Sphagnum farming from species selection to the production of growing media: a review

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SUMMARY

Sphagnum farming - the production of *Sphagnum* biomass on rewetted bogs - helps towards achieving global climate goals by halting greenhouse gas emissions from drained peat and by replacing peat with a renewable biomass alternative. Large-scale implementation of Sphagnum farming requires a wide range of know-how, from initial species selection up to the final production and use of *Sphagnum* biomass based growing media in horticulture. This article provides an overview of relevant knowledge accumulated over the last 15 years and identifies open questions.

KEY WORDS: bog, founder material, harvest, horticulture, management, paludiculture, Paris Agreement, peatland, peat moss, sustainable land use, water quality

INTRODUCTION

To achieve the aims of the 'Paris Agreement' (UNFCCC 2015) - *i.e*. to limit global average temperature to less than 2 °C above pre-industrial levels - net greenhouse gas emissions must start to decrease in the coming few years and be reduced to zero by 2050 (Figueres *et al*. 2017). Drained peatlands cover only 0.5 % of the Earth's land surface but globally contribute 5 % of anthropic greenhouse gas emissions (Joosten *et al*. 2016) and 32 % of cropland emissions (Carlson *et al*. 2017). The importance of rewetting degraded peatlands for greenhouse gas emissions reduction in the land use sector is widely recognised (Leifeld & Menichetti 2018). Sustainable peatland use concepts, as well as the replacement of peat in growing media, are promulgated by the UN Food and Agriculture Organisation (Biancalani & Avagyan 2014) and included in national climate commitments, *e.g*. in the German Climate Action Plan 2050 (BMUB 2016). Sphagnum farming leads not only to a reduction of greenhouse gas emissions from land use by rewetting drained peatlands, but also to replacement of a strategic fossil resource by a renewable alternative.

Large-scale implementation of Sphagnum farming requires knowledge encompassing the entire production sequence; from the selection of cultivation material, acquisition of founder material, establishment and management of the production site, up to harvesting, transport and storage of the biomass and its subsequent processing and application in growing media. This article reviews the available information, including experience gained from *Sphagnum* vegetation restoration and *Sphagnum* gathering (see Box 1 and Table 1), and identifies gaps requiring further research.

BOX 1

In recent times interest in fresh *Sphagnum* moss as a 'product' has been increasing, albeit with different backgrounds and aims. In this respect it is useful to distinguish between the following three types of activity.

***Sphagnum* vegetation restoration** aims to re-establish *Sphagnum* dominated vegetation on degraded bogs (including sites where peat extraction has occurred) for nature conservation, erosion control or carbon sequestration with no intention to harvest the re-established mosses (*e.g*. Wheeler *et al*. 1995, Shuttleworth *et al*. 2015, González & Rochefort 2014, Clarkson *et al*. 2017, Karofeld *et al*. 2016, 2017).

***Sphagnum* gathering** is the collection of *Sphagnum* (*e.g*. for orchid cultivation) from wild populations which are not (or minimally) managed to maintain or increase yields. *Sphagnum* gathering takes place *e.g.* in Chile (Zegers *et al*. 2006, FIA 2009, Díaz & Silva 2012), Australasia (Denne 1983, Buxton *et al*. 1996, Whinam & Buxton 1997) and recently also in Finland (Silvan *et al.* 2012, 2017; Joosten 2017).

Sphagnum farming aims to cultivate *Sphagnum* biomass for harvest, originally as founder material for restoration (Money 1994), but increasingly nowadays as an agricultural crop, *e.g*. as a raw material for horticultural growing media (Gaudig *et al*. 2014, 2017; Pouliot *et al*. 2015). This new type of peatland agriculture includes the selection of highly productive species and active management to maximise yields.

Table 1. Overview of selected *Sphagnum* vegetation restoration projects ≥ 3 ha and Sphagnum farming trials. Smaller *Sphagnum* vegetation restoration projects have been implemented, *e.g*. in Estonia (near Tässi), Germany (peatland Dalumer Moor), Lithuania (Aukštumala peatland) and the United Kingdom (Wales). Further information at www.sphagnumfarming.com.

Location	**Country**	**Former land use**	**Size in ha** total area *(moss area)*	**Duration**
***Sphagnum* vegetation restoration on degraded bogs**				
Quebec (16 sites)	Canada	milled peat extraction	575	since 1995
New Brunswick (10 sites)	Canada	milled peat extraction	167	since 1997
Saskatchewan (2 sites)	Canada	milled peat extraction	83	since 1999
Manitoba (1 site)	Canada	milled peat extraction	220	since 2006
Alberta (4 sites)	Canada	milled peat extraction	92	since 2009
Ilperveld	The Netherlands	grassland	*(3)*	since 2013
Sphagnum farming on cutover bog				
Saint-Marguerite-Marie	Canada	block-cut peat extraction	*(1.6)*	1992–2001
Shippagan 1	Canada	block-cut peat extraction	3.6 *(2.5)*	2004–2012
Ramsloh	Germany	milled peat extraction	*(0.12)*	2004–2014
Shippagan 2	Canada	block-cut peat extraction	2.0 *(0.6)*	since 2012
Twist (Drenth)	Germany	milled peat extraction	5.0 *(2.6)*	since 2015
Twist (Provinzialmoor)	Germany	milled peat extraction	5.0 *(2.3)*	since 2015
Malpils	Latvia	milled peat extraction	*(0.1)*	since 2015
Sphagnum farming on former drained bog grassland				
Rastede	Germany	grassland	14.0 *(5.6)*	since 2011
Sphagnum farming on other degraded bogs				
Saint-Modeste	Canada	remnant of natural bog within milled peat extraction field	1.0 *(0.3)*	since 2013

SELECTION OF CULTIVATION MATERIAL

Sphagnum farming is similar to other agricultural practices in that it aims to maximise yields and limit costs. A first step is the selection of cultivation material on the basis of productivity and suitability for the intended use of the crop.

Productivity

Natural productivity of *Sphagnum* varies widely among species. Global average dry biomass production is 260 g m^{-2} yr^{-1}, while the maximum measured value is 1450 g m^{-2} yr^{-1} (Gunnarsson 2005). The highest mean values have been reported for *Sphagnum cristatum* (840 g m^{-2} yr^{-1}), *Sphagnum falcatulum* (770 g m^{-2} yr^{-1}) and *Sphagnum subnitens* (590 g m^{-2} yr^{-1}) growing under hyper-oceanic climate conditions in New Zealand (Stokes *et al.* 1999, Gunnarsson 2005), for *Sphagnum fuscum* (800 g m^{-2} yr^{-1}), *Sphagnum magellanicum* (790 g m^{-2} yr^{-1}) and *Sphagnum rubellum* (960 g m^{-2} yr^{-1}) in the German humid Rhoen mountains (Overbeck & Happach 1957), and for *Sphagnum palustre* in the warm temperate, humid Kolkheti Lowlands in Georgia (mean 575 g m^{-2} yr^{-1}; Krebs *et al.* 2016). Species of the *Sphagnum recurvum* group grow under relatively eutrophic conditions with generally high natural productivity (Gunnarsson 2005).

So far, only randomly sampled material from wild populations of a few species (*Sphagnum fallax*, *Sphagnum fimbriatum*, *Sphagnum flavicomans*, *S. fuscum*, *S. magellanicum*, *Sphagnum papillosum*, *S. palustre*, *S. rubellum*) has been tested in Sphagnum farming field trials (Krebs *et al.* 2012, Gaudig *et al.* 2014, 2017; Pouliot *et al.* 2015, Graf *et al*. 2017) and several more species have been tested in the glasshouse (*e.g*. Campeau & Rochefort 1996, Johnson 1998, Picard 2010, Gaudig *et al*. 2014).

Selection of highly productive wild provenances will lead to increased productivity. The existence of a genetic basis for productivity is illustrated by the differences between taxonomical sections of the genus *Sphagnum*. While most species of Sections *Acutifolia* and *Sphagnum* are characterised by low rates of production and decomposition, species of Section *Cuspidata* have higher productivity but also higher decomposition rates (Johnson & Damman 1991). However, productivity is also dependent on site conditions such as water regime and nutrient availability (Rydin & McDonald 1985, Aerts *et al.* 1992, Lamers *et al*. 2000, Limpens & Berendse 2003; see ‘Managing a Sphagnum farming site’ on pages 10–13 of this review). Cultivation (and research) will be required to optimise between site conditions and genotypes. Apart from genotype, other genetic properties that may influence productivity include sex and ploidy. Several species have dioecious gametophytes (*i.e*. of different sexes), *e.g*. *S. fallax* (Weston *et al.* 2018).

The role of ploidy deserves extra attention. Polyploid varieties of many agricultural crops display higher productivity and resistance than varieties with lower ploidy (Henry & Nevo 2014). About 70 % of all *Sphagnum* species have haploid gametophytes with chromosome number $n = 19$ while a smaller portion have $n = 38$ (Cronberg 1993). Populations of some species, *e.g*. *S. papillosum*, have both chromosome numbers. These species may provide valuable insights into the link between ploidy and yield. Further research is needed on the relationship between *Sphagnum* genotypes (including ploidy) and productivity, as well as the role of sex in this context.

Suitability for the intended purposes

Sphagnum biomass is already an important raw material for many valuable products (Pouliot *et al*. 2015, Glatzel & Rochefort 2017). Requirements for biomass quality depend on the end use.

Compactness, *i.e*. dry mass *per* unit length of moss, as well as the number of open pores in the *Sphagnum* leaves and stems, determines water holding capacity and capillarity (*cf*. Hayward & Clymo 1982, Titus & Wagner 1984), which is an important determinant of suitability as a raw material for growing media (*cf*. Jacobs *et al*. 2009). Plant cultivation experiments show that numerous *Sphagnum* species can be used in growing media (see ‘Application of *Sphagnum* biomass in growing media’, page 16; also Appendix).

Largely entire *Sphagnum* plants from Sections *Acutifolia*, *Cuspidata*, *Rigida*, *Sphagnum* and *Subsecunda*, partially dried, are suitable for absorbing toxic substances or oil (Hagen *et al*. 1990). Intact, undecomposed *Sphagnum* is also required for hygiene products and surgical dressings. For many years *Sphagnum* was an officially recognised pharmaceutical product in Britain, where surgical dressings were made from “*Sphagnum imbricatum*”, *S. palustre*, *S. magellanicum* and *S. papillosum* during World War I, although “*S. recurvum*” was not suitable (Hotson 1918, 1921).

AVAILABILITY, COLLECTION AND PRODUCTION OF FOUNDER MATERIAL

Sphagnum farming requires that sufficient *Sphagnum* material is available to populate the fields. Various founder materials may be applied, each with their own multiplication procedures.

***Sphagnum* spores**

Using *Sphagnum* spores as founder material has the advantage that the resulting cultures are species-pure and free from weeds. Furthermore, the material is genetically diverse (a result of sexual reproduction). Gahlert *et al*. (2012) found that spreading of *Sphagnum* spores on rewetted bog did not lead to germination, whereas spores germinated within one week if they were spread in petri dishes filled with peat, sterilised *Sphagnum* biomass or nutrient agar in a glasshouse. Plantlets developed from spores established successfully in the field, forming numerous new capitula within three months.

The potential availability of spores as founder material is large, since one capsule holds 18,500 to 240,000 spores (Sundberg & Rydin 1998) and each spore has potential to grow into a new plant. The practicality of using spores as founder material is still limited, however, because dioecious species rarely sporulate (Longton 1992, Cronberg 1993), capsules can only be collected manually, and the factors inducing sporulation and germination are incompletely understood (Sundberg 2000, Gahlert *et al*. 2012).

***Sphagnum* shoots**

Sphagnum may regenerate from the smallest plant parts (and even from brownish-coloured material), but not from single leaves (Clymo & Duckett 1986, Poschlod & Pfadenhauer 1989). This high capacity for vegetative regeneration makes shoots useful for both direct application as founder material and for multiplication prior to application. Campeau & Rochefort (1996) tested directly applied fragment lengths from 0.5 to 2 cm without finding any difference in capitula density after three months of growth. Lawn thickness and cover increased faster if large (5–10 cm) rather than small (0.1–0.3 cm) fragments were used (Gaudig *et al.* 2014).

Gathering Sphagnum *shoots from wild populations*

Shoots for use as founder material may be collected from wild populations by hand (picking, raking or cutting) or machine (excavator equipped with a shovel, a block-cut peat extraction device or a mowing bucket, Figures 1 and 7). In the Canadian 'moss layer transfer technique', developed for vegetation restoration purposes, the total vegetation is transferred from a donor site to the restoration site (Quinty & Rochefort 2003).

Collecting depth should not exceed 10 cm to allow satisfactory regeneration of the donor site (Campeau & Rochefort 1996). In North America, collection over frozen ground has proved successful (Quinty & Rochefort 2003). The ideal time is at the onset of thawing after a frost period, when the thawed upper centimetres of vegetation can be scraped off. In various countries, the scarcity and conservation status of *Sphagnum* mosses constrain the availability of donor material from wild populations.

Multiplying shoots for founder material

An alternative to using *Sphagnum* shoots from wild populations to populate new fields is to use shoots from already existing Sphagnum farming fields. For example, the initial Rastede Sphagnum farming site was partly established using cultivated *Sphagnum* from the Ramsloh site (Gaudig & Krebs 2016) and the extension of Rastede, from 4 ha to 14 ha in total, used *Sphagnum* harvested from 0.64 ha of the initial Rastede Sphagnum farming site (after five years' growth) as founder material for a new 3.8 ha *Sphagnum* production field.

The multiplication rate of *Sphagnum* material can be increased by cultivation under more controlled conditions. By cultivating vegetative *Sphagnum* on horticultural fleece in a shaded open greenhouse with sprinkle irrigation, a tenfold higher multiplication rate of species-pure founder material with fewer weeds was achieved compared to Sphagnum farming fields on bogs (C. Schade[1], personal communication 2014). To increase founder material production even further by allowing growth in all directions, submerged cultivation of *Sphagnum* has been tested. The mosses grew well under non-axenic conditions, but their growth rate did not exceed that of mosses growing on peat (Gaudig *et al.* 2014). The multiplication rate may be much higher under axenic conditions because the absence of faster-growing competitors like algae, fungi and bacteria should eliminate nutrient (including CO_2) and light limitation. However, the creation of axenic conditions is a challenge. Axenic cultivation starting from sterilised spores was tested successfully in bioreactors (Rudolph *et al*. 1988, Beike *et al.* 2014), the latter authors reporting a 30-fold increase in *Sphagnum* dry mass within four weeks. Micropropagation Services (EM) Ltd. specialises in vegetative micropropagation of *Sphagnum* from small samples of source material to produce easily and uniformly applicable juvenile plants embedded in liquid or firm gel or as plugs (Caporn *et al*. 2018).

Storage of shoots

Broad implementation of Sphagnum farming will require storage and transportation of *Sphagnum* shoots. A test with *Sphagnum palustre* showed that

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fresh shoots are more vital and, thus, better suited as founder material than shoots stored in a refrigerator at 6 °C for more than three months. The latter still develop lawns, but with significantly lower productivity than fresh mosses (Prager *et al*. 2012).

To reduce the abundance of weeds, storing *Sphagnum* in piles in the field for several months was tested in Canada with positive results (Hogue-Hugron & Rochefort, unpublished data), although further tests are needed to provide an explanation.

SETTING UP A SPHAGNUM FARMING SITE

Depending on its initial condition, preparation of a Sphagnum farming site may include surface levelling, creation of infrastructure for water management and the establishment of *Sphagnum* cover.

Site selection

Sphagnum farming may take place on a variety of substrates. Experience of *Sphagnum* cultivation has been gained on cut-over bogs after milled peat extraction, on cut-over bogs after block-cut peat extraction, on former drained bog grassland, on artificial floating mats, in rice paddy fields and in glasshouses (on/in water, on peat) (Figure 2). *Sphagnum* cultivation on artificial floating mats and rafts has been tested in Japan (Hoshi 2017) and Germany (Blievernicht *et al*. 2013). Wichmann *et al*. (2017) describe procedures for large-scale implementation and the associated high costs and risks (damage by wind, waves, ice drift and water birds). Hence, we focus here on soil-based outdoor Sphagnum farming on peat substrate. Climate (precipitation, temperature), characteristics of the peat layer (chemistry, hydraulic conductivity) and the

Figure 1. Manual (a, b) and mechanical (c, d) *Sphagnum* gathering from wild populations, for founder material in Germany (a) and Canada (c) or commercial use in Chile (b) and Finland (d). In (a) only the upper 5 cm of half a *Sphagnum* hummock was cut to favour regrowth. Photos: a) Jan Köbbing, b) Christel Oberpaur, c) Peatland Ecology Research Group and d) Matthias Krebs.

availability and quality of water are of major importance for successful Sphagnum farming (Brust *et al*. 2018). In addition to site selection, these starting conditions influence the planning, setting-up and management requirements for individual Sphagnum farming sites.

Figure 2. Overviews of Sphagnum farming sites, a) on cut-over bog in Canada; b) on former bog grassland in Germany (Rastede); c) on cut-over bog in Germany (Drenth); and d) on floating mats on a lake in Germany. Photos: a) Peatland Ecology Research Group, b) ASEA aerial, c) Jan Köbbing and d) Matthias Krebs.

Surface levelling

Site preparation must create an even, horizontal surface to ensure optimal water levels over the entire *Sphagnum* production field after rewetting. Sites from which peat blocks have been cut consist of separate depressions (*e.g*. 10–20 m wide, 50 m long in Canada) whose floors must be levelled. Milled peat extraction leaves large areas (several hectares) with more or less plane but often sloping surfaces. Levelling may be effected manually (*e.g*. using rakes and wooden planks) on small areas, or with tracked vehicles equipped with grading blades on larger sites. On sloping sites, terraces with different water level targets must be constructed to ensure water table levels within a few centimetres of the soil surface over the entire area (Quinty & Rochefort 2003, Blankenburg 2004). If the remaining upper peat layer has become hydrophobic after peat extraction (Quinty & Rochefort 2003) or plate-like, it may be necessary to scrape off about 5 cm with a cultivator bulldozer, an endless screw or an excavator before spreading the *Sphagnum* founder material.

On former bog grassland in Rastede, Germany, the fertilised, limed and degraded topsoil (30–50 cm) was removed with an excavator to create an even, horizontal peat surface and to construct causeways for management and harvesting (Wichmann *et al*. 2017, Figure 3). Whether topsoil removal on former bog grassland is necessary, and the depth of soil that should be removed, has not yet been finally clarified. However, topsoil removal should be minimised to reduce cost and carbon losses. An alternative approach adopted in a recent *Sphagnum* vegetation restoration trial on wet grassland in Wales (UK) was to fully invert the topsoil to produce a rougher surface for *Sphagnum* establishment (S.J.M. Caporn, unpublished data).

The peat surface is likely to move differentially over time due to peat swelling or frost action (Groeneveld & Rochefort 2002, Gaudig *et al*. 2017) but must be kept flat during the establishment phase.

Infrastructure for water management

Productive Sphagnum farming sites require water tables that are permanently close to the moss surface, making infrastructure for irrigation (to supply water during droughts) and drainage (to avoid prolonged flooding and erosion of moss fragments) essential. Possible sources of irrigation water, whose suitability depends on water quality (see ‘Water quality’, page 11), include streams, ditches, wells, ponds and artificial water reservoirs. Practical experience of improving water quality, for example using helophyte filters (constructed wetlands stocked with helophytes) which could potentially remove large amounts of solutes (*e.g*. Land *et al*. 2016), is not yet available.

Various types of pumps have been tested for Sphagnum farming (*cf*. Wichmann *et al*. 2017). Electric pumps need power, either from the electricity net (mains supply) or from wind turbines or solar panels with additional batteries to bridge periods of ‘dark lull’. Wind pumps are comparatively cheap but may not adequately cover periods with little wind and high evapotranspiration. However, they can be supplemented with a mobile electric pump and generator as an emergency power unit.

Small ditches, subsurface pipes, drip systems or sprinklers (for filtered water) can be used to transport irrigation water from the pump to the *Sphagnum* production fields (Figure 4). The irrigation system must be carefully adjusted to each individual Sphagnum farming site, with maximum distances between the irrigation elements depending on the hydraulic conductivity of the upper peat layer, *e.g*. 5 m in strongly humified (‘black’) (Gaudig *et al*. 2017) or 10–20 m in slightly humified (‘white’) peat (Gaudig *et al*. 2014, Brown *et al*. 2017).

To avoid flooding, the maximum water table level in the field must be regulated by an outflow. Simple but effective outflow constructions include pipe bends and weirs (Figure 4). In an ‘adjustable ditch’, a float valve opens automatically when the water table is too high (used at the Shippagan 2 and Saint-Modeste sites in Canada). Outflows should be easily adjustable to allow the water table to rise as the surface of the *Sphagnum* lawn grows upwards.

Regulation of both inflow and outflow is necessary for optimal water management. Manual water management requires frequent staff attendance, especially during the growing season. Automatic water management has been tested in Germany at the Rastede and Drenth pilot sites (three and seven irrigation units, respectively), and in Canada at Shippagan 2 and Saint-Modeste, but an electronic control centre may require very high investment costs (Wichmann *et al*. 2017). Installing a simple automatic regulation system for every individual irrigation unit seems to be more reliable and cost effective. At Rastede, Shippagan 2 and Saint-Modeste, electric pumps are switched on and off at preset minimum and maximum water levels, monitored by two sensors in the irrigation ditches.

***Sphagnum* establishment**

Rapid and successful establishment of a closed *Sphagnum* lawn is a key early stage in Sphagnum farming. *Sphagnum* productivity increases substantially as soon as vital (live green) *Sphagnum* covers > 90 % of the peat surface (Gaudig *et al*. 2017) and desiccation tolerance of the moss lawn increases. Next to quality and quantity of the *Sphagnum* founder material, site conditions are important factors for *Sphagnum* establishment.

Figure 3. Setting up a Sphagnum farming site on former bog grassland in Germany (Rastede), using an excavator for a) removal of the degraded topsoil and b) construction of causeways and irrigation ditches. Photos: Sabine Wichmann.

Figure 4. Water management components for Sphagnum farming sites: a) electric pump (Rastede); b) inlet into the irrigation ditches (Rastede); c) drip irrigation (Drenth); d) ‘adjustable ditch’ with an outlet (Shippagan 2); e) outlet with a data logger (Rastede); f) outlet (Saint-Modeste). Photos: a) and e) Sabine Wichmann, b) Greta Gaudig, c) Dorothea Rammes, d) and f) Peatland Ecology Research Group.

Introduction of Sphagnum

The higher the cover of *Sphagnum* founder material, the faster a closed *Sphagnum* lawn will establish (Campeau & Rochefort 1996). Application of a loose *Sphagnum* layer 1–5 cm thick encourages its establishment (Quinty & Rochefort 2003, Gaudig *et al*. 2017). Quinty & Rochefort (2003) suggest ~ 100 m³ of *Sphagnum* material *per* hectare for successfully re-establishing *Sphagnum* vegetation on cutover bog (area ratio 1:10 between collection and restoration sites with ~ 10 cm collecting depth), a volume that was used by Pouliot *et al*. (2015) for the Shippagan 1 Sphagnum farming site in Canada. At the Rastede Sphagnum farming site in north-west Germany, ~ 80 m³ of *Sphagnum* founder material *per* hectare (70–80 % cover) with manual replenishment of gaps in the developing moss carpets one year after installation (~ 10 m³ *Sphagnum per* hectare) was sufficient for successful establishment within 1.5 years (Gaudig *et al*. 2014, Wichmann *et al*. 2017). *Sphagnum* fragments should be applied at the start of the growing season (when long frosty periods are no longer probable) because the establishment phase is prolonged in winter, when *Sphagnum* grows only slowly (Lütt 1992, *cf*. Krebs *et al*. 2016). Moreover, moss fragments applied in spring are less likely to be washed away by snowmelt water.

Vital fragments or juvenile plants of *Sphagnum* are spread on the newly prepared bare peat surface (see ‘Surface levelling’, page 6) either by hand (at small scale, in basins or on very wet sites; *e.g*. Ramsloh and both Twist sites) or with a manure spreader mounted on a tracked vehicle (*e.g*. Rastede, *cf*. Wichmann *et al*. 2017) (Figure 5). Machines tend to spread the *Sphagnum* unevenly, making manual reworking necessary to ensure uniform cover.

Micropropagated mosses in liquid gel (see ‘Multiplying shoots for founder material’, page 4) stick to the peat surface and gain good capillary contact, as in the ‘hydroseeding’ method of Money (1995). In the last three years, plugs have successfully been applied for *Sphagnum* vegetation restoration in

Figure 5. Spreading of *Sphagnum* and straw mulch: a) manually; b) mechanically by a tractor driving along the edge of the field pulling a manure spreader or a machine that blows the straw onto the site; or by c) loading founder material onto a manure spreader mounted on a tracked vehicle which then d) drives directly on the field. Photos: a) and b) Peatland Ecology Research Group, c) Sabine Wichmann and d) lensescape.org.

the southern Pennines (England) and in Wales. Techniques to upscale the planting of micro-propagated materials (beads, gel, plugs) are currently being developed (Caporn *et al*. 2018). The use of gel in Sphagnum farming has not yet been tested in the field.

Especially when optimal water tables cannot be ensured, *e.g*. when surface height differences occur even after levelling (Gaudig *et al*. 2017), it might be advantageous to introduce a mixture of *Sphagnum* species with different water table demands (*cf*. Andrus *et al*. 1983). Under conditions of fluctuating water table (mean depth 29–73 cm below surface in summer), Chirino *et al*. (2006) found that *Sphagnum* species established better in monoculture than in mixtures. In Canada, Picard (2010) described mixtures with *S. fallax* as beneficial for improving the yields of targeted species (*S. magellanicum*, *S. papillosum*) during prolonged drought. In contrast, Limpens *et al*. (2003) supposed that a mixture with *S. papillosum* reduced drought stress for *S. fallax* on a hummock, while Robroek *et al*. (2007b) identified intensity and frequency of rain events as important for the expansion of hollow species in hummocks. More research is needed to determine whether and under which conditions a mixture of different *Sphagnum* species promotes biomass production.

If prepared sites cannot immediately be populated with *Sphagnum* material it may be useful to cover the bare peat with geotextile to prevent the establishment of weeds (S. Hogue-Hugron unpublished data).

Protective cover

Quinty & Rochefort (2003) recommend a loose straw mulch cover (minimum 3000 kg ha^{-1}) for improving microclimate (higher relative humidity, more stable temperatures). Straw cover may also support the establishment of micropropagated *Sphagnum* in gel (Caporn *et al*. 2018.). Straw thickness should not exceed 3 cm to allow sufficient light to reach the *Sphagnum* fragments (Gaudig *et al*. 2017) because moss growth is reduced when shading exceeds 50 % (Clymo & Hayward 1982).

Straw can be applied manually, with a tracked manure spreader driving over the field, or with a machine that blows the straw over the field from the side (Figure 5). This technology could be improved in terms of the width and uniformity of spreading.

In a large-scale Sphagnum farming project in Drenth (Germany), *Sphagnum* fragments covered with geotextile (50 % shade) grew much more slowly than *Sphagnum* fragments covered with straw, probably because the water-saturated geotextile led to anoxic conditions (Graf *et al*. 2017). If a sufficient water supply can be ensured, covering the *Sphagnum* fragments is unnecessary for protection against desiccation (Krebs *et al*. unpublished data). On the other hand, a (straw) cover leads to more balanced surface temperatures (lower during daytime and higher at night; Quinty & Rochefort 2003), which may encourage *Sphagnum* growth by avoiding temperatures above 27 °C, which reduce photosynthesis (Johansson & Linder 1980), and by providing higher temperatures at night (Gerdol *et al*. 1998, Robroek *et al*. 2007a). However, this effect has not yet been tested in Sphagnum farming sites with continuously high water tables.

MANAGING A SPHAGNUM FARMING SITE

Commercial Sphagnum farming involves regular on-site controls, precise water management, weed management of production fields, cleaning of irrigation ditches and mowing of causeways.

Water management

Water table management in the establishment phase

Water management must be very precise and, therefore, carefully controlled especially during the establishment phase. *Sphagnum* fragments lying on the peat surface are sensitive to desiccation as they are more vulnerable to water losses than a dense *Sphagnum* lawn (Price & Whitehead 2001, Price *et al*. 2003). Campeau & Rochefort (1996) found highest growth rates of *Sphagnum* fragments at water table level 5 cm below the peat surface. Inundation must be avoided to prevent washing away of founder material (Rochefort *et al*. 2002, Tuittila *et al*. 2003).

Water table management in the production phase

Several studies have shown that the growth of *Sphagnum* is highest at high water tables (close to, but below, the capitula), regardless of the natural ecological niche of the species (Hayward & Clymo 1983, Lütt 1992, Robroek *et al*. 2009). Under natural conditions, *Sphagnum* growth is often reduced in summer because of water deficits (Robroek *et al*. 2009, Rydin & Jeglum 2009). Thus, in Sphagnum farming it may be opportune to overcome this deficit by direct water supply.

Quantitative water demand

Sphagnum farming sites with drained and dry surroundings (*e.g*. in degraded bog landscapes) are subject to downward and sideward seepage and increased evapotranspiration as a result of the 'oasis effect' (Edom 2001). These increased water losses have to be compensated, especially during (warm) periods with already high evapotranspiration losses

(Brust *et al*. 2018). Therefore, *Sphagnum* production fields require irrigation to maintain high water tables and soil moisture levels (suction pressures, *cf*. Price *et al*. 2003). Annual irrigation volumes amounted, on average, to 1600 m^3 *per* hectare of *Sphagnum* production field (160 mm) at the Rastede Sphagnum farming site in north-west Germany (annual means of temperature 9.8 °C, and of precipitation 849 mm) and double this volume in drier years (Brust *et al.* 2018). At Shippagan 2, Canada (annual mean temperature 4.8 °C, precipitation 1077 mm yr^{-1}) the much smaller evapotranspiration and seepage losses resulted in substantially lower irrigation demands of 74–130 mm (Brown 2017). To reduce irrigation water demand, water tables can be lowered, resulting in smaller losses by both evapotranspiration and seepage, but also in lower *Sphagnum* growth rates.

In general, spatially differentiated air humidity as a result of the 'oasis effect' causes evapotranspiration rates to decrease with a) increasing size of the Sphagnum farming site, b) better orientation along the prevailing direction of dry winds, and c) increasing extent of wet surroundings and their wetness. Evapotranspiration might also be reduced by the wind breaking effect of trees (Limpens *et al*. 2014) or shrubs, especially if they are in blocks orientated perpendicular to the prevailing dry wind direction. Additionally, drainage ditches installed to remove excess water from Sphagnum farming sites should not be too close to cultivated areas because they promote seepage losses.

Water quality

Sphagnum species grow optimally when their nutrient stoichiometry is balanced without nutrient limitation or oversupply (Aerts *et al.* 1992, Bragazza *et al.* 2004, Fritz *et al.* 2012, Temmink *et al.* 2017). Solute supplies that would be much too small to maintain conventional crop plants may actually be poisonous to *Sphagnum*, which has extraordinarily small nutrient needs and tolerances.

Solutes are supplied to the upgrowing *Sphagnum* by atmospheric deposition, by release from the (mineralised and formerly fertilised) peat soil, and by irrigation water. In regions with high atmospheric loads, particularly of NH_3 and NH_4^+ (resulting in dry and wet deposition), additional solutes supplied by irrigation water may have detrimental effects on *Sphagnum* growth. The quality of available water may influence species selection as *Sphagnum* species differ in their growth responses to pH, bicarbonate and other solutes (Hájek *et al.* 2006). A high input of solutes may cause a shift in *Sphagnum* species at the expense of less competitive target *Sphagnum* species (Temmink *et al.* 2017).

The quality of the irrigation water is determined by its origin. In Canada, irrigation water is usually taken from natural peatland lakes (Shippagan 2) or water drained from peat extraction fields (Saint-Modeste). Drainage water from agriculturally used surroundings may have high loads of nitrogen (N), phosphorus (P), and potassium (K) (Temmink *et al.* 2017). P and K are mainly accumulated in the *Sphagnum* mosses next to the irrigation ditch, with plant tissue concentrations decreasing sharply with increasing distance from the ditch. High concentrations of single elements in the mosses can be toxic (Limpens *et al.* 2011) and should be avoided. In particular, N levels should be kept low although the negative effect of N can be reduced by high availability of P and K and optimisation of other growth factors (*e.g.* light and moisture levels) so that N is prevented from accumulating to toxic levels by dilution through increased biomass growth (Carfrae *et al*. 2007, Limpens & Heijmans 2008, Fritz *et al.* 2014). Temmink *et al.* (2017) estimated that, when the *Sphagnum* was growing well, the Rastede Sphagnum farming site took up N at 35–56 kg ha^{-1} yr^{-1}.

Groundwater may also be used for irrigation, but in this case calcium (Ca) and bicarbonate (HCO_3^-) must be taken into account. Most *Sphagnum* species are sensitive to high concentrations of Ca and HCO_3^-, and concentrations > 500–800 µM are detrimental (Vicherová *et al.* 2015, Smolders & Fritz unpublished data), in particular when high cation loads are combined with high pH (Clymo & Hayward 1982, Karofeld 1996, Harpenslager *et al.* 2015, Rammes 2016, Vicherová *et al.* 2017).

Short-term use of irrigation water with suboptimal quality may be possible if rainwater dilution sufficiently reduces the concentrations of detrimental solutes (*e.g.* in Malpils, Latvia). In Canada, Latvia and Germany, *Sphagnum* production fields are irrigated in summer, while excess precipitation water is discharged in winter and might be stored off-site for use when irrigation is needed in summer.

Avoiding solute concentrations that would be damaging for *Sphagnum* may be achieved by:

- careful selection of the source of irrigation water;
- regular cleaning of the supply ditches to remove accumulated solutes;
- pre-treatment of the water, *e.g.* by constructed helophyte filters;
- keeping other site conditions optimal so that accumulation is avoided/retarded by maximising *Sphagnum* biomass growth;
- on-site storage of solute-poor surplus water from intense rainfall events during periods with high

evaporation losses by temporarily allowing higher-than-optimal water levels; and

- designing *Sphagnum* production fields with larger distances between irrigation ditches (although still ensuring a sufficient water supply for the entire field) in order to fully exploit the purification capacity of the *Sphagnum* between the ditch and the centre of the production field (Temmink *et al*. 2017).

Fertilisation

As nutrients are removed with the harvested *Sphagnum* biomass, frequent harvesting may change existing nutrient limitations, in particular for P (Krebs *et al.* 2018), especially in regions with low nutrient inputs by irrigation and atmospheric deposition. Whether and how fertilisation may balance nutrient stoichiometry and stabilise - or even enhance - *Sphagnum* growth demands further study.

Management of vascular plant growth

The presence of vascular plants and mosses (other than those applied) in *Sphagnum* production fields is almost inevitable because their diaspores are continually introduced from the surroundings. Vascular plants may facilitate *Sphagnum* growth by improving microclimate (especially when conditions are hydrologically suboptimal, *e.g*. with low water tables or large water table fluctuations), reducing photoinhibition, and providing mechanical support promoting length increment (‘nurse plants’; Pedersen 1975, Murray *et al*. 1993, Rydin & Jeglum 2009, Pouliot *et al*. 2011). Reliable nurse plants are *Eriophorum* species or ericaceous shrubs at dry sites and *Polytrichum* moss species (*e.g. P. strictum*) at sites with frost heaving (Quinty & Rochefort 2003, Groeneveld *et al*. 2007). On sites with optimal hydrology, nurse plants may not be needed to improve microclimate but are probably still important for reducing photoinhibition. The microclimatic effects of nurse plants at sites with insufficient soil moisture deserve further investigation.

On the other hand, vascular plants may retard *Sphagnum* growth by shading, litterfall, and competition for water and nutrients (Tomassen *et al*. 2003). Furthermore, the quantities of vascular plant biomass and seed in the *Sphagnum* biomass product has to be minimised when it is to be used as a raw material for horticultural growing media (see ‘Application of *Sphagnum* biomass in growing media’, page 16). Therefore, the vascular plant cover on *Sphagnum* production fields should be kept at a low level, *e.g*. by regular mowing.

The frequency of mowing is determined by the species present, the site conditions promoting vascular plant growth, the amount of litter produced, and the end use of the cultivated *Sphagnum* biomass. Vascular plant cover was less than 40 % and decreasing with succession in Canada (Guêné-Nanchen *et al.* 2017), but in Germany it could only be kept below 20–30 % by regular mowing (Gaudig *et al.* 2017). Mowing of vascular plants (mainly *Juncus* species on nutrient-rich sites) was tested at Rastede using a) a strimmer, b) a single-axle mower equipped with cutter bar and triple tyres to adapt to the low bearing capacity of *Sphagnum* production fields, and c) an excavator with mowing bucket on an elongated arm (Figure 6). Only the excavator could mow from the causeway and thus avoid causing compaction by driving on the *Sphagnum* production fields. In contrast to the other devices, the excavator with mowing bucket removed the mown material so that a mulch layer - which possibly hampers moss growth by shading - did not develop. Standard tractors with wide tyres were used for mowing the causeways to prevent seed dispersal. A mowing robot was successfully tested at the Twist sites, although mowing took a long time and the robot was unable to cross the ditches. In Canada (Shippagan 1), mowing is considered to be unnecessary because the rhizomatous dominant vascular plant (*Eriophorum angustifolium*) has low cover and low litter production (Guêné-Nanchen *et al.* 2017).

Control of fungal pests

Fungi are common in *Sphagnum* mires and peatlands (Thormann 2011, Kostka *et al*. 2016). Mosses have many fungal associates, some growth stimulating and others growth retarding. Parasitic or pathogenic fungal species of the genera *Galerina* and *Sphagnurus* have been identified at the Rastede site. Effective measures for controlling *Sphagnurus paluster* without affecting *Sphagnum* are applications of the fungicide Myclobutanil (Landry *et al*. 2011) and use of the fungus *Trichoderma virens* as an antagonist (Irrgang *et al.* 2012), but both have been tested only in the glasshouse so far. Investigation is required into the extent of *Sphagnum* growth reduction by fungi in the field and the impact of fungal infection of the *Sphagnum* biomass on growing media quality.

Control of disturbing animals

Animals may disturb water management infrastructure, cause nutrient inputs and damage the sensitive *Sphagnum* lawn by trampling. Experience at Rastede has shown that a minimum distance of 10 m between irrigation ditches on the *Sphagnum* production fields and drainage ditches in the surroundings is required to prevent muskrats (*Ondatra zibethicus*) from creating connecting drains.

In some regions migratory birds cause damage *via* trampling and nitrogen input from droppings. Fences may protect against cattle, roe deer (*Capreolus capreolus*), moose (*Alces alces*), boar (*Sus scrofa*) and the general public.

HARVESTING

Timing and frequency of harvests

Dry mass productivity of *Sphagnum* on Sphagnum farming sites mainly ranges between 3 and 6 t ha^{-1} yr^{-1} in Germany (Gaudig *et al*. 2014) or between 0.3 and 2 t ha^{-1} yr^{-1} in Canada (Pouliot *et al*. 2015). Decomposition of *Sphagnum* biomass is a continuous process and, in a typical peatland environment, only 85 % of the primary production is preserved after one year (Lütt 1992). Nonetheless, the rate of *Sphagnum* biomass accumulation may remain constant over some years in an established *Sphagnum* production field (Gaudig *et al*. 2017). At the latest, when decomposition starts to approach production, it is time to harvest. The choice of harvesting time needs to balance technical feasibility (minimum lawn height), site accessibility, growth rate, decomposition losses, regeneration potential and economic aspects,

Figure 6. Weed management at the Rastede Sphagnum farming site using: a) brush cutter / strimmer; b) single-axle mower with cutter bar and triple tyres; c) excavator equipped with an extra-long arm and a mowing bucket, operating from a causeway. Photos: Sabine Wichmann.

i.e. sales prospects (Gaudig *et al*. 2017). Additionally, seasonal variations in *Sphagnum* biomass quality may be pertinent (see 'Application of *Sphagnum* biomass in growing media', page 16). From the first regrowth experiments at the Ramsloh site, a harvesting frequency of once every 3–5 years seems to be feasible (Gaudig *et al*. 2014, Krebs *et al*. 2018).

Harvesting technique

As for the collection of founder material (see 'Gathering *Sphagnum* shoots from wild populations', page 4), various devices can be used to harvest *Sphagnum* biomass. During the first harvest of cultivated *Sphagnum* at Rastede, an excavator with long arm and mowing bucket and a tractor with double or wide tyres towing a dumper for transport of the harvested biomass both operated on the causeways (Figure 7; see also Radio Bremen 2016). Naturally grown *Sphagnum* is collected from Finnish bogs by an excavator when the ground is frozen in winter (Silvan *et al*. 2012, 2017) or with a forestry vehicle ('forwarder') equipped with bogie tracks and a bucket grapple in summer (Anttila 2016). In northern USA, long *Sphagnum* mosses are scraped from wild populations by a small crawler tractor in winter (Elling & Knighton 1984) or are collected using tracked machinery and sledges for haulage (mossman381 2012). So far, no available harvesting machinery is capable of driving on very wet (not frozen) *Sphagnum* production fields without damaging the residual moss layer. The land has low bearing capacity and, although the ground pressure exerted by machinery with wide tracks may be less than 50 g cm^{-2} (Wichmann *et al*. 2016), adding the weight of wet mosses (loading capacity) presents an additional challenge. There is a need for further development and testing of devices to cut, collect and transport the wet moss biomass.

Regrowth and re-establishment after harvest

The regrowth potential of the residual *Sphagnum* lawn requires more study, but seems to depend on the age and/or the thickness of the residual *Sphagnum*,

Figure 7. Harvesting techniques for Sphagnum farming using a) an excavator operating from a causeway, equipped with b) a mowing bucket or c) a modified excavator for block-cut peat extraction, which tests in Canada have shown can also harvest *Sphagnum*. Photos: a) Gerd Block, b) Sabine Wichmann and c) Benoit St-Hilaire).

harvesting technique, *Sphagnum* species, and site conditions after harvest - in particular water table. At Ramsloh, manual removal of the uppermost 2–5 cm resulted in the regrowth of new capitula on 80 % of the *Sphagnum papillosum* plants after one year and almost 100 % after 2.5 years, with average water table level 4 cm below the (harvested) *Sphagnum* surface (Gaudig *et al*. 2014, Krebs *et al*. 2018). The decision on whether to harvest only the upper *Sphagnum* biomass or all of it is determined by the expected speed of regrowth of the residual *Sphagnum* compared to the speed of new establishment, and by related costs - *i.e*. income foregone due to reduced yield *versus* the additional expense of spreading new *Sphagnum* fragments.

STORAGE AND TRANSPORT OF *SPHAGNUM* BIOMASS

Storing or transporting large volumes of heavy, wet *Sphagnum* may be a problem if compaction affects the physical properties of the lowermost layers and increases the risk of self-heating. Storing the biomass in piles (Germany) or squeezing out the water (Finland) reduces its water content to 70–80 % (Kumar 2017) and makes it dry enough for further processing. To reduce transport costs, it may be appropriate to further reduce the water content by active drying (see ‘Processing for growing media’, this page). Chilean moss is dried to a moisture content of 19–20 % and compressed to different formats (150 g, 250 g, 500g, 1 kg, 3 kg, 5 kg and 7 kg packs); for example, the 5 kg quantity is compressed into blocks of 30 × 30 × 50 or 30 × 30 × 60 cm for global shipping (Alpha Moss 2015, Lonquén 2018).

PROCESSING FOR GROWING MEDIA

The processing of harvested *Sphagnum* biomass for use in growing media encompasses drying, ‘hygienisation’ (*i.e.* treatment of the biomass to kill most pathogens and seeds or vegetative parts of vascular plants to phytosanitary standard) and screening (*cf*. Kumar 2017). Active drying can take place in foil tunnels, glasshouses or with heat (stove, conveyor drier, waste heat from biogas plants). Drying with heat (stove) at 70 °C for at least 24 hours resulted in the loss of absorbency properties (B. St-Hilaire, unpublished data). Dry biomass becomes crumbly and electrostatic, and must be moistened before processing in the growing media plant (Kumar 2017). At moisture contents below 20 % the *Sphagnum* biomass became hydrophobic and rewetting was difficult and time-consuming (Kumar 2017). A century ago, many methods for drying peat were studied and it may be worthwhile to revisit these methods for the drying of *Sphagnum* biomass. Further research is needed on the effect of drying temperature and duration on the physical properties of the *Sphagnum* biomass and to discover the minimum and maximum moisture thresholds that should not be exceeded.

Killing the seeds and vegetative parts of vascular plants, together with parasites, in the harvested *Sphagnum* biomass (‘hygienisation’) is conducted by water vapour treatment or gamma radiation (Kumar 2017, Thieme 2017). Both methods work well, but gamma radiation is rather expensive whereas water vapour treatment is already widely applied in growing media production (Thieme 2017). Alternatively, moist *Sphagnum* can be placed in transparent bags and left in the sun for six weeks in summer (Oberpaur *et al*. 2012).

In Germany, *Sphagnum* biomass was separated into coarse and fine fractions using a standard screening line designed for peat (Kumar 2017). Growing tests with different fragment sizes produced by shredding the biomass with a garden shredder have been conducted in Canada (Aubé *et al*. 2015, St-Hilaire *et al*. 2017). These studies (lengths 0.5–2 mm and > 2–4.75 mm for an experiment with lettuce in substrate compacted into pellets, and < 6.3 mm and 6.3–19 mm for another experiment with *Zinnia* and basil) showed no significant influence of fragment length on plant yields (St-Hilaire *et al*. 2017). Further research is needed to determine the optimal lengths of *Sphagnum* fragments for various applications in growing media.

A growing medium mix containing 50 % *Sphagnum*, dried and packed in 70-litre plastic bags, was stored for seven months without changes in inorganic solute composition (Kumar 2017).

The European standard DIN EN 12580 describes the standard method for determining the volume of traded growing media and constituents. This includes measuring bulk density by passing the material through a mesh screen with defined mesh widths, allowing it to fall into a 20 L cylinder which is finally weighed. It will be difficult to transpose this method to fresh *Sphagnum* biomass. Since *Sphagnum* is loose when dry and more compact when it is wet, moisture content influences its bulk density. Also, the size of *Sphagnum* fragments affects the results. Long (15–20 cm) fragments of *S. palustre* with 91 % water content had a bulk density of 90 g L^{-1}, while dry mosses (with 10 % water content) had a bulk density of only 8.5 g L^{-1} (G. Schmilewski, unpublished data). Before they were incorporated into a growing medium, these *Sphagnum* fragments were shredded, leading to a bulk density of 10 g L^{-1} for fragments < 10 mm long (G. Schmilewski, unpublished data). Considerably higher bulk densities ranging from 25 g L^{-1} (water content 29 %) to 283 g L^{-1} (water content 92 %) were determined by S. Kumar (unpublished data).

APPLICATION OF *SPHAGNUM* BIOMASS IN GROWING MEDIA

Suitability of individual *Sphagnum* species

Sphagnum species are grouped into different sections with differing characteristics (Daniels & Eddy 1985, Michaelis 2011). Differences in stem structure and in the sizes of leaves, hyaline cells and pores, and intrinsic properties (*i.e*. decomposition rate, see ‘Productivity’, page 3) determine their suitability for use in growing media. Various species of different origins have so far been tested for their suitability in substrate (growing media) applications, namely: *S. capillifolium*, *S. fimbriatum*, *S. flavicomans*, *S. fuscum* and *S. rubellum* (Section *Acutifolia*); *S. magellanicum*, *S. palustre* and *S. papillosum* (Section *Sphagnum*); *S. fallax* and *S. riparium* (Section *Cuspidata*); and *S. squarrosum* (Section *Squarrosa*) (see Appendix). All of these species proved to be suitable as growing media constituents in horticultural experiments. However, results differed depending on the proportion of *Sphagnum* in the potting mix and the plant under cultivation (see the next section below).

Substrates based on *S. fallax* seemed to cause chlorosis, reduced growth and die-back of seedlings more often than substrates containing other *Sphagnum* species (Emmel & Kennet 2007), although *Tagetes* seedlings were propagated without problems and lettuce even produced more biomass in substrates containing increasing proportions of *S. fallax* (0–50–100 %), with the best growth in 100 % *Sphagnum* (M. Emmel unpublished data, Thieme 2017). Seedlings of tomato, cucumber and lettuce cultivated in *S. magellanicum*, *S. fuscum* and *Sphagnum* mixes had a significantly greater fresh weight than the controls (white peat or mineral wool), whereas *S. riparium* worked for lettuce but performed less well for tomato and cucumber (Reinikainen *et al*. 2012). As yet, it is not known why substrates containing *S. fallax* and *S. riparium* (both belonging to Section *Cuspidata*) sometimes cause severe damage to the cultivated plants and at other times support excellent growth.

Proportion of *Sphagnum* biomass in a growing medium and suitability for various crops

Sphagnum biomass has been tested in different mixtures with peat or other growing media constituents. Azaleas grown in mixtures of white peat with 0, 25, 50, 75 and 100 % by volume of *Sphagnum palustre* did not show significant differences in fresh weight (Ueber & Gaudig 2014). Also in a weight-replacement series with white peat, substitution by *Sphagnum fuscum* and a mixture of *Sphagnum* species up to 100 % was beneficial for the growth of all tested cultivars (A. Kämäräinen, unpublished data; see Appendix). In contrast, the fresh weight of *Petunia* decreased with increasing proportions of *Sphagnum palustre*, *S. papillosum* and *S. magellanicum* (M. Emmel, unpublished data). Further research is needed on the suitability of various *Sphagnum* species at different proportions in growing media for the cultivation of a range of plants (Schmilewski & Köbbing 2016). Generally, it can be concluded that a proportion up to 50 % by volume of *Sphagnum* biomass in potting substrates is trouble-free for most cultivars. The proportion of *Sphagnum* biomass may be greater for many crops (Blievernicht *et al*. 2012b, 2013).

Horticultural experiments on *Sphagnum* as a growing medium constituent (Appendix) have been carried out for:

- ornamental plants: *Azalea*, *Begonia*, *Cyclamen*, *Fuchsia*, *Impatiens*, Orchideaceae, *Pelargonium*, *Petunia*, *Poinsettia*, *Tagetes*, *Verbena*, *Zinnia*;
- vegetables: seedlings of cauliflower (*Brassica oleracea* var. *botrytis*), Chinese cabbage (*Brassica rapa* ssp. *pekinensis*), cucumber (*Cucumis sativus*), lettuce (*Lactuca sativa*), tomato (*Solanum lycopersicum*);
- herbs: basil (*Ocimum basilicum*); and
- shrubs and trees: apple (*Malus* sp.), *Calluna*, kiwi fruit (*Apteryx* sp.), *Rhododendron*.

Adjustments in crop management, *e.g*. in irrigation, will be necessary because *Sphagnum* and peat have different physical properties (Blievernicht *et al*. 2012b, Kämäräinen *et al*. 2018).

The pressed potting soils used in vegetable propagation must be stable enough for mechanical processing and suitable as substrates for various vegetables. The peat in pressed potting soil can be replaced with *Sphagnum* biomass at a rate of 25 % by volume without loss of quality or stability (Emmel 2017). Chinese cabbage grew similarly in pressed potting soils containing 0–53 % by volume of *Sphagnum* biomass, while lettuce had lower growth rates at higher *Sphagnum* proportions. Pure

Sphagnum is not a suitable substrate for seedling production, because the wide pores of the substrate do not allow the seeds to be distributed evenly (Thieme 2017).

Quality challenges

Sphagnum biomass may contain secondary metabolites, which may hamper root growth and lower the yield of the cultivated plant. This effect does not seem to depend on *Sphagnum* species, but on the processing method or (more likely) on the origin of the biomass (stress caused by conditions at the production site). Research in Germany (SPHAKO project) identified five phenolic acids originating from secondary metabolism of *Sphagnum* (S. Irrgang, unpublished data) which, according to the literature, may lead to allelopathic effects. Currently, these substances are tested for harm or toxicity to other plants when applied directly. Further research on allelopathic effects is needed.

The effect of growing and harvesting conditions during Sphagnum farming on the properties of the *Sphagnum* biomass is also insufficiently clear as yet. Impurity of harvested material, *i.e.* the inclusion of residues of other moss species and vascular plants, may cause undesired nitrogen immobilisation in the growing medium as a result of higher availability of easily degradable carbon sources and increased microbial activity, which is not a problem with pure *Sphagnum* biomass. Research is needed to determine how much non-*Sphagnum* material and different ‘weed’ species may be included in the growing media. The biological and physical stability of *Sphagnum* in mixes also requires further investigation.

ENVIRONMENTAL AND ECONOMIC ASPECTS

Sphagnum farming provides a sustainable land use option for degraded bogs. The benefits for climate change mitigation (Beyer & Höper 2015, Günther *et al*. 2017), nutrient retention (Temmink *et al*. 2017), and biodiversity (Muster *et al*. 2015, Gaudig & Krebs 2016) have been quantified for Germany. Adapted management and harvesting regimes may enhance these benefits. For example, harvesting according to the mosaic-cycle concept can increase biodiversity (Muster *et al*. 2015) although it may also lead to reduced yields.

Economic studies of setting up the Sphagnum farming sites in Germany (Ramsloh, Rastede) have revealed that investment costs are high (especially the cost of founder material) but there is large potential for reducing them (Wichmann *et al*. 2017). Further research is needed to evaluate the long-term effects of Sphagnum farming and to assess profitability and environmental benefits in countries other than Germany.

CONCLUSIONS AND OUTLOOK

Since the first efforts towards cultivating *Sphagnum* to substitute for peat in growing media (Gaudig & Joosten 2002) and first field trials in Germany and Canada from 2004 onwards, much progress has been made. An increasing number of researchers explore increasingly detailed questions relating to Sphagnum farming. More and more demonstration sites are being established in various parts of the world (Table 1), and progressively more practical experience is being gained, also through knowledge exchange between practitioners of *Sphagnum* vegetation restoration, *Sphagnum* gathering and Sphagnum farming.

However, Sphagnum farming is still in its infancy and large-scale commercial implementation is still lacking. Currently, the production costs of farmed *Sphagnum* biomass are still too high to compete with peat, especially because the external costs of peat extraction are not accounted for (S. Wichmann, unpublished data). More research into Sphagnum farming is needed to reach technological maturity and to reduce costs, *e.g.* through the selection of highly productive *Sphagnum* taxa as well as *Sphagnum* breeding and mass propagation of founder material, as in the current German research project MOOSzucht. One might expect traditional selection methods to work rapidly because the cropped ‘plant’ is haploid, meaning that a single beneficial genetic change would immediately reveal itself in the phenotype. Further understanding is likely to emerge from the SPHAGNOME project, which is investigating gene-to-trait relationships in the genus *Sphagnum* (Weston *et al.* 2018). The optimisation of site conditions and production of *Sphagnum* biomass in paludiculture is currently being investigated in several Sphagnum farming projects in Germany (MOOSWEIT, KlimDivMoos, MoosKult), Latvia and Canada (Table 1). These projects include studies on fungal impact, regeneration and harvest frequency, and on the economics of the entire cultivation cycle at farm level (MOOSWEIT). Further research on the processing of *Sphagnum* biomass and the development of machinery is needed. A machine which can harvest *Sphagnum* biomass while driving on the production field is currently being developed in the TESPER project.

More research is also needed on applications of the cultivated *Sphagnum* biomass. The introduction of *Sphagnum* biomass as a growing media constituent is currently being investigated in the projects SPHAKO (in combination with compost), MoosKult and TeiGa.

Alongside research on technical aspects, the implementation of large-scale Sphagnum farming requires modifications to the political and legal framework that will effectively initiate a paradigm shift in how peatlands are used for agricultural purposes (*cf*. Wichmann 2018). To achieve the climate goals, economic incentives for reducing greenhouse gas emissions are crucial. The recognition of *Sphagnum* as an agricultural crop (to secure subsidies) and payments for the provision of additional ecosystem services would stimulate the expansion of Sphagnum farming.

Sphagnum farming offers a clear opportunity to make a contribution to tackling pressing societal challenges. Research, industry and policy partners should seize this opportunity by joining forces to scale up Sphagnum farming.

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Appendix: List of plant cultivation experiments with *Sphagnum* biomass.

Application	**Plant species cultivated**	***Sphagnum* species tested**	**Fractions (Vol.-%) of *Sphagnum* tested**	**References**
Seedling test	Pak choi (*Brassica napus* var. *chinensis*)	*S. magellanicum,* *S. fimbriatum,* *S. palustre,* *S. papillosum*	0/ 25/ 50/ 75/ 100	Emmel 2008
	Chinese cabbage (*Brassica rapa car. pekinensis*)	not specified	0/ 50/ 80/ 85/ 100	Grantzau & Gaudig 2005
	Chinese cabbage (*Brassica rapa car. pekinensis*)	*S. fimbriatum,* *S. fallax,* *S. palustre*	0/ 50/ 100	Grantzau & Gaudig 2005
	Chinese cabbage (*Brassica rapa car. pekinensis*)	*S. magellanicum,* *S. fimbriatum,* *S. palustre,* *S. papillosum*	0/ 25/ 50/ 75/ 100	Emmel & Kennett 2007
	Chinese cabbage (*Brassica rapa car. pekinensis*)	*S. fallax,* *S. squarrosum,* *S. magellanicum,* *S. papillosum,* *S. capillifolium,* *S. palustre*	5/ 50/ 100	Thieme 2017
	Chinese cabbage (*Brassica rapa car. pekinensis*)	*S. palustre,* *S. fallax*	0/ 25/ 50/ 75/ 100	M. Emmel (unpublished data)
	Kohlrabi (*Brassica oleracea* var. *gongylodes)*	*S. magellanicum,* *S. fimbriatum,* *S. palustre,* *S. papillosum*	0/ 25/ 50/ 75/ 100	Emmel & Kennett 2007

Application	**Plant species cultivated**	***Sphagnum* species tested**	**Fractions (Vol.-%) of *Sphagnum* tested**	**References**
Seedling test	Lettuce (*Lactuca sativa*)	*S. fallax,* *S. squarrosum,* *S. magellanicum,* *S. papillosum,* *S. capillifolium,* *S. palustre*	5/ 50/ 100	Thieme 2017
	Spinach (*Spinacia oleracea)*	*S. magellanicum,* *S. fimbriatum,* *S. palustre,* *S. papillosum*	0/ 25/ 50/ 75/ 100	Emmel & Kennett 2007
Pressed pot substrate	Chinese cabbage (*Brassica rapa car. pekinensis*)	*S. papillosum*	0/ 25/ 42/ 53	Emmel 2017
	Lettuce (*Lactuca sativa*)	*S. papillosum*	0/ 25/ 42/ 53	Emmel 2017
Pellets	Lettuce (*Lactuca sativa*)	*S. flavicomans,* *S. magellanicum,* *S. rubellum,* *Sphagnum* mix *(S. rubellum/ S. magellanicum)*	0/ 25/ 50	St-Hilaire *et al*. 2017
Seedling cultivation	Cauliflower, lettuce, tomato	*S. magellanicum*	50	Oberpaur *et al*. 2010
	Cucumber (*Cucumis sativus* ‘Highmark II’)	*S. papillosum,* *S. fallax*	0/ 50/ 100	Emmel & Kennett 2007
	Cucumber	*S. fuscum,* *S. magellanicum,* *S. riparium,* *Sphagnum* mix		Reinikainen *et al*. 2012
	Lettuce	*S. magellanicum*	40/ 50/ 60	Oberpaur *et al*. 2010, 2012

Application	**Plant species cultivated**	***Sphagnum* species tested**	**Fractions (Vol.-%) of *Sphagnum* tested**	**References**
Seedling cultivation	Lettuce	*S. fuscum,* *S. magellanicum,* *S. riparium,* *Sphagnum* mix		Reinikainen *et al*. 2012
	Tagetes	*S. palustre,* *S. fallax*	0/ 50/ 100	M. Emmel (unpublished data)
	Tomato	*S. fuscum,* *S. magellanicum,* *S. riparium,* *Sphagnum* mix		Reinikainen *et al*. 2012
Herbs	Basil	*S. rubellum,* *S. magellanicum,* *Sphagnum* mix (*S. rubellum*/ *S. magellanicum*)	0/ 40/ 80/ 100	St-Hilaire *et al*. 2017
	Sweet basil (*Basilicum occimum*)	*S. fuscum*	0/ 25/ 50/ 100 (dry weight)	A. Kämäräinen (unpublished data)
Fruit nursery	Kiwi fruit seedlings	*S. magellanicum*	33/ 40/ 80	Arévalo *et al*. 2016
Ornamental plants	*Azalea* ‘Sachsenstern’	*S. palustre*	0/ 25/ 50/ 75/ 100	Ueber & Gaudig 2014
	Begonia-Elatior-Gr. ‘Bellona’	*S. magellanicum,* *Sphagnum* mix (*S. fimbriatum*/ *S. palustre*/ *S. magellanicum*; *S. rubellum*/ *S. magellanicum*)	0/ 40	Grantzau 2004
	Begonia-Elatior-Gr. ‘Berseba’ (rooted cuttings)	*S. fuscum,* *Sphagnum* mix (*S. fuscum*/ *S. magellanicum*/ *S. balticum*, *S. papillosum*/ *S. rubellum*)	0/ 25/ 50/ 75/ 100 (dry weight)	A. Kämäräinen (unpublished data)

Application	**Plant species cultivated**	***Sphagnum* species tested**	**Fractions (Vol.-%) of *Sphagnum* tested**	**References**
Ornamental plants	*Calluna vulgaris* 'Aphrodite'	*S. fimbriatum,* *S. papillosum,* *S. fallax*	0/ 25/ 50/ 75/ 100	Blievernicht *et al*. 2012b
	Cyclamen 'Leuchtfeuer'	not specified	0/ 20/ 40/ 60	Grantzau 2002
	Dendranthema 'Yellow Marettimo'	*S. fallax,* *S. palustre,* *S. papillosum,* *S. magellanicum*	0/ 50/ 100	Emmel & Kennet 2007
	Erica gracilis	*S. palustre*	0/ 25/ 50/ 75/ 100	Ueber & Gaudig 2014
	Fuchsia 'Beacon'	not specified	0/ 50	Grantzau (personal communication)[1]
	Gaultheria procumbens	*S. palustre*	0/ 25/ 50/ 75/ 100	Ueber & Gaudig 2014
	Impatiens Neug.-Gr. 'Timor'	*S. magellanicum,* *Sphagnum* mix (*S. fimbriatum*/ *S. palustre*/ *S. magellanicum*; *S. rubellum*/ *S. magellanicum*)	0/ 40	Grantzau 2004
	Impatiens walleriana	*S. fallax,* *S. magellanicum*	0/ 50/ 100	Emmel & Kennet 2007
	Pelargonium x hortorum 'Kim'	*S. magellanicum*	0/ 15/ 30	Jobin *et al*. 2014
	Pelargonium zonale 'Silke'	not specified	0/ 50	Grantzau (personal communication)[1]
	Pelargonium zonale 'Victoria'	not specified	0/ 50	Grantzau (personal communication)[1]

[1] E. Grantzau, Chamber of Agriculture Lower Saxony, Horticultural Training and Research Centre Ahlem, Germany, 2005.

Application	**Plant species cultivated**	***Sphagnum* species tested**	**Fractions (Vol.-%) of *Sphagnum* tested**	**References**
Ornamental plants	*Pelargonium zonale* ‘Tango Lavender’ (rooted cuttings)	*S. fuscum*, *Sphagnum* mix (*S. fuscum*/ *S. magellanicum*/ *S. balticum*/ *S. papillosum*/ *S. rubellum*)	0/ 25/ 50/ 75/ 100 (dry weight)	A. Kämäräinen (unpublished data)
	Petunia	*S. palustre*, *S. papillosum*, *S. magellanicum*	0/ 25/ 50/ 75/ 100	M. Emmel (unpublished data)
	Petunia x hybrida ‘Wave’	*S. magellanicum*	0/ 15/ 30	Jobin *et al*. 2014
	Petunia ‘Sublima White’	not specified	0/ 50	Grantzau (personal communication)[1]
	Poinsettia ‘Primero Red’	*S. palustre*	80	Blievernicht *et al*. 2012a, 2013
	Poinsettia ‘Scandic Early’	*S. palustre*	80	Blievernicht *et al*. 2012a, 2013
	Poinsettia ‘SK 79’	*S. palustre*	80	Blievernicht *et al*. 2012a, 2013
	Tagetes patula ‘Hero Spry’	not specified	0/ 50/ 80/ 85/ 100	Grantzau & Gaudig 2005
	Tagetes patula ‘Hero Spry’	not specified	0/ 50/ 100	Emmel 2008
	Verbena hybrida (rooted cuttings)	*S. fuscum*, *Sphagnum* mix (*S. fuscum*/ *S. magellanicum*/ *S. balticum*/ *S. papillosum*/ *S. rubellum*)	0/ 25/ 50/ 75/ 100 (dry weight)	A. Kämäräinen (unpublished data)
	Zinnia	*S. rubellum*, *S. magellanicum*, *Sphagnum* mix (*S. rubellum*/ *S. magellanicum*)	0/ 40/ 80/ 100	St-Hilaire *et al*. 2017

[1] E. Grantzau, Chamber of Agriculture Lower Saxony, Horticultural Training and Research Centre Ahlem, Germany, 2005.