoots as founder material (Figure 1a). The necessary working steps, related costs and a description of the pilot site consisting of *Sphagnum* production fields, irrigation ditches and causeways (Figure 1c) is presented in detail in Wichmann *et al.* (2017). In addition, we investigated the establishment costs for extension of the pilot site in 2016 and incorporated the new cost data for comparison.

The management costs of the Sphagnum farming site are annual costs. They encompass all costs related to water management and site maintenance. Based on five years of experience, we used real life data from the pilot site to calculate plausible values. For example, we chose the most efficient practice of weed mowing on the *Sphagnum* production fields to extrapolate costs instead of calculating real life working hours of trial and error with different mowing equipment. In addition, spreading of additional *Sphagnum* for replenishing gaps in the developing moss carpet in the second year after establishment, as conducted in 2012 (Gaudig *et al.* 2014), was not necessary in 2017 for the extended area and thus was not taken into account as an essential management measure.

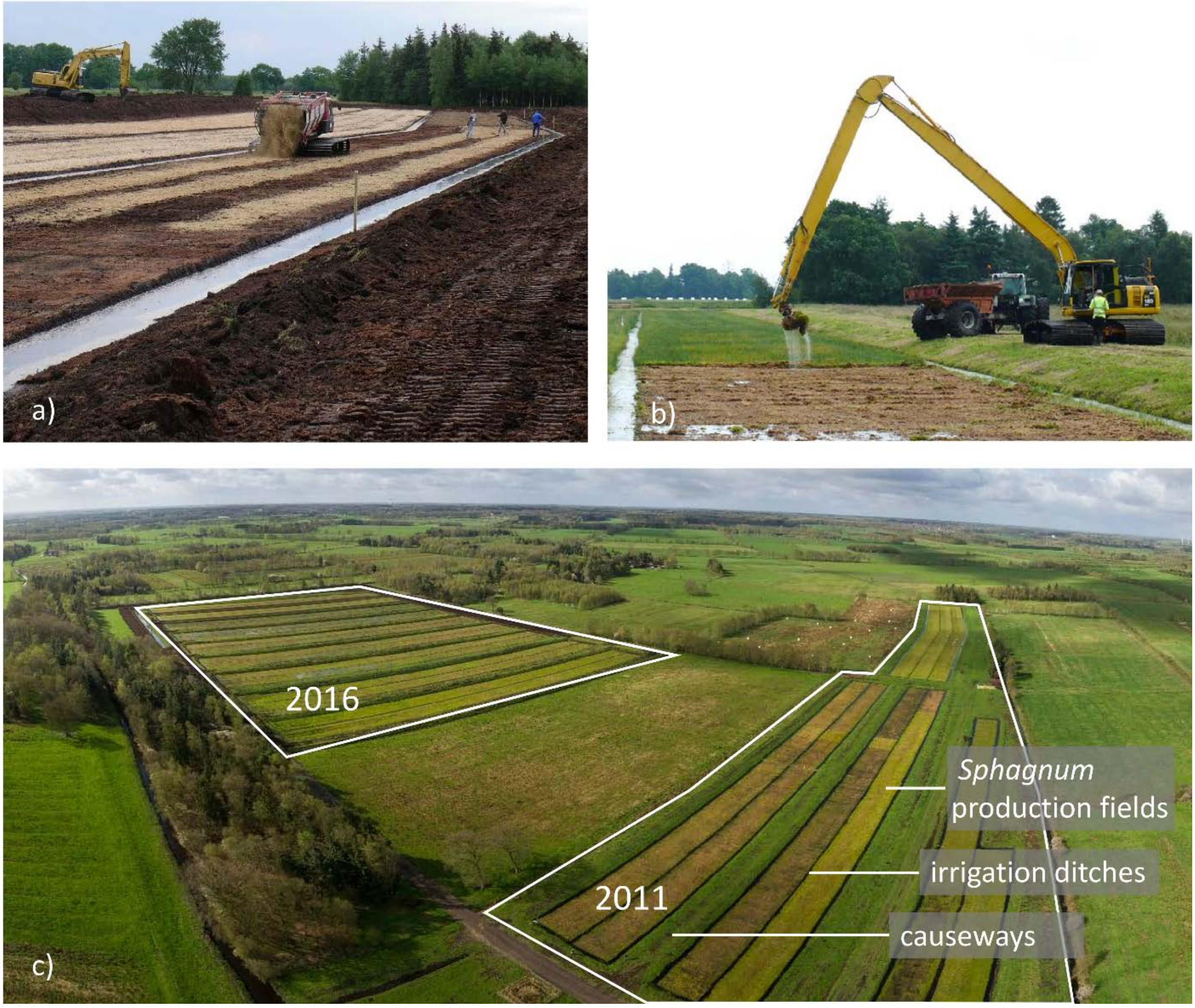

Figure 1. a) Spreading *Sphagnum* shoots with an adapted snow groomer during establishment of the Sphagnum farming pilot. b) First harvest using an excavator with long arm and mowing bucket. c) Aerial view of the pilot site with the five-year-old section established in 2011, the extension section established in 2016 and the surrounding drained grassland. Photos: a) and b) Sabine Wichmann, c) ASEA aerial.

Figure 2. Timeline of the first five years of Sphagnum farming on former bog grassland (dark grey) (Rastede, Lower Saxony) and assumptions for repeated harvests with a rotation length of five years and a total cultivation time of 20 years (light grey).

The first mechanical harvest of the Sphagnum farming site was conducted in June 2016 ($t = 5$). An excavator standing on the causeway was equipped with a long arm and mowing bucket to cut the mosses and load the biomass into a tractor-pulled dumper (Figure 1b) for transport off the site. The mowing bucket and tractor were fitted with GPS trackers (Wintec WBT-202) to log operation times. The transport costs were based on peat handling and include loading of the harvested *Sphagnum* biomass and road transport to the processing plant at a distance of 70 km.

Biomass processing was tested in a commercial plant producing growing media for professional horticulture (Torfwerk Moorkultur Ramsloh), using its standard equipment. The processing steps encompassed drying the harvested biomass in piles in the field or on concrete to a water content of 70–80 %, cleaning in the vapour treatment facility for peat to prevent germination of seeds and sprouting of other plant parts, and separating it into fine and coarse fractions in the screening line usually used for peat (Kumar 2017). The harvest, transport and processing costs were calculated for the years t = 5, 10, 15 and 20 (Figure 2).

Revenue data and calculation

The revenues of Sphagnum farming depend on *Sphagnum* productivity (accumulated biomass in dry mass tons per hectare), the yield (harvested biomass in dry mass tons per hectare), the conversion factor from weight to volume (calculating the yield in m^3 per hectare), the selling price (€ per m^3 according to the application) and non-market payments (€ per ha).

Sphagnum productivity was determined on the pilot site. Before mechanical harvesting, the above-ground biomass accumulated over five years was cut with scissors on 30 plots (randomly distributed over the production fields, cf. Hurlbert 1984, size: 15 × 15 cm). For each plot, *Sphagnum* species, other mosses, vascular plants and litter were separated and dried to constant weight (80 °C for 48 h, Hendry & Grime 1993). Values of the dry mass of *Sphagnum* biomass after five years' growth were used to calculate the average annual productivity. In addition to the mean value, we used the lowest and highest value within the 1.5× interquartile range (IQR) of the lower quartile and upper quartile, respectively, to define three productivity levels.

It was not possible to directly measure the harvested yield. Therefore, we analysed the biomass remaining after harvest on 30 plots (size: 15 × 15 cm) by determining the dry mass of the different biomass components as described above. We compared values of the mean dry *Sphagnum* biomass remaining after mechanical harvest and the mean dry *Sphagnum* biomass grown over five years to determine the fraction of biomass remaining on the land after harvesting. This was subtracted from the biomass productivity (low, mean and high values) to calculate the respective harvested yields. Dry mass yields were converted into volumes (m^3), since volume is the usual trading unit for growing media constituents and substrates. To calculate the conversion factor, the bulk densities of 16 biomass samples of different *Sphagnum* species and origins was determined according to the European standard DIN EN 12580. Considering the water content, we calculated the mean dry mass bulk density and used ± 1 standard deviation as the high and low levels of the conversion factor in the sensitivity analysis (Table 1).

Since *Sphagnum* biomass is used not only as an alternative to peat in growing media but also for applications of higher market value (e.g. for orchid

Table 1. Overview of sensitivity analysis varying input variables for profitability assessment and break-even price calculation. Abbreviations for variables as in the equations, DM = dry mass.

Input variable	Unit	Levels of variation	
Costs (*C*)			
Establishment costs (E_0)	€ ha^{-1}	2	Scenario A: high costs (year: 2011) Scenario B: medium costs (year 2016)
Management costs (M)	€ ha^{-1}	2	Scenario A: high costs (period: 2011–2016) Scenario B: medium costs (reduction by 25 %)
Revenues (*R*)			
Productivity	DM t ha^{-1} yr^{-1}	3	Low / Mean / High
Harvested yield	%	1	Mean
Bulk density (conversion factor)	DM g L^{-1}	2	Low / High
Market price	€ m^{-3}	3	Low / Medium / High
Non-market income	€ ha^{-1}	2	No additional revenues / Medium payment level

cultivation or as founder material for Sphagnum farming sites), we considered three price levels in the profitability calculation. Market revenues are related to harvest and processing and were, therefore, calculated for the years t = 5, 10, 15 and 20. Additionally, the effect of annual public non-market payments on profitability and break-even price was tested (Table 1).

As for the costs, we used the data from the first rotation period to calculate revenues for the following three harvests, assuming constant *Sphagnum* biomass productivity and constant prices over the total cultivation time.

Investment appraisal

Costs and revenues of Sphagnum farming are spread irregularly over the total cultivation time (T) of 20 years. As is common for permanent cultures, Sphagnum farming requires a one-off investment for establishment at the beginning and management costs every year, whereas harvesting costs and market revenues arise every five years. Therefore, we conducted an investment appraisal discounting all cash flows of costs (C) and revenues (R) that occur at a time (t) to a Present Value (PV, $t = 0$) (Equation 1, Equation 2). We used a discount rate (r) of 3 % since bank interest rates have been low in Germany for many years. Inflation was excluded from the discount rate (i.e. real discount rate in contrast to nominal discount rate), and from all cash flows which were thus measured in the value of t_0. If the Net Present Value (NPV) (Equation 3) is positive, future revenues can cover the initial investment costs for establishment (E_0) and all further costs related to management (M), harvest (H), transport (S) and processing (P). Transferring the NPV to an Annuity (A) results in a constant annual value spread over the whole lifetime (Equation 4).

$$PV\,(C) = E_0 + \sum_{t=0}^{T} \frac{(M+H+S+P)_t}{(1+r)^t} \qquad [1]$$

$$PV\,(R) = \sum_{t=0}^{T} \frac{R_t}{(1+r)^t} \qquad [2]$$

$$NPV = PV\,(R) - PV\,(C) \qquad [3]$$

$$A = NPV * \frac{(1+r)^T * r}{(1+r)^T - 1} \qquad [4]$$

RESULTS

Establishment costs

Data on establishment costs were collected by installing a Sphagnum farming trial on 4 ha in 2011 and on another 10 ha in 2016 (Figure 1c). The data from 2011 represent a high cost scenario, the data from 2016 represent a medium cost scenario. Major cost determinants were the origin of the founder material (purchase vs. own production) and the size of the area influencing proportionate costs, as well as the time requirement and cost rates for site preparation.

The establishment costs amounted to about € 128,000 per hectare net area of *Sphagnum* production fields in 2011 (Wichmann *et al.* 2017) and to € 98,000 in 2016 (Figure 3). For site preparation, the cost in 2016 was higher than in 2011 (+148 %), for two reasons. First, prices for machinery use increased, e.g. by 54 % for an excavator hour. Secondly, the time required doubled (496 h ha^{-1} vs. 248 h ha^{-1}) because of adverse weather conditions (frost, fog) and because more peat was moved than in 2011 in order to create an even surface despite large depressions. Thus, site preparation was the most important cost item in 2016 (Figure 3). However, the higher costs were outweighed by lower proportional investment in water management, due to a larger irrigated area (2 ha in 2011 vs. 5.6 ha in 2016). Additionally, the cost of *Sphagnum* shoots, which dominated the establishment costs in 2011, was 41 % lower in 2016 because own founder material had been cultivated. Total establishment costs were 23 % lower in 2016 (medium cost scenario) than in 2011 (high cost scenario) (Figure 3). Detailed calculations are included in the Appendix (Table A1).

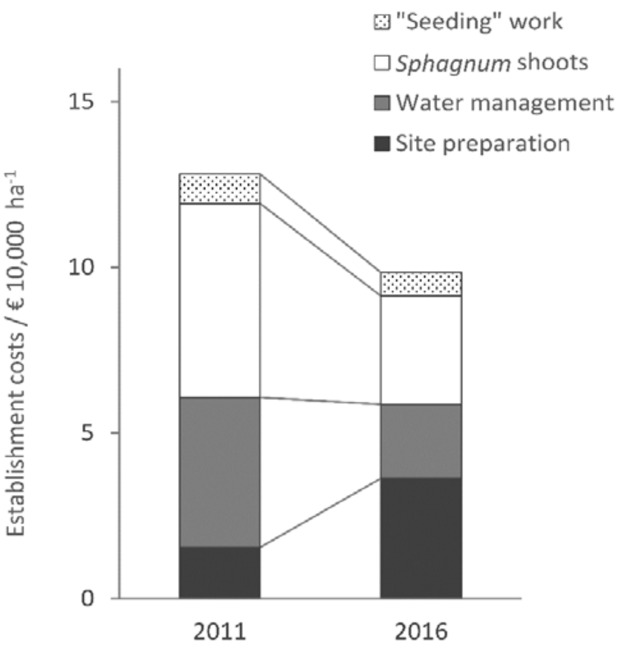

Figure 3. Costs of establishing a Sphagnum farming pilot site on former bog grassland in 2011 (2 ha of *Sphagnum* production fields) (cf. Wichmann *et al.* 2017) and of the extension to 5.6 ha in 2016 (cf. Table A1).

Management costs

During the first rotation period (2011–2016), 73 % of the total management costs were related to site maintenance (Figure 4). The dominating activity was weed control on the *Sphagnum* production fields by regular mowing of vascular plants with a single-axle motor mower (6–8 times per year), followed by cleaning of the irrigation ditches with an excavator and mowing bucket (in 2013 and 2015) and mulching of the causeways with a tractor (4–6 times per year) (Figure 4). Maintenance costs were lower in 2011 (establishment phase) and in the year (2016) ending with harvest in June (see Figure 6b; Table A2).

Harvesting and processing costs

Harvesting an area of 0.58 ha in June 2016 took five days of 9–12 working hours each. The total time of 55 hours included frequent waiting periods because the harvested *Sphagnum* biomass was used directly to enlarge the pilot site and the performance of the "seeding" machine spreading the founder material was the limiting factor. For the labour costs of the two machine operators, we used their actual working hours as a very conservative estimation (55 hours each, i.e. 94 h ha^{-1} per person, € 23 h^{-1}). For the machines, GPS tracking allowed us to determine a realistic performance of 50 h ha^{-1} for harvesting and loading (excavator and tractor) and an additional 12 h ha^{-1} for field transport (tractor, 50–300 m one way). Costs for excavator and tractor operation during harvest in 2016 totalled about € 12,600 ha^{-1}, while transport and processing costs added up to € 7.43 m^{-3} (Table A2).

Yield, bulk density and price levels

For calculating market revenues, we used different levels of three factors: yield arising from low, mean or high productivity, bulk density and price level (Table 1). During five years of cultivation (May 2011 to April 2016), dry mass productivity reached mean values of 24 t ha^{-1} (low: 15 t, high: 34 t) (Figure 5a), i.e. 4.9 t ha^{-1} yr^{-1} (low: 3.1 t, high: 6.8 t). On average, 35 % of the grown-up biomass remained after harvesting in June 2016 (Figure 5a). For the profitability calculation we assumed an average harvested dry mass yield of 16 t ha^{-1} (low: 10 t; high: 22 t), i.e. 3.2 t ha^{-1} yr^{-1} (2.0 t; 4.4 t). For the conversion factor, we chose 20 and 38 g L^{-1} based on the determination of mean dry mass bulk density ± 1 standard deviation (29.0 ± 9.36 g L^{-1}, Figure 5b, cf. Table A3). The market value of *Sphagnum* biomass varies strongly according to the application. It ranges from € 25 m^{-3}, a common price for the slightly decomposed *Sphagnum* peat ('white peat') used in horticultural growing media, through e.g. € 165 m^{-3} for use in the cultivation of orchids, to € 750 m^{-3} for the *Sphagnum* shoots that were used as founder material to populate the pilot site in 2011 (Wichmann *et al.* 2017).

Extrapolation to 20 years: Present Values, Annuities and break-even price

To estimate costs over the total cultivation time of 20 years, we calculated two scenarios which differ in terms of establishment and management costs based on the experience of the field trial.

Cost Scenario A reflects high costs. We used the cost data of the first rotation with establishment in 2011, management and first harvest (Tables A1, A2) to extrapolate corresponding costs to the following rotations. For management we estimated average values of € 5,943 ha^{-1} for the years of harvest (t = 5, 10, 15, 20), reflecting reduced effort due to slow vascular plant regrowth, and € 11,266 ha^{-1} for the other years (Figure 6b). The total $PV(C)$ ranged from € 312,000 to € 356,000 ha^{-1} (Figure 7, Table A4) depending on harvested yield and bulk density, which influenced the costs of harvesting, transport and

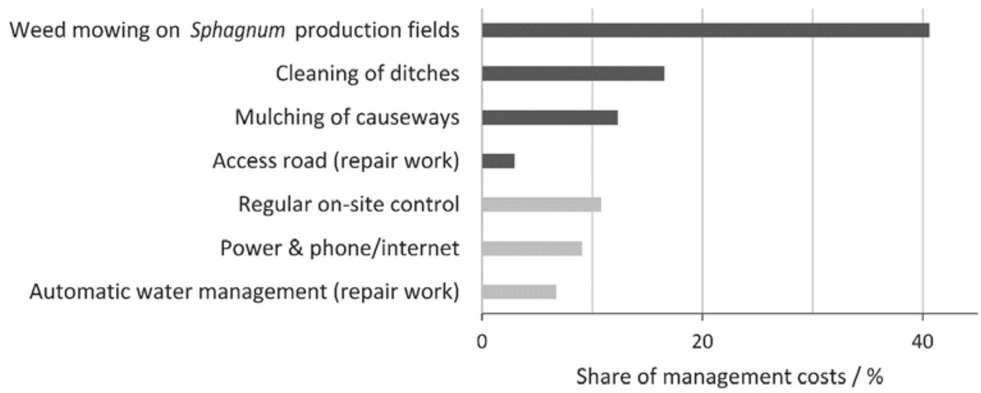

Figure 4. Management costs in 2011–2016 showing the shares of the single cost items for site maintenance (dark grey) and water management (light grey).

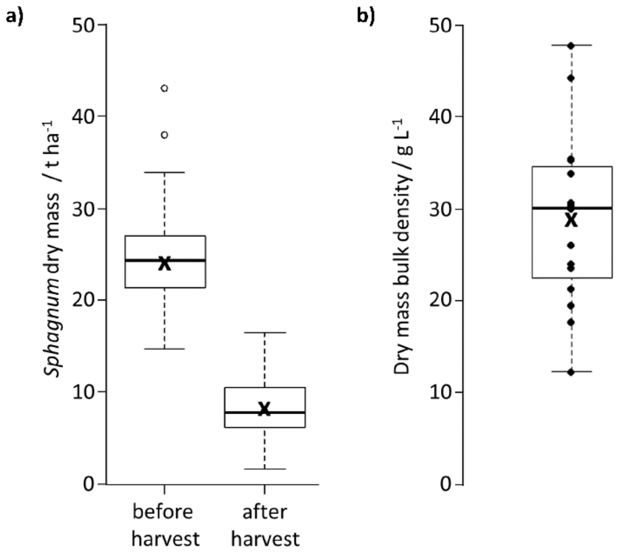

Figure 5. a) *Sphagnum* dry mass after five years of growth, before and remaining after harvest (each $n = 30$); and b) dry bulk density (n = 16, cf. Table A2). The plot shows the median (bold line), the mean (x), the upper and lower quartiles (including 50 % of the data and creating the box), the whiskers representing the lowest and highest values still within 1.5 interquartile range (IQR) of the lower and upper quartile, respectively, and the outliers (o), i.e. the values outside these ranges.

processing. Management costs constituted the largest share (44–50 %) and establishment costs were the second most important (36–41 %) (Figure 6a).

Cost Scenario B reflects medium costs. We used the lower establishment cost value of the year 2016 (Figure 3) and assumed a 25 % reduction in management costs. Consequently, the *PV (C)* reduced to a range of € 243,000 to € 287,000 ha^{-1} (Table A4), which is a saving of € 69,000 ha^{-1} compared to Cost Scenario A.

The Present Value of the revenues (*PV (R)*) ranged very widely, from € 18,000 to € 2,312,000 ha^{-1} (Figure 7, Table A4). The negative *NPV*s (Figure 7) showed that a price of € 25 m^{-3} did not cover the costs of Sphagnum farming. At a price of € 165 m^{-3}, mean or high average dry mass yields (3.2 and 4.4 t ha^{-1} yr^{-1}) were cost-covering when a low bulk density (20 g L^{-1}) was assumed. Selling *Sphagnum* biomass for € 750 m^{-3} resulted in a positive annuity of € 16,200 ha^{-1} yr^{-1} even in case of low yield (2 t ha^{-1} yr^{-1}) and high bulk density (38 g L^{-1}) (Figure 8a), and up to € 131.500 ha^{-1} yr^{-1} at high yield (4.4 t ha^{-1} yr^{-1}) and low bulk density (20 g L^{-1}) (Figure 8c).

In addition to calculating profit or loss with three given price levels, we determined price levels at which production costs were covered. The break-even price ranged from € 115 to € 423 m^{-3} for Cost Scenario A and from € 93 to 330 m^{-3} for Cost

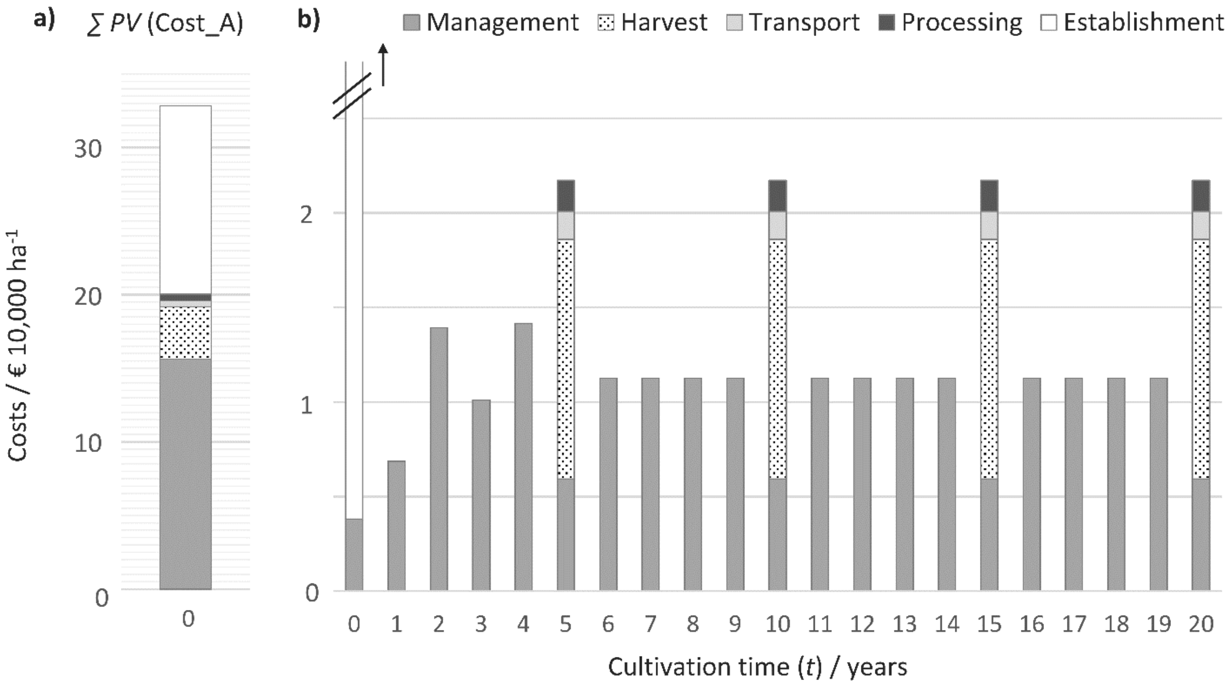

Figure 6. Costs in Scenario A (dry mass average yield: 3.2 t ha^{-1} yr^{-1}, 20 g L^{-1}): a) *PV (C)*, i.e. all costs discounted ($r = 3$ %) and summed for the year of establishment ($t = 0$); b) costs of establishment, management, harvest, transport and processing according to their occurrence during the cultivation time ($t = $x).

Scenario B (Table 2), equating to a reduction of about 21 % (€ 22–93 m^{-3}, 19–22 %).

In addition to market revenues, EU agriculture is commonly supported by public payments. We assumed a non-market income through agricultural subsidies of € 300 ha^{-1} yr^{-1}, comparable with the average level of current EU direct payments (Pillar I) in Germany (EC 2017). Additionally, we assumed the remuneration of ecosystem services provision at € 1,000 ha^{-1} yr^{-1}. The non-market income reduced the break-even price by about 7 % (€ 6–26 m^{-3}, 5–8 %) (Table 2).

DISCUSSION

Profitability at farm level

Influence of price levels

The pilot site allowed a first cost and profitability assessment for large-scale, mechanically implemented Sphagnum farming based on real-life data. Our data show that *Sphagnum* biomass cultivated on former bog grassland cannot compete with peat at its current market price; but also indicate that, with medium and high yields at low bulk density, profitability is achieved if the *Sphagnum* is

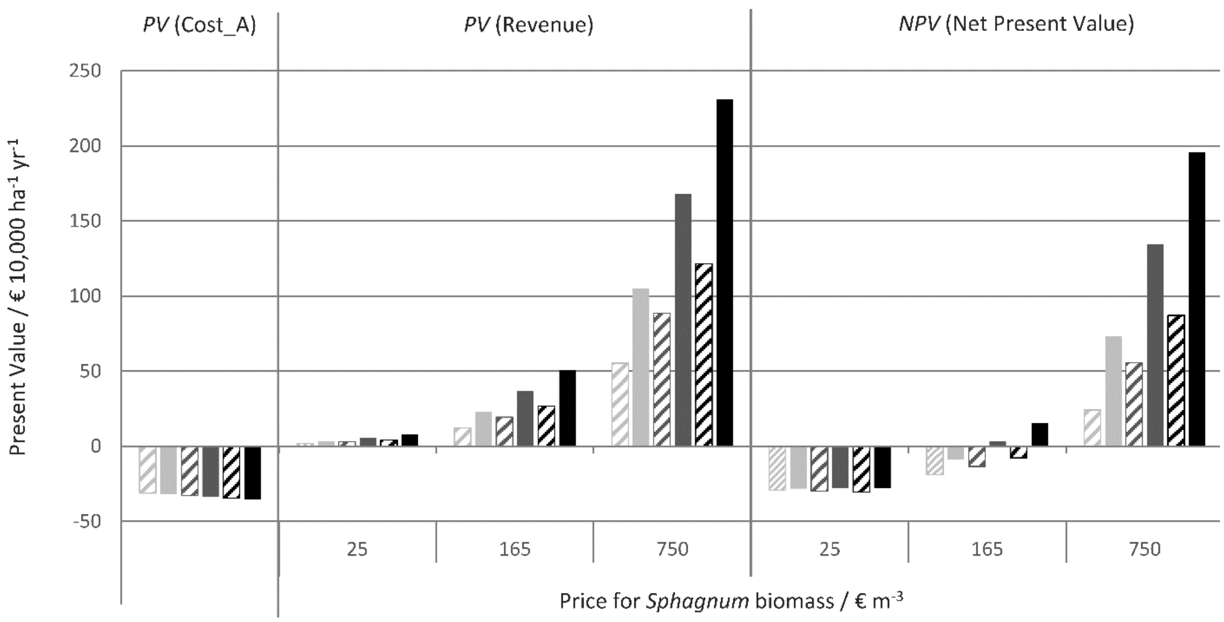

Figure 7. Present Values (*PV*) of Sphagnum farming for high costs (Scenario A) and Revenues and the resulting Net Present Values (*NPV*) according to price level (€ 25, € 165 or € 750), average dry mass yield (light grey: 2.0; dark grey: 3.2; black: 4.4 t ha^{-1} yr^{-1}) and the conversion factor for bulk density (solid fill: 20 g L^{-1}; hatched fill: 38 g L^{-1}).

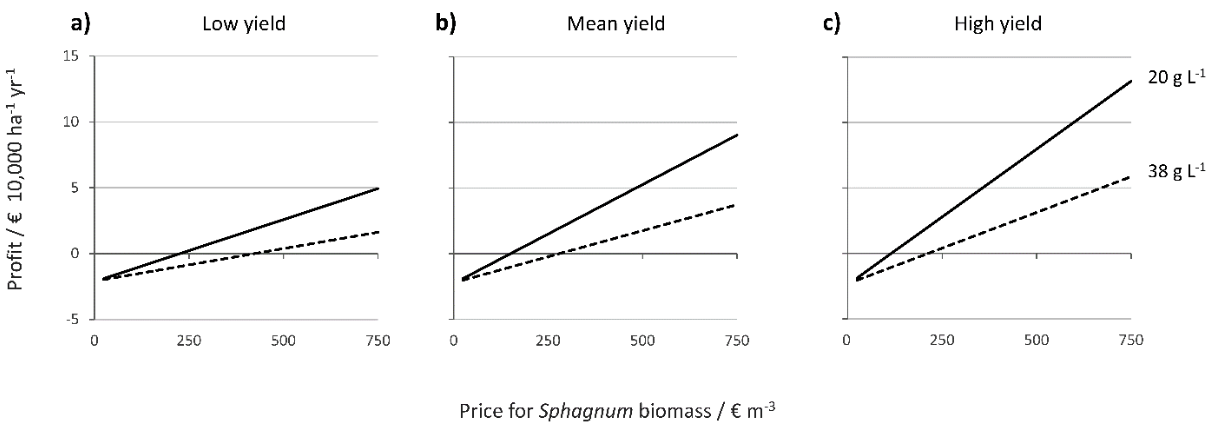

Figure 8. Profitability of Sphagnum farming given as Annuity (T = 20 years; r = 3 %) for Cost Scenario A according to the average dry mass yield (low, mean or high; 2.0, 3.2 or 4.4 t ha^{-1} yr^{-1}), the conversion factor for bulk density (solid line: 20 g L^{-1}; dashed line: 38 g L^{-1}) and the price level (range € 25 to € 750 m^{-3}).

used as a growing medium for orchids (Figure 7, Table A4). The break-even price (Table 2), with a maximum of € 423 m^{-3}, lies well below the € 750 m^{-3} paid for *Sphagnum* shoots used as founder material in Germany. Thus, Sphagnum farming for the production of founder material is profitable even in the most pessimistic scenario of low yield, high bulk density and high costs (Figure 8a). Cheaper founder material has a positive feedback effect that will further reduce the costs of Sphagnum farming, lower break-even prices and improve the competitiveness of cultivated *Sphagnum* biomass.

Potential for cost reduction

We identified a high potential for reducing the break-even price by optimisation and cost reduction (Table 3). The cost of *Sphagnum* shoots as founder material and the investment in water management were the most important cost items during the establishment in 2011 but were, respectively, 41 % and 51 % lower in 2016 (Figure 3). However, these figures still incorporate the high research- and site-specific costs for the electronically controlled automatic water management. The higher costs for site preparation in 2016 compared to 2011 underline the need for reducing topsoil removal, both for limiting GHG emissions from peat soil and for limiting establishment costs. Careful site planning with a dense grid of height measurements and establishing several terraces can minimise peat removal related to levelling the uneven surface. Choosing a cost-efficient irrigation system, minimising topsoil removal, a decreasing price of founder material and scale effects reduce costs considerably (cf. Wichmann *et al.* 2017). Based on current knowledge, a scenario with establishment costs less than € 50,000 ha^{-1} seems feasible (Table A1). Further implementation is required, however, to verify the options for cutting the costs of Sphagnum farming.

Table 2. Break-even price for Sphagnum farming at high cost (Scenario A) and medium cost (Scenario B) according to the harvested yield and bulk density. Prices in square brackets show the effect of an additional non-market income (€ 1300 ha^{-1} yr^{-1}) for Sphagnum farming (DM = dry mass).

	Productivity	DM t ha^{-1} yr^{-1}	3.1		4.9		6.8	
	Average yield	**DM t ha^{-1} yr^{-1}**	**2**		**3.2**		**4.4**	
	Harvested yield	DM t ha^{-1}	10		16		22	
	Bulk density	**DM g L^{-1}**	**38**	**20**	**38**	**20**	**38**	**20**
	Harvested volume	m^3 ha^{-1}	263	500	421	800	579	1,100
Scenario A)	**Break-even price**	€ m^{-3}	423 [397]	226 [212]	278 [262]	150 [141]	213 [201]	115 [109]
Scenario B)	**Break-even price**	€ m^{-3}	330 [301]	177 [163]	220 [204]	119 [111]	170 [159]	93 [87]

Table 3. Key factors for profitability of Sphagnum farming and key uncertainties in calculation.

	Key factors for profitability	Key uncertainties in calculation
Costs	• Availability of founder material (own reproduction or mass propagation) • Cost-efficient irrigation system • Large sites (scale effects) • Minimised topsoil removal • Maximised share of *Sphagnum* production fields compared to infrastructure • Optimised management costs (e.g. weed mowing) • Technological maturity (e.g. adapted machinery)	**Basic assumptions** • Rotation length of 5 years • Total cultivation time of 20 years **Limited data and experience** • Only one pilot site • Only the first 5 years
Revenues	• High productivity • Niche markets with higher prices • Marketing: Top-up by end consumer for renewable growing media • Eligibility for agricultural subsidies • Payments for ecosystem services	**Yield** • Bulk density → harvested volume • Share of remaining biomass • Regrowth potential

Ahead of the high initial costs, management costs were identified as most important for the Present Values (Figure 6a). Optimising weed mowing on the *Sphagnum* production fields seems most promising since it caused the highest costs (41 %, Figure 4). In order to identify cost-efficient management options further research is needed on different machinery (single-axle mower vs. excavator; autonomous vehicles), the mowing regime (frequency, with or without removal of cuttings), influence on *Sphagnum* productivity and coverage of weeds as well as tolerable quantities of non-*Sphagnum* biomass in the growing media. Large-scale harvesting of cultivated *Sphagnum* using an excavator with mowing bucket proved to be a feasible option. Developing alternative mowing machinery that can drive onto the production fields without harming *Sphagnum* productivity would allow reduced causeways and an enlarged share of production area (Wichmann *et al*. 2017).

Uncertainties

While the field trial provided good data on productivity and costs for the first rotation period (five years), major uncertain points of the NPV calculations encompass the harvested volume (few data on bulk density), the assumption on remaining biomass for regrowth and the up-scaling to a total cultivation time of 20 years (Table 3).

Profitability obviously depended on the harvested yield. Additionally, we clearly showed that the bulk density is equally important. Low yields with low bulk density and high yields with high bulk density delivered comparable results (Figure 8). Since the conversion factor is little investigated as yet (Figure 5b, Table A3), it adds uncertainty to the calculations of both revenue and cost. The wide range of dry mass bulk density (for sensitivity analysis we used 20 and 38 g L^{-1}) is confirmed by literature values of 14 and 29 g L^{-1} (Schmilewski 2018), on which basis the values applied in our calculations appear to be comparatively conservative estimates. However, the bulk density of *Sphagnum* biomass needs to be investigated throughout the production chain from field to flowerpot and in relation to *Sphagnum* species, fragment size, moisture content, processing, growing media composition and its stability over lifetime.

Basic assumptions of the investment appraisal still have to be proven by real practice. The optimal rotation length, the regrowth potential and the possible total cultivation time have to be tested. A total cultivation time shorter than 20 years strongly increases annual costs whereas altering the discount rate has limited effect (Wichmann *et al*. 2017). Although we assumed an equal share of biomass remaining for regrowth (35 % of the grown-up biomass) to calculate harvested yields, it is likely that the share is larger in the case of low productivity and smaller in the case of high productivity. Furthermore, to forgo about one third of the grown-up biomass and leave it for regrowth of the *Sphagnum* lawn may turn out to be less feasible and less profitable than to harvest the total biomass and accept the costs of new establishment.

Research on *Sphagnum* productivity, including the selection of species, provenances and breeding, will increase yields (Gaudig *et al*. 2018). Further large-scale Sphagnum farming sites are needed to implement options for cutting costs, to identify further improvements and to enlarge the basis of reliable cost data. Finally, revenues need to cover not only proportionate variable and fixed production costs as calculated in this study but also general, land (purchase or tenure) and marketing costs as well as risk premium and entrepreneurial profit.

Market prospects of *Sphagnum* biomass

'Niche markets'

The price for the produced *Sphagnum* biomass has, not surprisingly, the highest effect on profitability (Figure 8). High-value applications with high revenues allow entry to the European market with the first yields of Sphagnum farming sites at cost-covering prices despite higher initial costs. Next to use as founder material for Sphagnum farming and restoration (regional provenances), 'niche markets' encompass substrates for carnivorous plants, for vivaria with amphibians, reptiles and spiders, or for hanging baskets, wreaths and vegetation walls (Wong *et al.* 2016). The high capacity to absorb and retain fluids and anti-microbial properties offer a wide range of applications. Using *Sphagnum* biomass as insulation and packaging material, for food preservation, medical dressings, nappies and sanitary towels are among traditional (Thieret 1956, Glime 2007) as well as current applications (Zegers *et al.* 2006). Further research on biological properties and compounds will probably pave the way for new utilisation options (Taskila *et al.* 2015) such as, for instance, *Sphagnum* extracts as sources of natural sunscreen (Mejía-Giraldo *et al.* 2015).

Nowadays, the major field of application is the cultivation of ornamental plants, in particular orchids, that turned *Sphagnum* biomass into an international high-value commodity with the image of 'Green Gold' (Orchard 1994). *Sphagnum* moss gathered from wild populations in countries such as Chile, New Zealand, Australia and China is sold mainly to the global centres of orchid production in

Asia like Taiwan, Japan and South Korea (Whinam *et al*. 2003, FIA 2009, INFOR 2010). Europe plays a minor role in the worldwide *Sphagnum* market. In 2009, 72 % of the Chilean export volume went to Asia and only 10 % to Europe (INFOR 2010). In 2018, the total exports from Chile had increased by 19 % in volume and by 60 % in revenues, whereas the share that went to Europe had decreased to less than 5 % of total volume as well as revenues (INFOR 2019). A total quantity of about 9000 m^3 of *Sphagnum* was imported to The Netherlands, France and Germany in the year 2013 (Schmilewski 2017). To produce this amount of *Sphagnum* biomass, 41 to 167 ha of *Sphagnum* production fields with high to low yields (220 m^3 to 54 m^3 ha^{-1} yr^{-1}) would be required. In the light of overexploitation of sensitive peatland ecosystems in the Southern Hemisphere (e.g. Zegers *et al*. 2006) and the long distance transport, sustainably cultivated *Sphagnum* gains a competitive edge on the European market. Niche markets with higher revenues are important to start up commercial scale Sphagnum farming. Addressing larger markets is necessary, however, to establish Sphagnum farming as alternative to predominant drainage based bog grassland farming in North West Germany.

Renewable substitute for peat in horticulture

The medium-term objective of Sphagnum farming is to replace considerable quantities of peat in professional horticulture in order to contribute to phasing out peat extraction. The current price of peat is obviously so low that *Sphagnum* biomass cannot compete (Figure 6), but the market price does not account for the external costs related to peat extraction. European politicians, environmental organisations and consumers are increasingly aware of negative effects such as climate change and biodiversity loss. The acceptance of higher prices for plants grown in peat-free or peat-reduced growing media can be assumed. Since the share of growing media costs in total horticultural production costs is low (< 2 %), increasing its price from € 25 to € 125 m^{-3} would increase the final product price by only 10 %. A break-even price around € 100 m^{-3} seems achievable for cultivated *Sphagnum* biomass (Table 2). The growing media industry already pays higher prices for alternative raw materials, such as € 35–45 m^{-3} for coco products; and the use of coco products nevertheless almost tripled from 2005 to 2013 (Schmilewski 2017). Depleted resources of 'white peat' in Central Europe (Schmatzler 2012), the dependence on imports from Scandinavia, Ireland and especially the Baltic countries with higher prices due to increasing labour and transport costs (Falkenberg 2008), and phasing-out plans as discussed already for the UK (Alexander *et al*. 2008, DEFRA 2010), Switzerland (Federal Council of Switzerland 2012, 2017) and Germany (BMUB 2016) will increasingly restrict extraction and utilisation of peat. On functioning markets, shortage increases product prices. Additionally, instruments such as carbon taxation may internalise the external costs of peat utilisation into production costs and thus also increase market prices of peat as well as the economic competitiveness of alternative raw materials in the future.

Although attempts to replace peat date back to the 1980s (Gruda 2012), the application rates of alternative constituents in growing media remain low with an average share of 25 % in Europe and 19 % in Germany (Schmilewski 2017). The share is considerably lower in professional substrates than in potting soils for the hobby market; it was 11 % vs. 27 % for growing media produced in Germany in 2013 (ibid.) compared to 7 % and 6 %, respectively, in 2005 (Schmilewski 2008a), i.e. the use of alternative constituents increased mainly in hobby market products. Raw materials such as green-waste compost, composted bark and wood fibre are limited, however, in their qualitative suitability to fulfil professional demands (Schmilewski 2008b). Critical undesired properties like high pH, high salt content and poor water holding or air capacity need to be compensated by mixing with other raw materials, usually peat (ibid.).

In contrast, *Sphagnum* biomass has similar properties to 'white peat', can replace peat at 50 % by volume for most potting substrates and has been successfully used with larger shares up to 100 % in a wide range of horticultural applications (Gaudig *et al*. 2018). In tests with cucumber, tomato and lettuce *Sphagnum* biomass proved to be a better growing medium than 'white peat' or mineral wool, leading to a recommendation that *Sphagnum* biomass could be harvested from wild populations in Finland (Silvan *et al*. 2012). In 2016, a total amount of 15,000 m^3 was collected industrially, but technology and logistics still need improvement (Tekes 2017). The environmental impact is reduced compared to peat extraction as stressed by Silvan *et al*. (2017). Nevertheless, collecting *Sphagnum* biomass from living bogs is falsely claimed to be "climate neutral" (Joosten 2017). Removing biomass from (near-)natural bogs prevents it from turning into peat and contributing to the long-term carbon store. Furthermore, an average harvesting depth of 30 cm (Silvan *et al*. 2017) is likely to extract not only fresh *Sphagnum* biomass but also slightly decomposed peat.

While Finland produces 0.9 million m^3 of growing media, Germany is with 8.4 million m^3 the most important producer country and responsible for 24 % of the European production (Schmilewski 2017). Considering the use of 'white peat' for growing media production, Germany also ranks first in Europe (23 %), followed by the traditional producer countries Netherlands and Italy as well as Latvia and Lithuania which have been gaining importance since the 1990s (all between 9–12 %) (ibid.). To substitute the current annual German industry demand of ~3.5 million m^3 of 'white peat' with cultivated *Sphagnum* biomass, one third of the bog grassland area in Northwest Germany (35,000 ha) would be sufficient (Wichmann *et al*. 2017). In addition, *Sphagnum* biomass may be used in pressed pot substrates (Emmel 2017) to reduce the share of 'black peat', i.e. highly decomposed peat, for which the current German industry demand amounts to 3.2 million m^3 (Schmilewski 2017) to 6 million m^3 (Falkenberg 2008). The future demand will be less, however, if other – including not yet known – substitutes become available, if countries and regions currently relying on imported peat-based growing media from Germany start to produce substrates from own renewable resources, and if soil-free plant production methods expand. Ecological issues such as the CO_2 footprint will determine the choice of growing media and cultivation methods in the near future (Gruda 2019).

Is Sphagnum farming an alternative to drained bog grassland?

Sphagnum farming has been proved to be technical feasible. This includes establishing commercial *Sphagnum* cultures on formerly drained bog grassland, ensuring high productivities and using existing machines for harvesting and processing the grown-up biomass. *Sphagnum* biomass is a valuable product for a wide range of applications, especially for the large growing media market. From the farmer's point of view, there are still major obstacles to Sphagnum farming: founder material is rare, the investment costs are high, first revenues are received only after five years, special machinery is needed, productive land is lost due to the currently high share of infrastructure, European and regional regulations limit the transformation of grassland into permanent cultures, the eligibility for agricultural subsidies is insecure, and incentives for mitigating GHG emissions are missing. In contrast, drained bog grassland for dairy farming is an established land use, considered as typical cultural landscape and supported by agricultural payments. For abandoning current peatland utilisation, Röder & Osterburg (2012) identified short term opportunity costs of € 1700 ha^{-1} yr^{-1} for North West Germany, the highest standard gross margin values across Germany. The long-term profitability, however, which includes covering the costs of dairy cowsheds, machines, labour and land, is highly dependent on public payments, mainly via Pillar I and Pillar II of the EU Common Agricultural Policy (CAP). According to statistical data, 67 % of the ten-year average net profit of € 736 ha^{-1} yr^{-1} for dairy farms located in Lower Saxony was provided by public payments, with the share ranging from 36 % in years with a high milk price to 99 % during the milk price crisis in 2014/15 and 2015/16 (BMEL 2018 and previous years).

From the societal perspective, stopping drainage and raising peatland water levels to the surface is required to contribute to climate protection. To align agricultural policy to climate policy, agricultural subsidies for drainage-based peatland use need to be phased out in a first step and in a second step raising water levels should be prescribed. To initiate the paradigm shift to climate-smart agriculture on peatlands, a set of attractive economic incentives will be necessary such as compensating for the high initial investment, facilitating large-scale implementation by supporting advice and cooperation, long-term schemes remunerating reduced GHG emissions as well as the provision of other ecosystem services and increasing market demand for climate friendly products, e.g. via public procurement (Wichmann 2018). Sphagnum farming is currently the only alternative for rewetted bog sites that combines productive use with substantial peat preservation, but research and development are still at an early stage. This study provided a first micro-economic assessment of Sphagnum farming based on experience at a single pilot site. Further research is needed to improve technical maturity, cut costs and assess the external effects of Sphagnum farming compared to peat extraction and agriculture on drained peatlands. The first results indicate benefits through reduced GHG emissions (Günther *et al*. 2017), sequestered nutrients (Temmink *et al.* 2017) and increased biodiversity (Muster *et al.* 2015, Gaudig & Krebs 2016). Decision making on peatland use alternatives requires a complete picture of costs and benefits for the whole society; the profitability at farm level is only one part of this.

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AUTHOR CONTRIBUTIONS

SW collected the cost data, designed and conducted economic analyses and wrote the manuscript. MK and GG mainly supervised the set-up and performance of the Sphagnum farming field trial and contributed data on *Sphagnum* biomass accumulation. SK contributed data on bulk density. All authors revised the manuscript critically before (re)submission.

REFERENCES

Alexander, P.D., Bragg, N.C., Meade, R., Padelopoulos, G., Watts, O. (2008) Peat in horticulture and conservation: the UK response to a changing world. *Mires and Peat*, 3, 08, 10 pp.

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

Blievernicht, A., Irrgang, S., Zander, M., Ulrichs, C. (2012) The youngest peat - Sustainable production of *Sphagnum* sp. and its use as growing media in professional horticulture. Extended Abstract No. 247, *Proceedings of the 14th International Peat Congress* (Stockholm, Sweden), International Peat Society, Jyväskylä.

BMEL (2018) *Die wirtschaftliche Lage der landwirtschaftlichen Betriebe. Buchführungsergebnisse der Testbetriebe des Wirtschaftsjahres 2016/2017* (*The Economic Situation of Agricultural Businesses. Accountancy Data of Test Farms for the Business Year 2016/2017*). Bundesministerium für Ernährung und Landwirtschaft (BMEL), Bonn, 182 pp. Online at: https://www.bmel-statistik.de/landwirtschaft/ testbetriebsnetz/testbetriebsnetz-landwirtschaft-buchfuehrungsergebnisse/, accessed 05 Sep 2018.

BMUB (2016) *Klimaschutzplan 2050: Klimaschutzpolitische Grundsätze und Ziele der Bundesregierung* (*Climate Protection Plan 2050: Climate Protection Policy Principles and Goals of the Federal Government*). Bundesministerium für Umwelt, Naturschutz, Bau und Reaktorsicherheit (BMUB), Berlin, 91 pp. Online at: www.bmub.bund.de/fileadmin/Daten_BMU/Download_PDF/Klimaschutz/klimaschutzplan_2050_bf.pdf, accessed 08 Mar 2019.

Bonn, A., Allott, T., Evans, M., Joosten, H., Stoneman, R. (eds.) (2016) *Peatland Restoration and Ecosystem Services: Science, Policy and Practice*. Cambridge University Press/British Ecological Society, Cambridge, 493 pp.

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.

Crump, J. (ed.) (2017) *Smoke on Water - Countering Global Threats From Peatland Loss and Degradation. A UNEP Rapid Response Assessment*. United Nations Environment Programme and GRID-Arendal, Nairobi and Arendal, 70 pp.

DEFRA (2010) *Consultation on Reducing the Horticultural Use of Peat in England*. Department for Environment, Food and Rural Affairs (DEFRA), UK, 39 pp. Online at: www.gmmineralsplan.co.uk/docs/NP024.pdf, accessed 08 Mar 2019.

DIN EN 12580 (2014) Soil improvers and growing media - Determination of a quantity. DIN EN 12580:2014-02, 14 pp. Online overview at: https://www.din.de/en/getting-involved/standards-committees/nal/european-committees/wdc-beuth:din21:186297263, accessed 05 Dec 2019.

EC (2017) *CAP Explained. Direct Payments for Farmers 2015–2020*. European Commission, 12 pp. Online at: https://ec.europa.eu/agriculture/ sites/agriculture/files/direct-support/direct-payments/docs/direct-payments-schemes_en.pdf, accessed 16 Jul 2019.

Eggelsmann, R. (1986) Subsidence of peatland caused by drainage, evaporation, and oxidation. In: *Proceedings of the Third Symposium on Land Subsidence, Venice*, International Association of Hydrological Sciences Publ. No. 151, 497–505.

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

Emmel, M. (2017) Torfmoos statt Schwarztorf in Presstopferden - wie viel ist möglich? (*Sphagnum* instead of peat in pressed pots substrate - how much is possible?). *Gemüse*, 11, 18–21 (in German).

Falkenberg, H. (2008) Torfimporte aus dem Baltikum - Bedeutung für die Torf- und Humuswirtschaft in Deutschland (Peat imports from the Baltic States - Importance for the peat and growing media industry in Germany). *Bergbau*, 3, 132–135.

FAO (2014) *Towards Climate-Responsible Peatlands Management* (eds. Biancalani, R., Avargyan, A). Mitigation of Climate Change in Agriculture 9, Food and Agriculture Organisation of the United Nations (FAO), Rome, 117 pp.

Federal Council of Switzerland (2012) *Torfausstiegskonzept* (*Peat Phase-Out Concept*). Bericht des Bundesrates in Erfüllung des Postulats 10.3377 Diener Lenz, 31 pp. (in German). Online at: https://www.newsd.admin.ch/newsd/message/attachments/29089.pdf, accessed 08 Mar 2019.

Federal Council of Switzerland (2017) *Memorandum of Understanding Regarding the Reduction of Peat Use in the Production, Supply and Consumption of Packaged Soils for End Users in Switzerland*. Online at: https://www.bafu.admin.ch/dam/bafu/en/dokumente/wirtschaft-konsum/fachinfo-daten/Absichtserklaerung_Reduktion_Torfeinsatz.pdf.download.pdf/Absichtserkl%C3%A4rung_Torf_Sackerden_Final.pdf, accessed 08 Mar 2019.

FIA (2009) *Resultados y Lecciones en 'Uso y manejo del Musgo* Sphagnum (*Results and Lessons on the Use and Management of* Sphagnum *Moss*). Proyecto de Innovación en XI Región de Aysén, Serie Experiencias de Innovación para el Emprendimiento Agrario, Fundación para la Innovación Agraria (FIA), Spain, 52 pp. (in Spanish).

Gaudig, G., Krebs, M. (2016) Torfmooskulturen als Ersatzlebensraum (*Sphagnum* cultures as substitute habitat). *Biologie unserer Zei*t, 46, 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, 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, 1–30.

Glime, J.M. (2007) Economic and ethnic uses of bryophytes. In: *Bryophytes: Mosses, Part 1,* Flora of North America Volume 27, Flora of North America Association, New York and Oxford, 14–41. Online at: http://flora.huh.harvard.edu/FloraData/001/WebFiles/fna27/FNA27-Chapter2.pdf, accessed 03 Jan 2020.

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).

Gruda, N. (2012) Current and future perspective of growing media in Europe. *Acta Horticulturae*, 960, 37–43.

Gruda, N. (2019) Increasing sustainability of growing media constituents and stand-alone substrates in soilless culture systems. *Agronomy*, 9, 298, 1–24.

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, 1–16.

Hendry, G.A.F., Grime, J.P. (1993) *Methods in Comparative Plant Ecology: a Laboratory Manual*. Chapman and Hall, London, 276 pp.

Hofer & Pautz GbR (2005) *Integriertes Gebiets-Entwicklungs-Konzept Hankhauser Moor* (*Integrated Development Concept for the Hankhauser Moor*). Unpublished report, Hofer & Pautz GbR, Altenberge, Germany, 120 pp. (in German).

Hurlbert, S.H. (1984) Pseudoreplication and the design of ecological field experiments. *Ecological Monographs*, 54, 187–211.

INFOR (2010) *Exportaciones de Productos Forestales No Madereros 2009* (*Exportations of Non-Timber Forest Products 2009*). BOLETÍN N°5, Instituto Forestal Corporacion Nacional Forestal (INFOR), Spain, 18 pp. (in Spanish). Online at: https://wef.infor.cl/publicaciones/pfnm/2010/03/PFNM201003.pdf, accessed 05 Dec 2019.

INFOR (2019) *Productos Forestales No Madereros* (*Non-Timber Forest Products*). BOLETÍN N°33, Instituto Forestal Corporacion Nacional Forestal (INFOR), Spain, 26 pp. (in Spanish). Online at: https://wef.infor.cl/publicaciones/pfnm/2019/03/PFNM201903.pdf, accessed 05 Dec 2019.

Joosten H. (2015) Peatlands, climate change mitigation and biodiversity conservation. An issue brief on the importance of peatlands for carbon and biodiversity conservation and the role of drained peatlands as greenhouse gas emission hotspots. Nordic Council of Ministers. Online at: http://www.ramsar.org/sites/default/files/documents/library/ny_2._korrektur_anp_peatland.pdf, accessed 13 Jun 2019.

Joosten, H. (2017) Harvesting peatmoss from pristine peatlands is bad for the climate. *IMCG Bulletin*, September 2017, 8–9.

Joosten, H., Sirin, A, Couwenberg, J., Laine, J., Smith, P. (2016) The role of peatlands in climate regulation. In: Bonn, A., Allott, T., Evans, M., Joosten, H., Stoneman, R. (eds.) *Peatland Restoration and Ecosystem Services: Science, Policy and Practice*, Cambridge University Press/ British Ecological Society, Cambridge, 63–76.

Krebs, M., Gaudig, G., Matchutadze, I., Joosten, H. (2018) *Sphagnum* regrowth after cutting. *Mires and Peat*, 20, 12, 20 pp.

Kumar, S. (2017) *Sphagnum* moss as growing media constituent: some effects of harvesting, processing and storage. *Mires and Peat*, 20, 07, 11 pp.

Mejía-Giraldo, J.C., Gallardo, C., Puertas-Mejía, M.A. (2015) *In vitro* photoprotection and antioxidant capacity of *Sphagnum meridense* extracts, a novel source of natural sunscreen from the mountains of Colombia. *Pure and Applied Chemistry*, 87, 9–10.

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, doi: 10.1007/s10531-015-0922-8.

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

Orchard, M.J. (1994) Sphagnum moos - 'Green Gold'. *N.Z. Forestry*, 31–32. Online at: http://nzjf.org.nz/free_issues/NZJF39_2_1994/43385143-5312-4712-9FAE-2F85CAD03AB1.pdf, accessed 08 Mar 2019.

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

Röder, N., Osterburg, B. (2012) Reducing GHG emissions by abandoning agricultural land use on organic soils - A cost assessment. Paper prepared for Triennial Conference (Foz do Iguaçu, Brazil), International Association of Agricultural Economists (IAAE), 22 pp.

Schmatzler, E. (2012) Die Torfindustrie in Niedersachsen - Ergebnisse einer Umfrage zur Zukunft der Torfgewinnung in Niedersachsen (The peat industry in Lower Saxony - Results of a survey about the future of peat extraction in Lower Saxony). *Telma*, 42, 27–41 (in German).

Schmilewski, G. (2008a) Peat overs 77 percent of the growing media production in the EU. IPS Commission II survey. *Peatlands International*, 1/2008, 39–43.

Schmilewski, G. (2008b) The role of peat in assuring the quality of growing media. *Mires and Peat*, 3, 02, 8 pp.

Schmilewski, G. (2017) Growing media constituents used in the EU in 2013. *Acta Horticulturae*, 1168, 85–92.

Schmilewski, G. (2018) *Kultursubstrate und Blumenerden - Eigenschaften, Ausgangsstoffe, Verwendung* (*Growing Media and Potting Soils - Properties, Raw Materials, Use*). Flipbook, Industrieverband Garten (IVG), 254 pp. (in German). Online at: https://www.ivg.org/static/flipbook/flipbook.html, accessed 19 Jul 2019.

Silvan, N., Silvan, K., Näkkilä, J., Tahvnonen, R., Reinkainen, O. (2012) Renewability, use and properties of *Sphagnum* biomass for growing media purposes. Extended Abstract No. 55, *Proceedings of the 14th International Peat Congress*, International Peat Society, Stockholm, 6 pp.

Silvan, N., Jokinen, K., Näkkilä, J., Tahvnonen, R. (2017) Swift recovery of *Sphagnum* carpet and carbon sequestration after shallow *Sphagnum* biomass harvesting. *Mires and Peat*, 20, 01, 11 pp.

Taskila, S., Särkelä, R., Tanskanen, J. (2016) Valuable applications for peat moss. *Biomass Conversion and Biorefinery*, 6(1), 115–126.

Tekes (2017) EcoMoss: *Sphagnum* moss is ideal growth medium, ecological and recyclable. Online at: https://www.tekes.fi/en/tekes/results-and-impact/cases1/case-examples-2017/ecomoss-finnish-sphagnum-moss-is-cultivated-into-ecological-products-for-export/, accessed 02 May 2017.

Temmink, R.J.M., Fritz, C., van Dijk, G., Hensgens, G., Lamers, L.P.M., Krebs, M., Gaudig, G., Joosten, H. (2017) Sphagnum farming in a eutrophic world: The importance of optimal nutrient stoichiometry. *Ecological Engineering*, 98, 196–205.

Thieret, J.W. (1956) Bryophytes as economic plants. *Economic Botany*, 10(1), 75–91.

UN (United Nations) (2015) *Paris Agreement*, 25 pp. Online at: http://unfccc.int/files/essential_background/convention/application/pdf/english_paris_agreement.pdf, accessed 08 Mar 2019.

Whinam, J., Hope, G.S., Clarkson, B.R., Buxton, R.P., Alspach, P.A., Adam, P. (2003) *Sphagnum* in peatlands of Australasia: Their distribution, utilisation and management. *Wetlands Ecology and Management*, 11, 37–49.

Wichmann, S. (2018) *Economic Incentives for Climate Smart Agriculture on Peatlands in the EU*. Proceedings of the Greifswald Mire Centre 01/2018, ISSN 2627-910X, 38 pp.

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.

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.

Wong, J., Dickinson, B., Thorogood, A. (2016) *Assessing the Scale of Sphagnum Moss Collection in Wales*. NRW Evidence Report 185, Natural Resources Wales, 38 pp. Online at: https://cdn.naturalresources.wales/media/685033/report-185-assessing-sphagnum-moss-collection-wales.pdf, accessed 08 Mar 2019.

Yu, J. (2007) *Economically Sustainable Sphagnum Moss Products*. Report to the West Coast Development Trust and the MAF Sustainable Farming Fund, The Horticulture and Food Research Institute of New Zealand Ltd., 41 pp. Online at: https://ecitydoc.com/download/economically-sustainable-sphagnum-moss-products-grant-no-03-087_pdf, accessed 08 Mar 2019.

Zegers, G., Larraín, J., Díaz, F., Armesto, J. (2006) Impacto ecológico y social de la explotación de pomponales y turberas de Sphagnum en la Isla Grande de Chiloé (Ecological and social impact of *Sphagnum* pomponales and peat exploitation in the Isla Grande de Chiloé). *Revista Ambiente y Desarrollo*, 22(1), 28–34 (in Spanish).

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Appendix

Table A1. Costs of establishing a Sphagnum farming pilot site on former bog grassland, given as proportionate cost per partial net production area (€ ha^{-1}).

		Scenario A High costs	Scenario B Medium costs		Outlook Reduced costs
Data from		2011	2016	Compared to 2011	Estimates [c]
Establishment [a]					
- Site preparation	€ ha^{-1}	14,615	36,287	+ 148 %	14,000
- Investment for water management	€ ha^{-1}	45,952	22,334	- 51 %	10,000
- *Sphagnum* shoots[b]	€ ha^{-1}	58,467	34,779	- 41 %	20,000
- “Seeding work”	€ ha^{-1}	8856	5046	- 43 %	5000
Total	***€ ha^{-1}***	***127,862***	***98,446***	***- 23 %***	***49,000***

[a] Establishment cost in 2011, total net production area: 2 ha (cf. Wichmann *et al.* 2017), in 2016 for the extension area of 3.6 ha, total net production area: 5.6 ha.

[b] *Sphagnum* shoots as founder material were bought at a price of € 750 m^{-3} in 2011, costs in 2016 equate proportional costs of cultivating and harvesting own founder material over five years.

[c] Estimates are based on values from year 2011 (site preparation) and 2016 (“seeding work”), a medium break-even price of € 250 m^3 calculated for a total cultivation time of 20 years (Table 3 this study) and a cost-efficient irrigation system (cf. Wichmann et al. 2017).

Table A2. Costs of managing and harvesting a Sphagnum farming pilot site on former bog grassland (1st rotation period: 2011-2016), given as proportionate cost per partial net production area (€ ha^{-1}) and costs of transport and processing of harvested *Sphagnum* biomass (€ m^{-3}).

		1st rotation period (Scenario A - high costs)					
		2011	2012	2013	2014	2015	2016
Management [a]							
- Water management	€ ha^{-1}	2368	1799	3279	2934	2378	1221
- Site maintenance	€ ha^{-1}	1447	5075	10,653	7172	11,772	1897
Total	***€ ha^{-1}***	***3815***	***6874***	***13,932***	***10,106***	***14,150***	***3118***
Harvest							
- Mowing	€ ha^{-1}						5880
- Field transport	€ ha^{-1}	-	-	-	-	-	6772
Total	***€ ha^{-1}***						***12,652***
Transport, Processing							
- Loading [b]	€ m^{-3}	-	-	-	-	-	0.35
- Road transport [b]	€ m^{-3}	-	-	-	-	-	3.20
- Cleaning [c]	€ m^{-3}	-	-	-	-	-	3.24
- Screening [c]	€ m^{-3}	-	-	-	-	-	0.64
Total	***€ m^{-3}***	-	-	-	-	-	***7.43***

[a] Management costs from May 2011 till June 2016, i.e. 62 months in total; for details see Figure 4.

[b] Based on the costs of handling peat: loading with wheel loader at € 75 h^{-1} (20 minutes per lorry) and transporting with lorry and trailer (75 m^3, 21 t additional load) from field site to processing plant (70 km; € 240).

[c] Based on the costs of processing “white peat” in vapour treatment facility and screening line.

Table A3. Mean bulk density of fresh *Sphagnum* biomass (FM g L^{-1}) according to EN 12580 and calculated dry mass bulk density (DM g L^{-1}) in dependence of the water content.

Origin	**Predominant species**	**Sampling** Year	n	**Processing and storage**	**Water** %	**Mean bulk density** FM g L^{-1}	DM g L^{-1}
Sphagnum	*S. palustre,*	2013	4	none	93.8	199.5	12.3
farming on	*S. fallax*	2015	3	drying on a concrete slab	28.5	(24.9)[a]	(17.8)
bog grassland,		2015	3	chopping, pressing	87.2	153.3	19.6
NW Germany		2015	3	chopping	91.4	248.7	21.4
		2017	3	storage over winter in the field, vapour treatment, screening: fine fraction	91.5	282.8	24.1
		2017	3	storage over winter in the field, vapour treatment, screening: coarse fraction	87.3	237.6	30.1
Sphagnum	*S. papillosum*	2015	3	drying on a concrete slab	24.1	31.1	23.6
farming on		2015	3	storage in a pile	75.9	108.1	26.1
cut-over bog,		2015	3	storage in a bag	76.0	125.5	30.1
NW Germany		2015	3	vapour treatment, 10 min	84.8	223.6	33.9
		2015	3	vapour treatment, 20 min	78.7	166.6	35.4
		2015	3	vapour treatment, 20 min	82.3	269.9	47.8
Near-natural	*S. fuscum*	2016	3	pressing, screening: coarse fraction	87.5	243	30.4
peatland,		2016	3	pressing, vapour treatment	88.5	269	30.8
Finland		2016	3	pressing	87.0	274	35.5
		2016	n.a.[b]	pressing, screening: fine fraction	87.1	(343)	(44.3)
Mean ± 1 SD							*29.0 ± 9.36*

[a] Measuring the bulk density was hampered by the very dry and brittle biomass.

[b] The value was not measured according to EN 12580 but by the volumeter in the growing media production facility.

Table A4. Present Values (*PV*) of Sphagnum farming at high costs (Scenario A) and medium costs (Scenario B) at different levels of harvested yield, bulk density and price (DM = dry mass). Highlighted cells indicate positive Net Present Values (*NPV*), i.e. profitable cases.

Average productivity	**DM t ha^{-1} yr^{-1}**			**3.1**		**4.9**		**6.8**	
Average yield	**DM t ha^{-1} yr^{-1}**			**2.0**		**3.2**		**4.4**	
Harvested yield	**DM t ha^{-1}**			**10**		**16**		**22**	
Bulk density	**DM g L^{-1}**			**38**	**20**	**38**	**20**	**38**	**20**
Volume	**m^3 ha^{-1}**			**263**	**500**	**421**	**800**	**579**	**1,100**
PV (Cost-A)			€ ha^{-1}	311,734	316,665	328,317	336,207	344,900	355,749
PV (Cost_B)			€ ha^{-1}	243,260	248,191	259,843	267,733	276,426	287,275
PV (Revenue)	**Price (€ m^{-3})**	**25**	€ ha^{-1}	18,436	35,028	29,497	56,045	40,559	77,062
		165	€ ha^{-1}	121,676	231,185	194,682	369,896	267,688	508,607
		750	€ ha^{-1}	553,074	1,050,840	884,918	1,681,344	1,216,762	2,311,848
NPV_A	**Price (€ m^{-3})**	**25**	€ ha^{-1}	-293,298	-281,637	-298,820	-280,162	-304,342	-278,687
		165	€ ha^{-1}	-190,058	-85,481	-133,635	33,689	-77,213	152,858
		750	€ ha^{-1}	241,340	734,175	556,601	1,345,137	871,862	1,956,099
NPV_B	**Price (€ m^{-3})**	**25**	€ ha^{-1}	-224,824	-213,163	-230,346	-211,688	-235,867	-210,213
		165	€ ha^{-1}	-121,584	-17,006	-65,161	102,163	-8,738	221,332
		750	€ ha^{-1}	309,814	802,649	625,075	1,413,611	940,336	2,024,574