Establishing *Sphagnum* cultures on bog grassland, cut-over bogs, and floating mats: procedures, costs and area potential in Germany

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SUMMARY

Sphagnum biomass is valued as a high-quality constituent of horticultural growing media. The cultivation of *Sphagnum* (peatmoss) was tested successfully on peat soil and on artificial mats floating on acidic water bodies. But whether Sphagnum farming is economically feasible is unclear. Drawing on experience gained during four research projects in Germany we compared the procedures, costs and area potential for establishing large-scale *Sphagnum* cultures. Establishment costs were clearly lower for soil-based cultivation (€8.35 m^{-2} to €12.80 m^{-2}) than for water-based cultivation (€17.34 m^{-2} to €21.43 m^{-2}). Relating costs to the predicted dry mass yield over the total cultivation time resulted in values of €1,723 t^{-1} on cut-over bog, €2,646 t^{-1} on former bog grassland, €9,625 t^{-1} on floating mats without pre-cultivation and €11,833 t^{-1} on pre-cultivated *Sphagnum* mats. The high production costs of the mats (without pre-cultivation 54 % and with pre-cultivation 63 % of total costs) resulted in the highest overall costs. In the case of soil-based *Sphagnum* cultures, the costs of purchasing *Sphagnum* diaspores were most influential (on bog grassland 46 % and on cut-over bog 71 % of total costs). The lowest costs relate to cut-over bog because of the smaller effort required for site preparation compared to taking off the topsoil of former bog grassland and the limited costs for the assumed irrigation system. In the case of former bog grassland, the high investment costs for the project-specific automatic water management boosted the establishment costs. Taking into account potential savings on the irrigation system and the high area potential, bog grassland emerges as the most promising land category for Sphagnum farming in Germany.

KEY WORDS: cost assessment, degraded bogs, growing media, paludiculture, Sphagnum farming

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INTRODUCTION

Sphagnum biomass is regarded as a high-quality constituent of horticultural growing media (Emmel 2008, Oberpaur *et al.* 2010, Blievernicht *et al.* 2013) and is suitable for a wide range of additional applications (Zegers *et al*. 2006).

'Wild' *Sphagnum* is harvested in countries with extensive natural peatlands (*e.g.* Finland; Reinikainen *et al.* 2012) or *Sphagnum*-dominated (secondary) wetlands ('pomponales' in Chile; Díaz *et al.* 2008, Domínguez 2014). In countries where drainage has degraded almost all of the domestic peatland area, such as Germany (98 %) and The Netherlands (95 %) (Barthelmes 2016), the few bogs that are still covered by natural vegetation are strictly protected. Under these circumstances, the cultivation of *Sphagnum* ('Sphagnum farming') can provide *Sphagnum* biomass for peatland restoration (Money 1994) and as a renewable substitute for slightly decomposed 'white' peat in horticultural applications (Gaudig *et al.* 2014). Additionally, a mosaic of land- and water-based *Sphagnum* (peatmoss) cultivation has been proposed as a vision for sustainable use of a bog landscape that has been drained for agriculture and peat cutting up to the present time (Figure 1, Gaudig *et al.* 2014).

Pilot studies have demonstrated the practical feasibility of establishing *Sphagnum* cultures on former bog grassland (Joosten *et al.* 2013), cut-over bogs (Kamermann & Blankenburg 2008, Gaudig *et al.* 2017), and mats floating on acidic water bodies created by the extraction of peat, sand, and lignite (Joosten 2010; Blievernicht *et al.* 2011, 2012). However, the economic feasibility of *Sphagnum* cultivation and the preconditions for large-scale implementation have not yet been investigated.

This article provides a first assessment of the cost of establishing commercial *Sphagnum* cultures at the three types of production site, compares the relevant establishment procedures, and analyses options for and constraints on Sphagnum farming.

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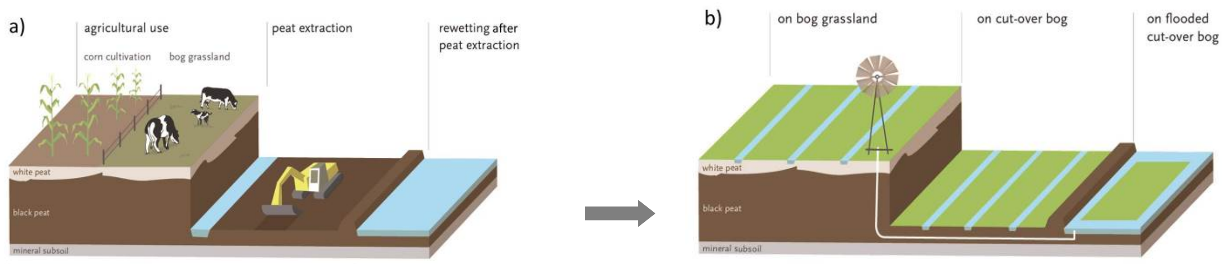

Figure 1. Mosaics of a) current land use on degraded bogs in NW Germany and b) *Sphagnum* cultures after rewetting (after Gaudig *et al.* 2014).

METHODS

Sphagnum farming is a new land use option. In contrast to conventional agricultural production methods, there are no established standard procedures or standard cost data available. Therefore, our cost assessment was conducted in two steps: a first qualitative step defining how *Sphagnum* cultures are established and which costs have to be considered; and a second quantitative step determining, for instance, the amount of time required and costs *per* hour of operating the machinery. Our cost calculations were based on experience from four research projects that aimed to establish *Sphagnum* cultures in Germany, on peat soil and artificial floatable mats (Table 1).

The MOOSGRÜN pilot trial was conducted on an area of approximately 4 ha of former bog grassland with a net production area of 20,268 m², making it possible to test mechanical establishment procedures and collect real-life data. We used daily time sheets to document the hours of labour and machinery provided by the industrial project partner for the individual work steps and compiled the invoices for purchase of materials and services provided by external enterprises.

The small pilot trial on cut-over bog (TORFMOOS) did not include cost assessments. However, on the basis of long-term experience of preparing cut-over sites for rewetting and restoration, it was possible to identify procedures and derive machinery costs for commercial upscaling. In order to create conditions favouring bog regeneration, peat companies in Lower Saxony are required to: (a) leave a waterlogging layer of at least 0.5 m of highly decomposed peat (H > 7, degree of humification according to von Post 1924); (b) create flat polders with surrounding surface bunds to retain precipitation; and (c) install outlets for surplus water (Blankenburg 2004, MU 2011). Additionally, some costs were assessed according to the trial on former bog grassland (MOOSGRÜN). The calculation was conducted for a fictional site of ~ 3 ha with a net production area of 20,000 m^2.

The first cost calculation for Sphagnum farming on floating mats was based on small trials and assumptions (MOOSFARM, reported in Joosten 2010). For this article, previous work has been revised in the light of experience gained by the practice partners in PROSUGA, when floatable mats were produced at industrial scale and successfully tested on man-made water bodies with an overall area of > 2,000 m^2.

The calculations encompassed site preparation or mat production and the establishment of the *Sphagnum* cultures. Planning costs (*e.g.* site identification, permissions) and costs of further management, maintenance, harvesting, *etc*. were not addressed. Generally, all enterprises involved in the projects supported our calculations by providing data on the costs of labour, machinery, investment and mat production. The price level refers to the year 2011, when field experiments were established on bog grassland and on floating mats at larger scale. For comparability, all costs were allocated to the net production unit, *i.e.* € *per* m^2 of *Sphagnum* lawn, and related to the harvestable amount of biomass.

Because *Sphagnum* is perennial, we assessed yields over the possible total cultivation time and conducted dynamic investment calculations. In addition to the initial establishment costs (E) in the first year ($t = 0$) we considered the intermediate costs (I) of some re-establishment occurring at a later time (t) and discounted costs back to present values (PV) with interest rate (i) (Equation 1). The present values of establishment costs were spread over the expected total cultivation time (T) and expressed as annuities (A), *i.e.* constant annual values (Equation 2).

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Table 1. Main features of *Sphagnum* culture pilot trials conducted within four German research projects (2004–2015).

Medium	Field site	Net production area (m^2)	Cost assessment	Project name (duration)
peat soil, highly decomposed (black peat)	cut-over bog (Ramsloh, Lower Saxony)	1,260	NO not included	TORFMOOS (2004–2007)
floating mats	several water bodies (resulting from peat, sand or lignite extraction)	230	YES assumptions	MOOSFARM (2007–2010)
floating mats	several water bodies (resulting from peat or lignite extraction)	2,030	NO not included	PROSUGA (2010–2013)
peat soil, slightly decomposed (white peat)	former bog grassland (Rastede, Lower Saxony)	20,268[a]	YES field data	MOOSGRÜN (2010–2015)

[a]The total pilot area of 4 ha included infrastructure such as causeways and irrigation ditches.

$$PV = E + \sum_{t=1}^{T} \frac{I_t}{(1+i)^t} \qquad [1]$$

$$A = PV * \frac{(1+i)^T * i}{(1+i)^T - 1} \qquad [2]$$

After assessing the procedures and costs for establishing *Sphagnum* cultures, we looked at the potential for upscaling pilots in Germany. Based on literature, we assessed the area potential for commercial Sphagnum farming on former bog grassland, on cut-over bogs, and on acidic water bodies.

RESULTS

Procedures for establishing *Sphagnum* cultures

Cultures on bog grassland

The soil-based Sphagnum farming site consists of three elements: *Sphagnum* production strips, narrow ditches for irrigation around each production strip, and bunds used as causeways. Before planning and preparing the site, one of two types of production system (PS) must be chosen (Figure 2). The first involves the use of adapted harvesting machinery that can drive onto the wet *Sphagnum* production strips without damaging them so that fewer causeways are needed and *Sphagnum* production strips can occupy a larger share of the total field area (PS 1; Figure 2 a). The second type of production system (PS 2; Figure 2 c) involves the use of an excavator with a mowing bucket for management and harvesting. The maximum width of the production strips is determined by the maximum operating range of the excavator arm from the causeway. The width of 10 m also ensures sufficient lateral water supply from the ditches to the peatmoss in the middle of the strips

Setting up the pilot trial on bog grassland at Rastede (Lower Saxony, NW Germany; Table 1) consisted of two phases: (a) preparing the site; and (b) initiating the *Sphagnum* culture (*cf*. Table 2). A tracked bucket excavator (Komatsu PC 160, working width 250 cm, tracks 2 × 130 cm) was used for all construction work and an adapted snow groomer equipped with a manure spreader was used for the ‘seeding’ work.

The irrigation system allowed us to control the water table and water inflow electronically, and to monitor the trial remotely *via* the internet. The automatic water management system was expected to reduce the need for inspection visits, provide data for hydrological monitoring, and ensure a sufficient water supply. To operate the pump, valves and control centre, the field site had to be connected to an electrical power supply. Thus, in the case of the pilot trial, construction work included the installation of approximately 400 m of underground cable connecting to the national power grid at the nearest farmyard, with horizontal drilling for a culvert passing beneath the major runoff ditch.

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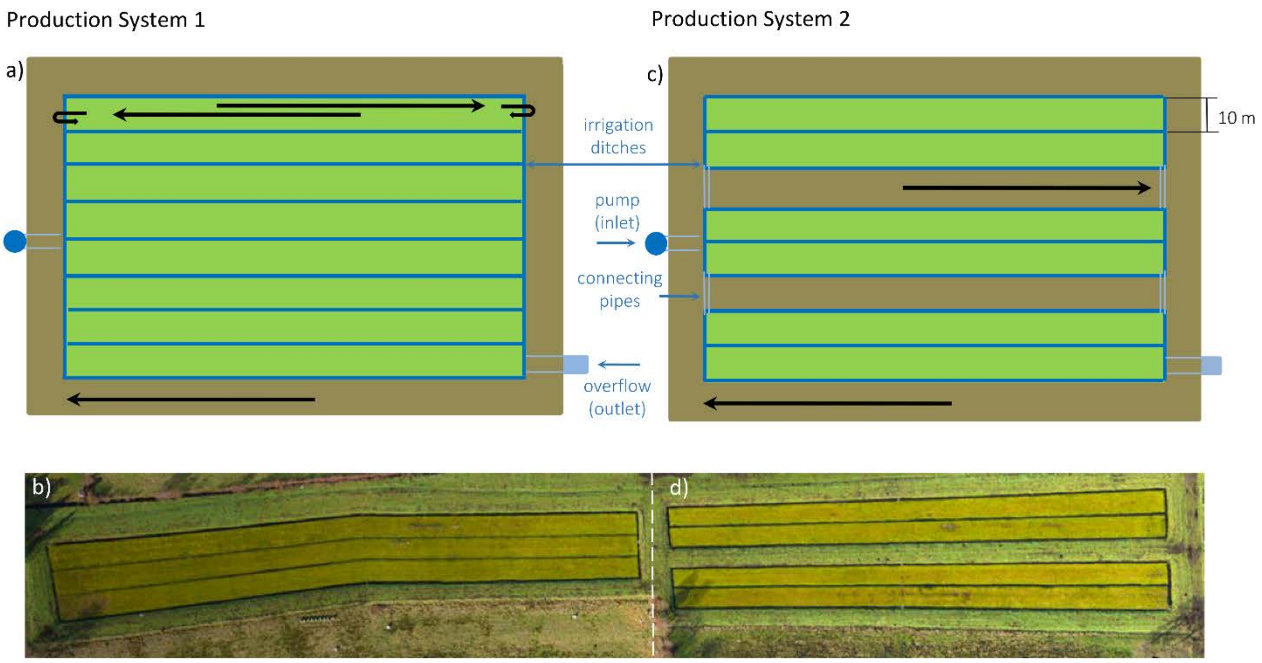

Figure 2. Soil-based *Sphagnum* culture (plan views). Production System 1 (PS 1) requires machines that can be driven (black arrows) onto the *Sphagnum* production strips (green), despite their low bearing capacity; the causeways (brown) provide a turning area for the machines and allow the transport of harvested biomass: a) schematic illustration, b) field experiment with three neighbouring production strips. Production System 2 (PS 2) provides more causeways for weed control machinery, moss harvesting and biomass transport: c) schematic illustration (following Wichmann *et al.* 2014), d) field experiment with 2 × 2 production strips.

Cultures on cut-over bogs

The work steps required to establish *Sphagnum* cultures on cut-over bogs are similar to those described for bog grassland (Table 2). The main differences relate to the initial site conditions. The even surface of bare peat that remains after milled peat extraction means that less effort is required to prepare the site. Instead of removing the topsoil, it is sufficient to adjust small height differences. A tracked vehicle equipped with a blade smooths the surface and removes peat for bunding, as is common in peatland restoration work (Figure 3a). An excavator shapes the bunds, which are used as causeways. A minimum height of 1 m is suggested for main bunds when restoring excavated sites (Blankenburg 2004).

It can be assumed that excavated sites are generally too distant from settled areas to allow a connection to the power grid. The field trial in Ramsloh (Table 1) was irrigated with ditch water using a wind pump. Water retention basins or wells might be necessary on large sites. To ensure a sufficient water supply in periods with little wind and high evaporation, investment costs for a mobile electric pump and generator (emergency power unit) were included. In the Ramsloh trial, underground irrigation pipes were installed every 5 m at a depth of 30 cm (Kamermann & Blankenburg 2008, Gaudig *et al.* 2017) to compensate for the low hydraulic conductivity of highly decomposed peat. Because the continuing functionality of the underground irrigation system over time is unclear (Gaudig *et al.* 2017), and considering the high effort required to install it, open ditches with the same spacing as the pipes (5 m) were assumed for large-scale implementation. Costs for their installation by a tracked vehicle equipped with a ditch-digging device, and an excavator to dig ditches along the causeways, were included in the calculation.

The calculation for upscaling Sphagnum farming on cut-over sites assumed mechanical spreading of moss diaspores and straw as demonstrated on bog grassland at Rastede (Table 2), as opposed to manual spreading as in the small field trial on cut-

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Table 2. The work steps required to establish *Sphagnum* cultures on bog grassland in Rastede (Lower Saxony, NW Germany).

Site preparation	**Removing the degraded topsoil and providing an even surface** • deciding on the type of production system (Figure 2) • pegging (size) and levelling (depth) of future production strips • transporting the excavator to the field site • taking off sod and the layer of topsoil (30–50 cm, laser-controlled) that is mineralised, limed and enriched with nutrients using a tracked excavator, creating an even surface on the production strips to ensure a homogeneous supply of water to all sub-fields
	Installing infrastructure for water management • excavating narrow ditches (approximately 50 cm wide, 50 cm deep) • constructing outflows for surplus water • installing pumps and underground pipes for irrigation • installing underground cables, sensors and a container for the control centre
	Constructing causeways as management and harvesting infrastructure • using the removed topsoil to build bunds and shaping the bunds as causeways
Initiating *Sphagnum* culture	**Purchase and storage of seeding material** • purchase and storage of *Sphagnum* biomass → diaspores • purchase and storage of straw → mulching
	Spreading *Sphagnum* fragments and straw mulch • transporting machinery, moss and straw to the field • loading the manure spreader, mounted on a snow groomer, with an excavator grab • spreading the moss and straw mulch → establishing the production strips
	Rewetting • initial filling of the ditches • adjusting outflows, refitting non-return valves → raising the water table immediately to minimise desiccation of diaspores

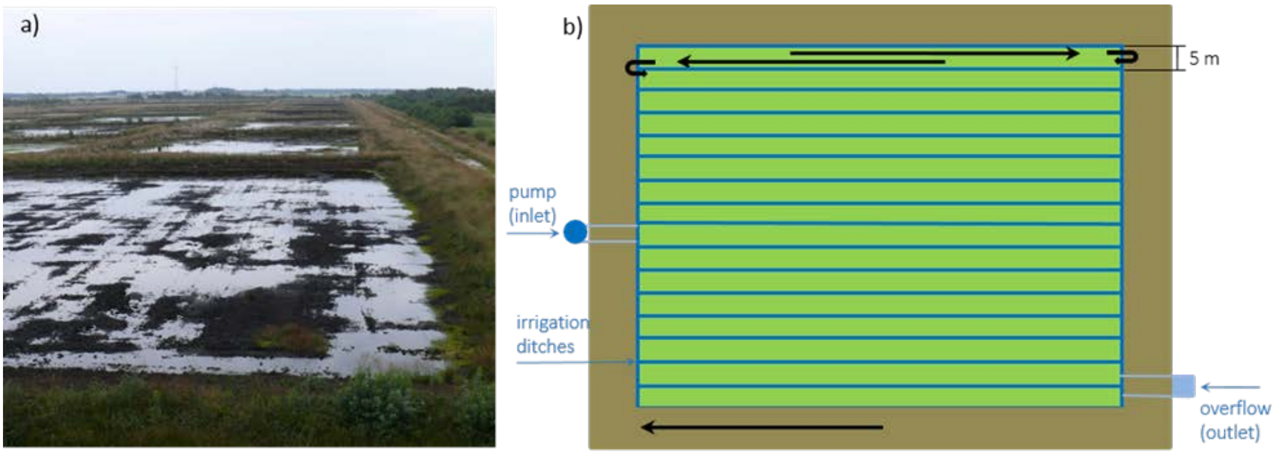

Figure 3. a) Cut-over bog divided into polders, as is commonly done in Germany for restoration purposes; b) schematic illustration (plan view) of Production System 1 on cut-over bog (CO-PS 1) with narrow (5 m) production strips (compare Figure 2a).

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over bog at Ramsloh. The diaspore application rate at Ramsloh was 7.9 L m^{-2} (~ 10 m^3 for 1,260 m^2; Kamermann & Blankenburg 2008, Table 1), and thus similar to that in the Rastede field trial (7.8 L m^{-2}). For comparability, we used the same diaspore price (€750 m^{-3}) instead of calculating the costs of manual collection as actually conducted within the project on cut-over bog. The fictional production site (CO-PS 1) assumed for the cost estimates extends to ~ 3 ha with 16 moss strips of 5 m × 250 m, *i.e*. it has a net production area of 20,000 m^2 (Figure 3b).

Cultures on floating mats

Two mat components were developed and field tested at large scale, namely: (a) floatable mats; and (b) pre-fabricated mats with *Sphagnum* fragments stitched onto a carrying material and rolled out on the floating mats, either directly after manufacture or after a period of pre-cultivation under sheltered conditions (Figure 4). Costs have been calculated for both of these production options.

For the floating mats, panels of polystyrene foam (2 cm thick) were used as floats to ensure permanent buoyancy. The cost calculations considered panels made of extruded polystyrene foam (XPS) (brand name *e.g*. Styrofoam), which require a higher initial investment but exhibited longer durability in wet environments than expanded polystyrene (EPS) (brand name *e.g*. Styropor). The panels were wrapped in an absorbent textile, *i.e*. recycled polypropylene (PP) fleece (Figure 4a), which ensured the supply of water to the mosses. The fleece connected the single XPS panels together to form a mat of width 1.20 m and length ~ 13 m, leaving a small gap after every second panel so that the long mat could be folded up for transport from the production plant to the field.

The field-tested *Sphagnum* mats consisted of recycled PP fleece, the *Sphagnum* diaspores (3–4 L m^{-2}), and a thin straw mat covering to reduce evaporation and to fix the mosses. The cost of the straw mats (chopped cereal straw between PP nets, €0.30 m^{-2}) was not included in the calculations because the field trials revealed some disadvantages. During pre-cultivation, the straw mats led to increased weed (*e.g*. cereal) occurrence and had to be lifted regularly because the moss grew through them. On floating mats without pre-cultivation, the straw mats led to conditions becoming too wet for the sensitive phase of moss lawn establishment. Finally, instead of decomposing in the field, the PP net only disintegrated leaving residues in the harvested biomass. For pre-cultivation, the straw mat was replaced with a thin, reusable shading fleece (€0.25 m^{-2}) that improved *Sphagnum* growth by ensuring a moist microclimate. For transport, the cost calculations assumed a separating layer of thin paper in place of the straw mat, to prevent moss fragments from sticking to the bottom side of the rolled-up *Sphagnum* mat.

For soil-based pre-cultivation (Figure 4b), the *Sphagnum* mats were rolled out on ground that had been covered with woven fabric and a thin (0.1 mm) polyethylene film. The moss was protected from direct sunlight by a tunnel covered with shading fabric that was rolled up temporarily for conditioning. An additional shading fleece reduced

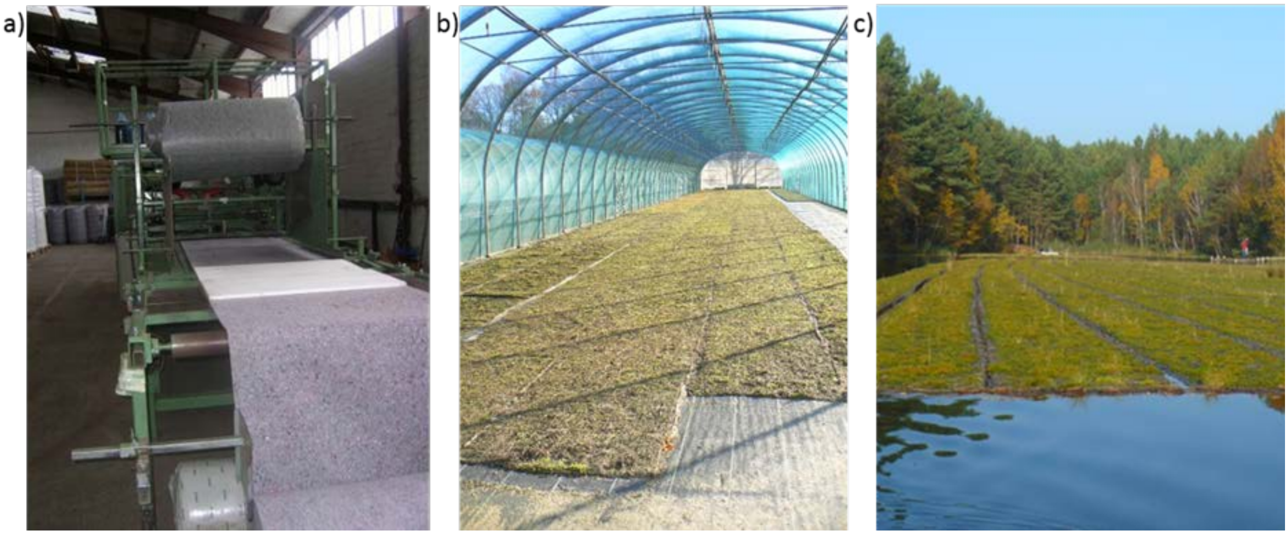

Figure 4. a) Stitching machine for mat production; b) pre-cultivation of *Sphagnum* mats in a shading tunnel (photo: C. Schade, NIRA); c) production site established on a flooded opencast lignite mine.

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evaporation. Natural precipitation was supplemented by artificial irrigation to ensure a sufficient water supply. In addition to manual weeding, the application of herbicides and fungicides was successfully tested. Pre-cultivation took 6–12 weeks, meaning that two or three runs can be realised within the annual vegetation period.

Long-distance transport of the mats from the production sites in NW Germany to the large-scale trials on artificial water bodies south of Berlin was by lorry. After unloading, transport to the shore and watering, a motorboat was assumed to pull, place and anchor the floating mats on the water body. The *Sphagnum* mats were rolled out on the floating mats and the single mat strips were reversibly connected to a larger production unit such that they could later be separated for harvesting (Figure 4c). To maintain good vitality of the *Sphagnum* diaspores, all work steps (including delivery and installation) must be carried out without delay.

Establishment costs

Cultures on bog grassland

Preparation of 3 ha of grassland for Sphagnum farming according to Production System 1 (GL-PS 1, 0.81 ha net production area) and Production System 2 (GL-PS 2, 0.87 ha net production area) took 50 working days. The main effort went into taking off and relocating the topsoil (Figure 5). This work step was more time-consuming for GL-PS 1 than for GL-PS 2. In contrast, GL-PS 2 required higher labour and machinery costs for constructing ditches, passages and causeways (Table 3).

Of the total establishment costs of €12.67 and €12.80 m^{-2} (Table 3), site preparation accounted for a minor fraction (GL-PS 1: 11 %, GL-PS 2: 12 %, Figure 6a). The most important cost element was the purchase of *Sphagnum* diaspores (46 %), whereas the seeding work (mainly labour and machinery) accounted for only 7 %. The investment costs for the automatic water management system amounted to 35 % of total cost. Major elements, totalling up to ~€75,000 (Table 3), were site or research specific; for example, the work required to connect the field site to the national power grid (including horizontal drillings), and the material and programming costs for the electronic water management control system. These costs were initially allocated to a relatively small area of ~2 ha. Enlarging the production area to 5.6 ha (in 2016) considerably reduced the proportionate initial cost of irrigation infrastructure *per* unit area (Figure 6a), further emphasising the influence of diaspore costs (46 % → 53 %).

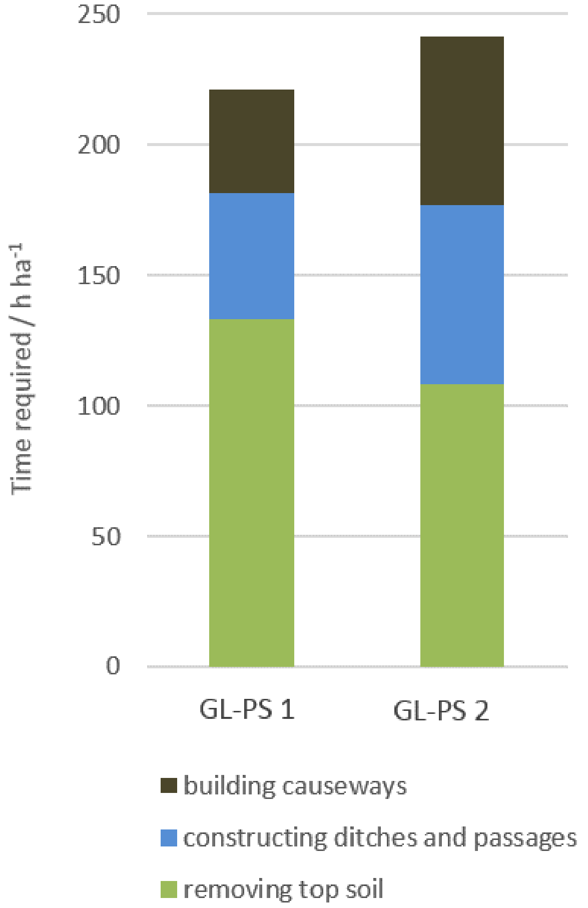

Figure 5. Time required to prepare the site for the pilot trial on former bog grassland, projected for a total area of one hectare to compare Production Systems 1 and 2 (Figure 2), with working steps distinguished.

Cultures on cut-over bogs

The purchase of *Sphagnum* diaspores accounted for 71 % of the total establishment cost of €8.35 m^{-2} (Table 4). Site preparation (7 %) and seeding work (10 %) were of only minor importance (Figure 6b). The investment cost for providing irrigation by wind and mobile pumps amounted to 12 % of the total cost.

Cultures on floating mats

The total investment cost for water-based Sphagnum farming amounted to €17.34 m^{-2}, increasing to €21.43 m^{-2} when pre-cultivation was included (Table 5). The *Sphagnum* diaspores (€750 m^{-3}) accounted for shares of 17 % and 14 %, respectively. The purchase of floating mats and *Sphagnum* mats incurred the highest costs (54 % and 63 % without diaspores), including surcharges added by upstream suppliers to cover their general costs and production risks (12 % and 15 %).

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Table 3. Labour, machinery and investment costs of establishing *Sphagnum* cultures on bog grassland in Rastede (Lower Saxony, Germany) in 2011. In order to calculate proportionate costs, some cost items (*) had to be related only to GL-PS 1 and GL-PS 2 (total: ~ 1.68 ha), while others (**) applied to the whole pilot area (2.03 ha net production area).

		Total		**GL-PS 1**	**GL-PS 2**	
Net production area (ha)		1.68 / 2.03		0.815	0.868	
Site preparation						
Transport of the excavator	€	1488	**	598	637	*1*
Pegging and levelling	€	408	*	197	210	*2*
Labour	€	9039	*	4221	4957	*3*
Excavator	€	13,302	*	6133	7169	*4*
Water outlets	€	358	*	346	471	*5*
Total	€	24,594		11,507	13,364	
Proportionate costs per *partial area*	€ m^{-2}	*1.46*		*1.41*	*1.55*	
Automatic water management						
Pump	€	4353	**	1750	1864	*6*
Electric water meter	€	1560	**	627	668	*7*
Valves	€	3540	*	885	885	*8*
Well shafts	€	1200	**	482	514	*9*
Polyethylene (PE) pipes	€	2266	**	911	970	*10*
Telephone and electricity cable	€	3749	**	1507	1606	*11*
Control and connection cable	€	3050	**	1226	1306	*12*
Installation of underground cables, closing gap to power grid	€	40,302	**	16,202	17,260	*13*
Connection for power supply	€	1510	**	607	647	*14*
Container	€	3800	**	1528	1627	*15*
Control cabinet	€	18,850	**	7578	8073	*16*
Labour (supporting work)	€	8901	**	3578	3812	*17*
Total	€	93,081		36,931	35,151	
Proportionate costs per *partial area*	€ m^{-2}	*4.59*		*4.53*	*4.52*	
Seeding work						
Sphagnum diaspores	€	98,388	*	47,639	50,749	*18*
Straw	€	500	**	201	214	*19*
Loading, storage and chopping	€	2726	**	1096	1168	*20*
Transport to the field, loading, supporting works	€	9705	*	4699	5006	*21*
Spreading with adapted snow-groomer	€	3034	**	1220	1299	*22*
Total	€	114,352		54,854	58,436	
Proportionate costs per *partial area*	€ m^{-2}	*6.73*		*6.73*	*6.73*	
Proportionate costs per *partial area (without* Sphagnum *diaspores)*	€ m^{-2}	*0.89*		*0.89*	*0.89*	
Overall establishment costs	€ m^{-2}	***12.79***		***12.67***	***12.80***	
Overall establishment costs (without moss)	€ m^{-2}	***6.94***		***6.82***	***6.95***	

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KEY TO TABLE 3

1: permits for road transport (oversize), forwarder costs, transport escort
2: labour, digital level (Trimble)
3: mainly operating the excavator (€23 h^{-1})
4: operating hours (€37 h^{-1}), including approximately 3600 L of diesel
5: passages, overflows with fixing device and outlets with non-return valves
6: dirty water motor pump (4 kW) with float switch
7: motor valves, €885 *per* piece
8: controlling water inlet
9: well shafts for valves
10: for water transport from pump to inlet: PE pipes (400m), T-piece, connection *etc*.
11: underground cable for telephone (420 m) and electricity (500 m + 100 m)
12: 1500 m, 1000 m, 500 m
13: horizontal drilling, material, labour (external company)
14: power connection by power grid operator
15: container for control centre, storage and shelter, size: 2.99 m x 2.43 m, 2.35 m internal height
16: material (control cabinet, terminal blocks, cables, cable ducts, adapter, *etc*.) and labour (installation and programming)
17: supporting installation works (container, cable, pipes, well shafts, valves *etc*.)
18: purchasing *Sphagnum* diaspores at a price of €750 m^3; amount spread on average: 78 m^3 ha^{-1}
19: 25 large square bales and round bales at €20 each
20: machinery and labour for loading (forklift), storage and chopping with a field chopper (contracting firm)
21: transport of diaspores/straw to the field (tractors with trailers), excavator for loading snow groomer, operators, supporting works
22: transport of snow groomer (forwarder), adaptation work (mounting manure spreader), seeding work (machine and operator)

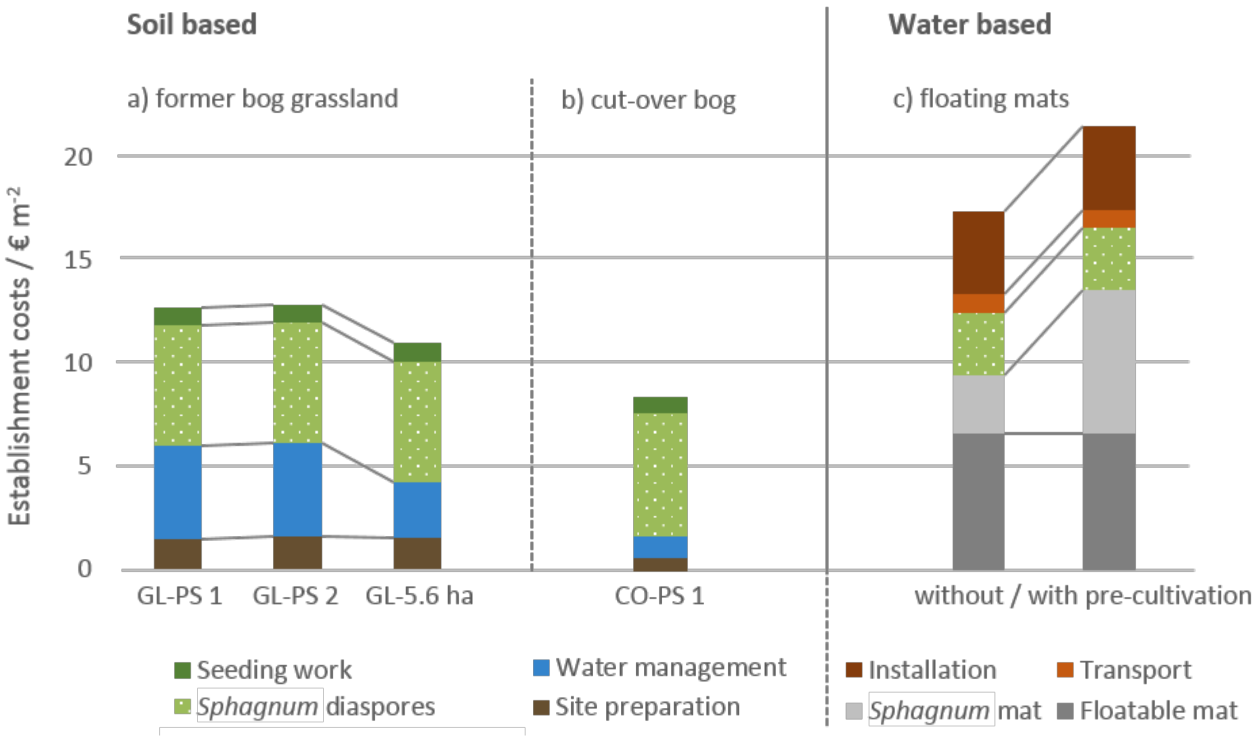

Figure 6. Establishment costs *per* net production area (€ m^{-2}), from left to right: a) on bog grassland for GL-PS 1, GL-PS 2, and with proportionate investment costs for automatic water management reduced by considering the area enlargement from 2 ha to 5.6 ha moss production in 2016 (third column); b) on cut-over bog for a fictional site CO-PS 1 with assumed water supply by wind pump and mobile pump; c) on floating mats without (left column) and with (right column) pre-cultivation of *Sphagnum* mats.

Table 4. Labour, machinery and investment costs of establishing *Sphagnum* cultures on a cut-over bog after milled peat extraction, at a fictional site (CO-PS 1) in Lower Saxony, Germany.

		CO-PS 1	
Net production area (m^2)		20,000	
Site preparation			
Pegging and levelling	€	1500	*1*
Smoothing and poldering	€	3840	*2*
Shaping and compacting causeways	€	2880	*3*
Irrigation ditches along the causeways	€	1360	*4*
Irrigation ditches in the field	€	2550	*5*
Water outlet	€	350	*6*
Total	€	12,480	
Proportionate costs per *partial area*	*€ m^{-2}*	*0.62*	
Water management			
Wind pump (basic supply)	€	15,000	*7*
Mobile pump (demand peaks)	€	5000	*8*
Total	€	20,000	
Proportionate costs per *partial area*	*€ m^{-2}*	*1.00*	
Seeding work			
Sphagnum diaspores	€	118,500	*9*
Straw	€	500	*10*
Loading, storage and chopping	€	2726	*10*
Transport to the field, loading, supporting work	€	9705	*10*
Spreading with adapted snow-groomer	€	3034	*10*
Total	€	134,465	
Proportionate costs per *partial area*	*€ m^{-2}*	*6.72*	
Overall establishment costs	***€ m^{-2}***	***8.35***	
Overall establishment costs (without moss)	***€ m^{-2}***	***2.42***	

KEY TO TABLE 4

1: analysing peat layer depth and profile of mineral subsoil for planning compartment as in the case of restoration
2: 48h, tracked vehicle with operator (€80 h^{-1}), according to experience in restoration work, surcharge of one-third for more careful smoothing
3: excavator with operator (€60 h^{-1}), causeway length: 720 m, required time: approximately 15 m h^{-1} (according to the MOOSGRÜN project)
4: excavator with operator (€60 h^{-1}), ditches: 680 m, required time: approximately 30 m h^{-1} (according to the MOOSGRÜN project)
5: tracked vehicle with ditch-digging device (€85 h^{-1}), ditches: approximately 3,750 m, required time: approximately 125m h^{-1}
6: one outlet (overflows with fixing device according to the MOOSGRÜN project)
7: wind pump, including installation work, for a basic water supply of 10 m^3 ha^{-1} d^{-1}
8: mobile pump + emergency power unit, to meet demand peaks of 100 m^3 ha^{-1} d^{-1}
9: quantity of *Sphagnum* diaspores: 79 m^3 ha^{-1} as in the TORFMOOS project; purchasing price: €750 m^{-3} according to the MOOSGRÜN project
10: according to the MOOSGRÜN project

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Table 5. Material, production and installation costs *per* square metre of water-based Sphagnum farming site.

Production of floatable mats			
Panels of extruded polystyrene (XPS), 2 cm thick	€ m^{-2}	2.53	*1*
Fleece, recycled polypropylene (PP) 350g m^{-2}	€ m^{-2}	1.80	*2*
Production costs	€ m^{-2}	1.20	*3*
Surcharge (20 %)	€ m^{-2}	1.11	*4*
[1] Purchase of floatable mat	**€ m^{-2}**	**6.64**	
Production of *Sphagnum* mats			
Sphagnum diaspores (4 L m^{-2})	€ m^{-2}	3.00	*5*
PP fleece, 350 g	€ m^{-2}	0.85	*6*
Production costs	€ m^{-2}	1.00	*3*
Surcharge (20 %)	€ m^{-2}	0.97	*4*
[2] Purchase of *Sphagnum* mats	**€ m^{-2}**	**5.82**	
Pre-cultivation			
Purchase of *Sphagnum* mats [2]	€ m^{-2}	5.82	
Transport from mat plant to pre-cultivation enterprise	€ m^{-2}	0.05	*7*
Costs of pre-cultivation	€ m^{-2}	3.00	*8*
Shrinkage/loss (5 %)	€ m^{-2}	0.44	*9*
Surcharge (20 %)	€ m^{-2}	0.60	*10*
[3] Purchase of pre-cultivated *Sphagnum* mats	**€ m^{-2}**	**9.91**	
Transport to the field site			
Transport of floatable mats	€ m^{-2}	0.48	*11*
Transport of *Sphagnum* mats	€ m^{-2}	0.40	*12*
[4] Forwarder costs	**€ m^{-2}**	**0.88**	
Installation on the water body			
Consumables	€ m^{-2}	0.50	*13*
Machinery/boat costs	€ m^{-2}	0.73	*14*
Labour costs	€ m^{-2}	2.77	*15*
[5] Installation costs	**€ m^{-2}**	**4.40**	
Establishment costs, without pre-cultivation [1+2+4+5]	***€ m^{-2}***	***17.34***	
Establishment costs, with pre-cultivation [1+3+4+5]	***€ m^{-2}***	***21.43***	

KEY TO TABLE 5

1: purchase price for 10,000 m^2 (January 2010), material prices fluctuate according to oil prices, XPS panel: 125 cm x 60 cm x 2 cm
2: price: €0.85 m^{-2}, required amount 3.33 m^2 (double ply, seam allowance, gap to allow folding) *per* mat unit (1.2 m x 1.31 m)
3: labour and machinery costs (stitching, packing, loading), consumables (stitching thread)
4: surcharge on material costs (for purchase, unloading, storage) and on production costs (risks)
5: no established market for *Sphagnum* of regional origin, purchasing costs in projects: €750 m^{-3} → €0.75 L^{-1}
6: high-quality fleece, comparable with new material
7: company owned lorry (one way = 25 km), loading
8: including labour, machinery, investment, and incidental costs for site preparation, establishment, management, harvest, loading
9: surcharge (5 %) on material and production costs for loss of parts not suitable for sale
10: surcharge (20 %) on production costs
11: €600 *per* lorry (about 500 km), assuming 20 pallets with piles of four folded mats, loading height: 2.20 m, 1,250 m^2 of mats
12: €600 *per* lorry (about 500 km), 1,500 m^2 of rolled-up mats
13: assuming costs of €5000 ha^{-1} for anchoring, fixing, tying together, protecting measures
14: wheel loader with pallet handler for unloading and transport to the shore, motorboats for water-based installation work
15: €26 h^{-1}, 4 workers, 5 days of 8 hours is assumed to be required for installing 1500 m^2

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Comparing establishment costs

Establishing *Sphagnum* cultures on water bodies (€17.34 / €21.43 m^{-2}, Table 5) was clearly the most expensive procedure when compared to establishment on bog grassland (€12.67 / €12.80 m^{-2}, Table 3) and cut-over bog (€8.35 m^{-2}, Table 4) (Figure 6). Sphagnum farming is generally characterised by high investment costs, but establishes a permanent culture allowing repeated harvests. If the initial establishment costs (Tables 3–5, Figure 6) are converted to annuities, *i.e.* constant annual payments spread over the whole lifetime, the results range from €5,600 ha^{-1} a^{-1} (cut-over bog, 20 years, interest rate 3 %) to €49,500 ha^{-1} a^{-1} (floating mats with pre-cultivation, 5 years, interest rate 5 %). The total cultivation time strongly influences the annual costs whereas altering the interest rate has limited effect (Figure 7).

For the soil-based cultures, 20 years appears to be a reasonable lifetime for investment decisions. *Sphagnum* is known to regenerate better than vascular plants, but we lack experience of long-term regeneration potential and whether harvesting could continue after 20 years. For floating mats, a limitation on the lifetime of materials has to be assumed, resulting in a total cultivation time of nine or ten years depending on the length of one rotation (Table 6).

To relate costs to yields, "best guestimates" of productivity and rotation length (Table 6) were derived from the pilot trials (Table 1). For soil-based cultures, two-thirds of the peatmoss productivity is harvested and one-third is left on the field for regeneration. Since we have no experience of regrowth after harvest for water-based cultures, we calculated intermediate costs for re-establishing *Sphagnum* mats to start a new rotation. Converting the establishment costs into annuities and relating them to the predicted harvestable amount of dry (bio)mass (DM) for the different *Sphagnum* cultures results in proportionate costs of €1,723 t^{-1} DM and €2,646 t^{-1} DM for soil-based, and €9,625 t^{-1} DM and €11,833 t^{-1} DM for water-based Sphagnum farming (Table 6).

Potential production area in Germany

Degraded bogs

Covering about 235,000 ha, Lower Saxony hosts around 70 % of Germany's remaining bog sites (Jensen *et al.* 2012). About 30,000 ha of bog was allocated to peat extraction for growing media production with permits phasing out by 2050 (NLWKN 2006). In 2011, poldering for restoration had begun on an area of ~15,000 ha, to be

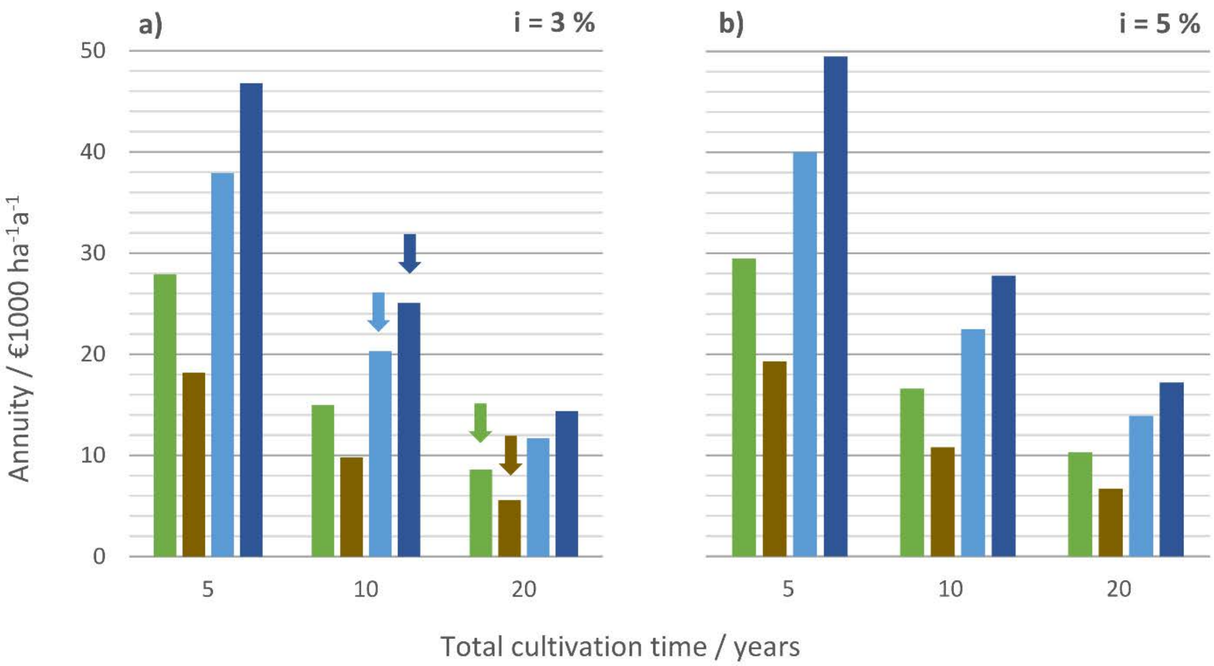

Figure 7. Annuities of initial establishment costs, calculated for an interest rate of a) 3 % and b) 5 %, for Sphagnum farming on former bog grassland (green), cut-over bog (brown) and floating mats without (light blue) and with (dark blue) pre-cultivation, and for assumed total cultivation times of 5, 10 and 20 years. The arrows indicate reasonable cultivation times for the different site types that have been used for further calculations.

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Table 6. Relation of the establishment costs to the harvested dry mass (DM) yield.

Sphagnum farming on:	Total cultivation time (years)	Annuity of establishment costs (i=3%) (€ ha^{-1} a^{-1})	Rotation length (years)	Harvested DM yield (t ha^{-1})	Average annual DM harvest (t ha^{-1} a^{-1})	Proportionate establishment costs (€ t^{-1} DM)
Former bog grassland	20	8,600	4	13	3.25	2,646
Cut-over bog	20	5,600	4	13	3.25	1,723
Floating mats - without pre-cultivation	9	38,500*	3	12	4	9,625
- with pre-cultivation	10	71,000*	2	12	6	11,833

* In addition to initial establishment costs, intermediate costs of re-establishing *Sphagnum* mats after harvest are included.

supplemented with another 12,500 ha by 2040 (Schmatzler 2012). Extraction sites with ongoing peat cutting and an intended agricultural after-use—which could encompass Sphagnum farming on cut-over bog—cover about 500 ha (~ 5 %) of the total area with extraction permits (pers. comm. 2013, engineering consultancy Hofer & Pautz GbR).

The large majority (around 60 %) of bog sites in Lower Saxony have been drained for agriculture or forestry (Jensen *et al*. 2012). Grassland has been converted to arable land (maize production) and peat extraction sites during recent decades, but remains the dominant land use on bogs encompassing around 90,000 ha (MU 2016).

Acidic water bodies

Acidic artificial water bodies result from peat, sand and lignite mining. In Germany, lakes originating in particular from opencast lignite mines cover a large area. There are about 500 lakes, of which more than 100 are larger than 50 ha (Nixdorf *et al*. 2000). Whereas about half of these lakes have neutral conditions, acidic water bodies occur especially in mining regions with Tertiary geology such as Lusatia in Eastern Germany. The total area of East German mining lakes is around 42,000 ha (Rümmler *et al.* 2003), with lakes over 50 ha accounting for ~ 36,000 ha (Nixdorf *et al.* 2000). Large lakes are flooded with foreign water, if possible, to increase their utilisation value (Lienhoop & Messner 2009); acidification by groundwater especially affects smaller lakes (Rümmler *et al.* 2004). Thus, most lakes are unsuitable for Sphagnum farming for various reasons including: pH too low; EC too high; pH too high after flooding with basic river water or liming; in use for watersports and recreation; or prioritised for natural development. Accordingly only a quarter, at maximum, of the total lake area seems appropriate, *i.e*. around 10,000 ha.

DISCUSSION

Quality of the data

Canadian experience of restoring cut-over bogs by transferring and mechanical spreading of “moss layer” and straw mulch (Quinty & Rochefort 2003, Landry & Rochefort 2009) stimulated the German trials on Sphagnum farming. By managing the water table to maximise productivity, and by testing new site types such as former bog grassland and floating mats, novel expertise on how to successfully cultivate *Sphagnum* for commercial purposes has been acquired. Further implementation will allow these procedures to be optimised.

For the first comprehensive cost assessments, the availability of real-life data and, thus, data quality differed for the three types of Sphagnum farming sites examined. Real figures (for the field trial on bog grassland, floatable mat production and pre-cultivation) had to be supplemented with estimates when data were missing (field installation of floatable mats on the water) or when the implementation was manual rather than mechanical (on cut-over bog). Because there is, as yet, little or no experience of management, harvesting and long-term cultures, we focused on comparing the establishment costs.

Sphagnum diaspores

The purchase of *Sphagnum* diaspores was the biggest cost factor for establishing soil-based cultures (bog grassland: 46 %, cut-over bog: 71 %;

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Figure 6a, b). For floating mats, diaspore costs were relatively less important (14 % and 17 %, Figure 6c). Although the diaspore application rate on bog sites (7.8 and 7.9 L m^{-2}; Table 3, Table 4) was double that for floating mats (4 L m^{-2}; Table 5), overall costs were considerably lower for soil-based than for water-based cultures (Figure 6).

So far, there is no market for living *Sphagnum* of regional provenance in Germany. Due to the lack of supply of *Sphagnum* diaspores in the necessary quantities, the supplier holds a monopoly position. Nevertheless, the price of €750 m^{-3} is assumed to represent the real provision costs since the mosses were collected and sorted manually to provide *Sphagnum* diaspores with a minimal fraction of vascular plants. An important factor of uncertainty results from giving the amount in m^3 since, depending on compaction, varying numbers of diaspores were delivered within the same volume. In the future, mechanical harvesting of *Sphagnum* on cultivation sites or *in vitro* production (Beike *et al.* 2015) is likely to increase diaspore availability and reduce the costs. Reduced diaspore costs will especially benefit soil-based Sphagnum farming.

Soil-based cultivation

Water management

The investment costs for infrastructure to provide precise water management was the second most important cost element. The two variants tested on cut-over bog and former bog grassland illustrated a wide range of possible costs ranging from around €20,000 for a wind pump supplemented by a mobile pump (€1.00 m^{-2}, Table 4) to €93,000 for the installation of a power supply and electronically controlled automatic water management system (€4.59 m^{-2}, Table 3). This large difference is caused solely by the choice of irrigation system and is independent of the previous land use. Alternatively, an electric pump powered by a wind turbine and/or solar panels could be used. Especially when investment costs are high, proportionate costs are reduced considerably when the infrastructure is used for a larger moss production area (Figure 6a, right). Identifying cost-effective, site-specific and reliable solutions for water management is a major challenge for commercial soil-based Sphagnum farming.

Site preparation: cut-over bog versus *former grassland*

Site preparation on cut-over bog (CO-PS 1: €0.62 m^{-2}, Table 4) incurred less than half the costs of site preparation on former bog grassland (GL-PS 1: €1.41 m^{-2}, Table 3), but played a minor role in the overall costs (7 % and 11 %, Figures 6b, 6a). This cost difference arises (a) because smoothing a cut-over site requires less effort than removing the topsoil from former bog grassland, (b) because a tracked vehicle with a wide blade is more efficient than an excavator, and (c) by scale effects (fictional CO-PS 1: 2 ha, GL-PS 1: 0.8 ha).

Site preparation: PS 1 versus *PS 2*

In planning the field trial on bog grassland, we aimed to compare two production systems (Figures 2a, 2c). Due to the limited size (3 ha) and triangular shape of the pilot site, the effort of preparation work (Figure 5) differed only moderately between the two systems. The proportionate cost of site preparation was 10 % higher for GL-PS 2 (€1.55 m^{-2}) than for GL-PS 1 (€1.41 m^{-2}) (Table 3). The share of the net moss production was 50 % for the field trial on former bog grassland. In the case of the fictional site on cut-over bog (CO-PS 1, 3 ha), the share was 68 % (Figure 6b). In PS 1 the area lost for infrastructure might be further reduced by enlarging the compartments.

When implementing PS 1 on former bog grassland at larger scale, more degraded topsoil accrues than is needed for constructing causeways. Therefore, it will be necessary to remove some topsoil from the site to maximise the moss production area. This objective is constrained by the high cost of transport and disposal if no sensible use for the removed peat can be identified. Using the mineralised top layer for causeways and—if further soil removal to compensate height differences is unavoidable—selecting less-decomposed peat layers for growing media production can be considered. In order to cut the costs of site preparation and to mitigate greenhouse gas emissions, topsoil removal must be reduced or avoided by developing alternative approaches for establishing *Sphagnum* directly on former grassland. It is inadvisable to establish PS 2 on cut-over bogs because the peat needed for causeway construction must be excluded from extraction—thus creating opportunity costs (income foregone)—but will nevertheless oxidise, releasing carbon dioxide to the atmosphere.

Challenges of upscaling pilots

The main challenge in establishing soil-based *Sphagnum* cultures is to provide an optimal water supply, avoiding drought and flooding which can hamper the establishment and productivity of moss lawn. Investigations on the suitability of potential production sites (*e.g.* water-holding capacity, water conductivity, availability and quality of irrigation water) and careful control of the water table, especially during the sensitive establishment phase, are prerequisites for successful Sphagnum farming.

The Ramsloh pilot trial was successfully established on cut-over bog (Gaudig *et al*. 2014). However, its transferability to conventional cut-over sites has yet to be proved feasible. On the Ramsloh site peat was initially excavated to create a small basin, the remaining peat layer was 160–195 cm thick, and spreading of both *Sphagnum* and straw mulch was conducted manually (Kamermann & Blankenburg 2008, Gaudig *et al*. 2017). Furthermore, the sufficiency of water supplied *via* irrigation ditches at 5 m spacing, as assumed for the cost calculations, has yet to be field tested on highly decomposed peat. If 50 cm of peat must remain beneath the floors of ditches as a seal to prevent vertical water loss, peat cutting must stop earlier to leave a 1 m (instead of a 0.5 m) peat layer, creating opportunity costs for the peat extracting company. Alternatively, the irrigation effort must be increased to compensate for the additional water loss.

Other field trials of Sphagnum farming on cut-over bogs after milled peat harvesting have been conducted in NW Germany by a state-run organisation and a business company, on areas of 2 ha (2002) and 1 ha (2012), respectively. These failed to establish closed *Sphagnum* lawns, most probably due to inadequate water management. Pouliot *et al.* (2015) demonstrated the feasibility of Sphagnum farming in trenches on previously block-cut peatland in Canada, but also stressed the importance of water management optimisation for improving productivity.

Water-based cultivation

Mats causing major costs

Cultivation on water bodies has the advantage of a permanent water supply. The intention is to imitate floating rafts in flooded peat pits and ditches, which are known to support high *Sphagnum* productivity (Money 1994). However, the high production costs of artificial floatable mats was the main factor contributing (54–63 %, Figure 6c) to the highest overall establishment costs for this approach amongst all of the *Sphagnum* culture methods investigated. Furthermore, the durability of cultures on mats is insufficiently understood. If they have to be replaced, disposal costs for the old floating mats must be taken into account. Generally, all work on open water, including not only the installation (Figure 6) but also the management and harvesting of the mats, requires more effort (*e.g.* time and work safety) than soil-based work.

Challenges of upscaling pilots

Water-based cultures are exposed to wind, waves and ice drift which may spill or sever *Sphagnum* biomass or damage the floating mats, especially on larger lakes. Waterfowl using the mats as artificial islands for roosting and nesting caused damage by picking out moss and increasing the supply of plant nutrients. A prerequisite for Sphagnum farming is an appropriate water quality and a water depth of at least 1 m throughout the year. Fluctuating water levels were a challenge on shallowly flooded cut-over bogs. When the water level was low, the roots of vascular plants (*e.g. Juncus effusus*) grew through the mats into the bottoms of the pools, thus anchoring the mats and causing their inundation when the water table subsequently rose again. Therefore, the calculations assumed that cultivation would be on former opencast lignite mines in the 'Lusatian Lakeland' and included costs for long-distance transport of the mats (Figure 6c).

Effects on profitability: relating establishment costs to lifetime and revenues

Higher establishment costs do not necessarily reduce profitability because they represent only part of the overall costs, along with management, harvesting and biomass processing. On the other hand, it is still unknown whether or not certain procedures could pay for themselves in terms of higher revenues by increasing either the quantity or the quality of *Sphagnum* biomass produced. For soil-based Sphagnum farming, the cost advantages of PS1 may be outweighed by reduced productivity due to weed mowing machinery compacting the peatmoss. In the case of water-based Sphagnum farming, pre-culture may be the most suitable way to produce high-value diaspores by growing weed-free 'monocultures' of the intended *Sphagnum* species (sheltered conditions, opportunity to use herbicides and fungicides).

Converting establishment costs to annuities (Figure 7) illustrates the high importance of the lifetime of *Sphagnum* cultures for profitability assessment. In comparison with the other approaches, water-based Sphagnum farming is very likely to involve a shorter total cultivation time and intermediate costs for re-establishing *Sphagnum* mats, which will reinforce the disadvantage of high initial costs. Relating the costs of initial and repeated establishment to the harvestable amount of biomass (€ t^{-1} DM; Table 6) confirms the outcome of the calculations relating costs to the net production area (€ m^{-2}; Figure 6), and on this basis water-based Sphagnum farming appears to be even

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less attractive. However, reasonable profitability estimates rely on verification of the values by long-term real-life data on total cultivation time, durability of the floatable mats, rotation length, regeneration potential after harvesting, and productivity development in the case of repeated cutting. Finally, cultivated *Sphagnum* biomass is not yet traded on the open market, and further investigations to convert dry mass yields (t ha^{-1}) into product volumes (m^3) for revenue calculations are indispensable.

Can the potential Sphagnum farming area meet the demand for white peat in Germany?

The total area (~500 ha) of cut-over peatland in Germany that can potentially be used for Sphagnum farming as new agricultural production is negligible. Rewetting and natural development has become the standard after-use procedure and has been implemented on thousands of hectares. However, several arguments may justify permitting Sphagnum farming instead of natural development—at least temporarily—on peat extraction sites that will become worked-out in the future. Firstly, whereas restoration has achieved limited success in previous decades (Rosinski 2012), Sphagnum farming creates surrogate habitats for rare bog species and improves the provision of ecosystem services (Wichmann *et al*. 2012, Beyer & Höper 2015, Muster *et al.* 2015, Gaudig & Krebs 2016). Secondly, compensation for the impacts of peat extraction might be provided more successfully by restoring other peatlands that have been drained but not extracted. Thirdly, cultivating *Sphagnum* allows the production of a renewable high-quality growing media constituent to reduce the industry's dependence on peat. If 50 % of each newly abandoned peat extraction area were to be rewetted for natural development (as is common practice) but arrangements were negotiated to establish Sphagnum farming as a temporary productive land use on the other 50 %, 5,000 ha of cut-over bog with a net production area of 3,500 ha could potentially be made available.

Germany's ~90,000 ha of bog grassland offers the highest theoretical potential for Sphagnum farming in the country. However, the current legal and policy framework hampers large-scale implementation, *e.g.* through regulations to protect permanent grassland as well as *via* subsidies for drainage-based agriculture and the production of 'biofuels'. Sphagnum farming on bog grassland has enormous potential to increase the provision of ecosystem services, mainly by conserving the carbon store (Günther *et al.* 2017). Adaptations of policy and legislation would be crucial, however, in achieving a shift towards such sustainable land use options (Wichmann *et al*. 2012).

An area of ~10,000 ha of acidic water bodies seemed appropriate for Sphagnum farming. The realistically achievable area is less, however, because only part of the lake surface can be covered by floating mats depending on the shape of the shoreline (*e.g.* bays) and the harvesting regime (*e.g.* space for boats between the mats), as well as for limnological reasons such as the inadvisability of both shading the whole water body and preventing natural oxygenation by wave action. Therefore, we assume a potential effective production area of 5,000 ha. The area of flooded cut-over bog that can potentially be dedicated to Sphagnum farming is very limited (see above), but covering water retention basins with floating mats in order to reduce evaporation (Figure 1) is a reasonable option.

The annual demand for white peat from the German peat and growing media industry is approximately 3.5 million cubic metres (Caspers & Schmatzler 2009). To estimate the potential of Sphagnum farming we assume that *Sphagnum* biomass can replace white peat at a volume ratio of 1:1, average *Sphagnum* dry mass productivities of 3.25, 4 or 6 t ha^{-1} a^{-1} (Table 6), and a bulk density of 30 g L^{-1}. On this basis, *Sphagnum* cultivation on 3,500 ha of cut-over peatland could meet around 10 % of the German demand for white peat. Floating mats extending to 5,000 ha could provide 19 % or 29 % of the demand (without or with pre-cultivated *Sphagnum* mats); but note that the calculation ignores any requirement for diaspores to re-establish (rather than regenerate) harvested *Sphagnum* mats. Finally, a net moss production area comprising 35,000 ha of the country's 90,000 ha of bog grassland could produce sufficient *Sphagnum* biomass to completely replace the white peat requirement of the German growing media industry.

CONCLUSIONS

- Bog grassland has the highest theoretical area potential for Sphagnum farming in Germany and establishment costs can be considerably reduced by choosing a cost-efficient irrigation system.
- Cut-over bogs require the least effort for site preparation, but the feasibility of Sphagnum farming on milled peat sites has yet to be proven by a large-scale field test. The current area potential in Germany is limited, since virtually all sites in Germany are assigned to natural development after peat extraction.

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- Floatable mats are not suitable as major *Sphagnum* cultivation sites because they incur the highest overall establishment costs and face challenges such as wind, waves, damage by water birds and limited area potential.
- Further implementation offers considerable potential for optimising procedures and reducing the costs of, for example, *Sphagnum* diaspores, water management and site preparation (mainly by minimising topsoil removal on bog grassland).
- Profitability assessments require further field experience and research into management, harvesting, processing, regeneration, rotation length and overall number of rotations.

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