Sphagnum farming in Germany – a review of progress

G. Gaudig, F. Fengler, M. Krebs, A. Prager, J. Schulz, S. Wichmann and H. Joosten

Institute of Botany and Landscape Ecology, University of Greifswald, Germany

SUMMARY

In ombrotrophic, nutrient-poor peatlands, the cultivation of peatmoss (*Sphagnum* spp.) is a promising paludiculture option. Since 2001 we have been studying peatmoss cultivation ('Sphagnum farming') in greenhouse and field experiments, paying special attention to propagation, propagule storage, establishment, productivity and regeneration. Our studies show that Sphagnum farming in Germany may provide a sustainable high-quality alternative to fossil white peat as a raw material for horticultural growing media. Sphagnum farming is, furthermore, a climate-friendly and sustainable land use option for abandoned cut-over bogs and degraded bog grassland.

KEY WORDS: degraded bog; sustainable land use; *Sphagnum* biomass; growing media

INTRODUCTION

To supply the ever-increasing demands from worldwide urbanisation, the cultivation of vegetables, fruits and flowers is increasingly taking place in pre-prepared 'growing media' that allow uniform high-quality plants to be grown at very high productivity levels (Altmann 2008). In the last few decades *Sphagnum* peat has emerged as the foremost constituent of these growing media (Joosten 1995, Alexander *et al.* 2008) because of its structural stability, low bulk density, high porosity, and low pH, nutrient and nitrogen immobilisation levels that allow easy adjustment to the requirements of individual crops (Schmilewski 2008). In the European Union some 20,000,000 m^3 of peat are used annually, supporting a horticulture industry with a turnover of €1.3 billion providing 11,000 jobs (Altmann 2008).

The highest quality peat is slightly humified *Sphagnum* peat ('white' peat) which, over the past 3000 years, has formed from *Sphagnum* mosses and constitutes the upper peat layer in *Sphagnum* raised bogs. In most countries of western and central Europe, the stocks of white peat are almost depleted (Joosten 2012). In addition, raised bog is now categorised as 'priority habitat' under the EU Habitats Directive (92/43/EEC) and many bogs are protected. To satisfy horticultural demands, white peat is imported in increasing volumes from the Baltic countries, Scandinavia and Canada (Joosten 1995). Wherever it occurs, peat extraction progressively destroys raised bogs and their typical biodiversity, carbon storage capacity, water regulation function and the palaeo-environmental archive.

Urgent action is required to reduce these negative environmental effects (Verhagen *et al.* 2009, LLUR 2012). The United Kingdom and Switzerland have already decided to reduce and eventually phase out the use of peat entirely (Secretary of State for Environment, Food and Rural Affairs 2011, Schweizerische Eidgenossenschaft 2012). However, these policies have so far had little effect on the volume of peat consumed (Denny 2013). The most important reasons for failing policy implementation are the extremely diffuse use of peat ('everybody everyday eats peat': virtually all vegetables consume some peat somewhere in their life cycle) and the limited supply of environmentally friendly, qualitatively and economically competitive alternatives (Schmilewski 2008).

The most promising alternative for peat in growing media is *Sphagnum* biomass which, not surprisingly, has similar physical and chemical properties to white peat. Over the last decade, growing media made from *Sphagnum* biomass have been tested on a wide variety of crops (Emmel 2008, Oberpaur *et al.* 2010, Blievernicht *et al.* 2012, 2013). They have generally performed as well as, or better than, standard peat-based media (Reinikainen *et al.* 2012). The cultivation of *Sphagnum* ('Sphagnum farming'), the technology of using *Sphagnum* biomass in industrial substrate production, and the use of growing media based on *Sphagnum* biomass in professional horticulture have been extensively studied in recent years (Gaudig & Joosten 2002, Gaudig & Joosten 2007, Landry *et al.* 2011), especially by the University of Greifswald in co-operation with various research and industrial partners (Table 1, Table 2, University of Greifswald 2014). In this article we summarise the main results.

Table 1. Sphagnum farming projects conducted by the University of Greifswald and associates. BMELV: German Federal Ministry of Food, Agriculture and Consumer Protection; DBU: Scholarship Programme of the German Federal Environmental Foundation; BMWi: German Federal Ministry of Economy and Technology.

Acronym	Project title	Period	Funding
PEATMOSS	Peatmoss as a renewable resource	2004–2007	BMELV
GEORGIA	Prospects of Sphagnum farming in the Kolkheti Lowlands, Georgia	2007–2010	DBU
MOOSFARM	Production of a sustainable and environmentally friendly substitute for peat in professional horticulture by Sphagnum farming on floating mats	2007–2010	BMWi
PROSUGA	Industrial cultivation of peatmoss for the production of innovative growing media for horticulture	2010–2013	BMWi
MOOSGRÜN	Peatmoss cultivation on bog grassland	2010–2014	BMELV

METHODS

We tested land- and water-based alternatives of Sphagnum farming both in the greenhouse and in the field. In the greenhouse, peatmoss (collected from natural sites) was cultivated in plant containers (12×12, 30×20 or 60×40 cm) filled with steamed peat (land-based approach) or on mats floating on a nutrient solution after Rudolph *et al.* (1988) (water-based approach). The mats were floating bodies of rigid foamed PolyStyrene wrapped in water-absorbent PolyPropylene fleece to guarantee water supply to the mosses. *Sphagnum* fragments of different species and sizes were deployed with an initial coverage of 40–100 %. Different water levels were maintained by irrigating (fine-mist spraying and directly refilling the container) with demineralised water. Mosses were fertilised with different nutrient solutions (Table 2) using a watering can or sprayer. To investigate submerged *Sphagnum* growth, fragments of six species (Table 2) were cultivated at 20 °C in one-litre Erlenmeyer flasks filled with a culture medium after Rudolph *et al.* (1988). Aeration was provided by an aquarium pump.

Field experiments were established in Lower Saxony (Germany) at Ramsloh (1,200 m² cut-over bog, 53° 4.31′ N, 07° 38.90′ E) in November 2004 and at Rastede (4 ha former bog grassland, 53° 15.80′ N, 08° 16′ E) in May 2011. Water levels were kept close to the surface by subsurface drainage pipes (Ramsloh) or surface irrigation (ditches spaced at 10 m, Rastede). Fragments or whole shoots of *Sphagnum* were spread manually (Ramsloh and part of Rastede) or by machines (2 ha of Rastede) and covered with straw mulch (cf. Quinty & Rochefort 2003). Floating mats (PolyStyrene/PolyPropylene, 30 m²) were installed on water bodies resulting from peat extraction and covered with moss and straw (fixed with a net to reduce bird and wave impact).

For both land-based and water-based approaches we investigated optimisation of site conditions for *Sphagnum* establishment, long-term *Sphagnum* productivity, diaspore recruitment and regeneration after harvest.

In randomised block designs (Hurlbert 1984) of permanent plots (greenhouse: 10×10 or 12×12 cm; field: 15×15 or 25×25 cm) we monitored:

- cover and abundance of vascular plant and moss species, using the scale of Londo (1976), with special consideration of *Sphagnum* spp. (monthly in the greenhouse, 1–3 times a year in the field);
- peatmoss growth (using cable ties, cf. Clymo 1970), *Sphagnum* lawn thickness (at five points in each plot), and number of capitula (cf. Hájek 2009) (monthly in the greenhouse, 1–3 times a year in the field); and
- species biomass (half-yearly or yearly) by harvesting above-ground biomass with scissors, separating different *Sphagnum* species, other mosses, vascular plants and straw, and drying to constant weight (80 °C for 48 h, Hendry & Grime 1993).

Table 2. Overview of Sphagnum farming experiments carried out in Germany by the University of Greifswald, 2004–2012.

focus	conditions	variables studied	project	reported by
vegetative propagation	greenhouse	*Sphagnum* species (*S. palustre*, *S. papillosum*, *S. fimbriatum*, *S. fallax*, *S. cuspidatum*, *S. magellanicum*), substrate (peat, floating mat, immersed in a culture medium with and without aeration), fragment size (chopped to 1–3 mm, 5–10 mm, 10–30 mm, 50–100 mm), fragment parts (capitulum, stem parts), application density (40 %, 80 %), shading	PROSUGA	this article
generative propagation	greenhouse	*Sphagnum* species (*S. papillosum*, *S. palustre*, *S. fimbriatum*), application density (30, 300, 1000, 2000, 3000, 9000 spores per cm²), age of spores (fresh, one year old), substrate (peat, *Sphagnum* biomass, polypropylene fleece, filter paper, straw mat, STOCKOSORB® gel, nutrient agar), fertiliser applied (nutrient solution after Rudolph *et al*. (1988) and concentrated twentyfold), transplanting young moss sprouts into the field	PROSUGA	Gahlert *et al*. (2012)
storage of propagules	greenhouse	*Sphagnum palustre*, substrate (peat, floating mat), duration of storage (0, 3, 6, 12, 20 months), temperature (+6 °C, -12 °C, -20 °C, -50 °C, -190 °C), material moisture (drying to 100 %, 80 %, 60 %, 30 %, 10 %, 5 % of original wet weight)	PROSUGA	Prager *et al*. (2012)
establishment of *Sphagnum* lawns	greenhouse	*Sphagnum* species (*S. palustre*, *S. papillosum*), *Sphagnum* mix (*S. magellanicum*/ *S. papillosum*), fragment size (whole moss shoots, chopped), substrate (peat, floating mat)	MOOSFARM	Joosten (2010)
	cut-over bog	*Sphagnum papillosum*, thickness and coverage of straw mulch (1.6 cm/40 %, 3.2 cm/80 %, 5.6 cm/99 %), cover of vascular plants	PEATMOSS	Kamermann & Blankenburg (2008)
	flooded bog, former bog grassland	*Sphagnum palustre*, fragment size (50–100 mm, 30–50 mm, 5–10 mm), straw mulch type (without, loose, quilt to a thin mat), substrate (peat, floating mat)	PROSUGA	this article
	former bog grassland	*Sphagnum* species (*S. palustre*, *S. papillosum*), fragment size (chopped to ~1 cm, whole mosses of length up to 15 cm), application density (40–50 %, 65–75 %, 80–90 %), coverage of straw mulch (with and without), site preparation method (sod removal, ploughing, herbicide application)	MOOSGRÜN	Krebs *et al*. (2012)

(continued overleaf)

Table 2 continued

focus	conditions	variables studied	project	reported by
productivity of *Sphagnum*	greenhouse	*Sphagnum* species *(S. magellanicum*, *S. papillosum*, *S. palustre, S. fimbriatum*, *S. rubellum*, *S. fallax),* water level (stable at 5 cm and 2 cm below capitula and rising with moss growth, stable at 2 cm below capitula initially and relatively sinking with moss growth, alternating between 2 cm (1 week) and 8 cm (3 weeks) below capitula), fertiliser application (nutrient solution after Gauger *et al*. 2002 and Rudolph *et al*. 1988, double and five-fold concentration of phosphorus or potassium, combination of double phosphorus and double potassium concentrations), shading (0 %, 20 %)	PEATMOSS	Gaudig *et al*. (2008)
	cut-over bog	water level (fluctuating between 40 cm below and 10 cm above peat surface), cover of vascular plants (up to 50 %)	PEATMOSS	Kamermann & Blankenburg (2008)
	flooded bog, greenhouse	*Sphagnum* species (*S. papillosum*, *S. palustre*, *S. fimbriatum*), *Sphagnum* mix (*S. magellanicum*/ *S. papillosum*), fragment size (whole moss, chopped), coverage type (nylon sling net, bird protection net), floating mat type (different artificial materials)	MOOSFARM	Joosten (2010)
	former bog grassland	*Sphagnum* species, fragment size, application density, coverage of straw mulch, site preparation method (see establishment on former bog grassland)	MOOSGRÜN	this article
regeneration of *Sphagnum*	cut-over bog	*S. papillosum*, cutting (manually to ~2 cm moss length, mechanically to 0 – ~5 cm moss length)	MOOSGRÜN	this article

Statistical analyses were carried out using R software (R Development Core Team 2009). Differences between treatments were tested by analysis of variance (Crawley 2005) and, in cases where sample sizes were unequal, with the non-parametric Kruskal Wallis test and a multiple comparison test after Siegel & Castellan (1988) using R package pgirmess (Giraudoux 2010).

RESULTS

Propagation and propagule storage

Generative and vegetative reproduction were investigated as alternative means of producing *Sphagnum* propagules for establishing large-scale Sphagnum farms. Spores of different *Sphagnum* species germinated well and built protonemata and first plantlets on various substrates in greenhouse experiments, but not in the field. When greenhouse-germinated *Sphagnum* was transplanted to the field after branches had formed, a closed lawn established within three months (Gahlert *et al.* 2012). Large (> 5 mm) vegetative fragments produced more biomass but far fewer capitula than small (1–3 mm) fragments in six months (Figure 1a). Moss capitula (top 0–1 cm) in particular, but also upper (1–2cm) stem parts produced abundant capitula when growing submerged under aeration, although no more so than on re-wetted peat (Figure 1b). Moss lawns developed from fresh *Sphagnum palustre* and plants that had been stored at 6 °C for up to twelve months developed similar coverages of green, vigorously-growing mosses. However, fresh plants produced significantly more biomass on peat than on floating mats. Thus, the shorter the time for which plants are stored, the better they are suited for *Sphagnum* establishment (Prager *et al.* 2012).

Establishment

In greenhouse experiments, large (5–10 cm long) *Sphagnum* fragments increased in length and cover faster than small fragments (1–3 mm long). These results were confirmed by field experiments, where *Sphagnum palustre* that was spread as entire plants established best on both peat (Krebs *et al.* 2012) and floating mats. At the Ramsloh site a dense, vigorously growing *Sphagnum papillosum* lawn (mean cover > 90%) developed in 3.5 years after one-off initial manual spreading of *Sphagnum* fragments (Figure 2). Establishment was faster in places with sparse straw coverage (Kamermann & Blankenburg 2008) and significantly slower both with extensive straw cover (90% straw cover after six months) and without straw. The results from Ramsloh indicate that establishment is accelerated by constant water levels close beneath the peat surface. This observation was confirmed at Rastede,

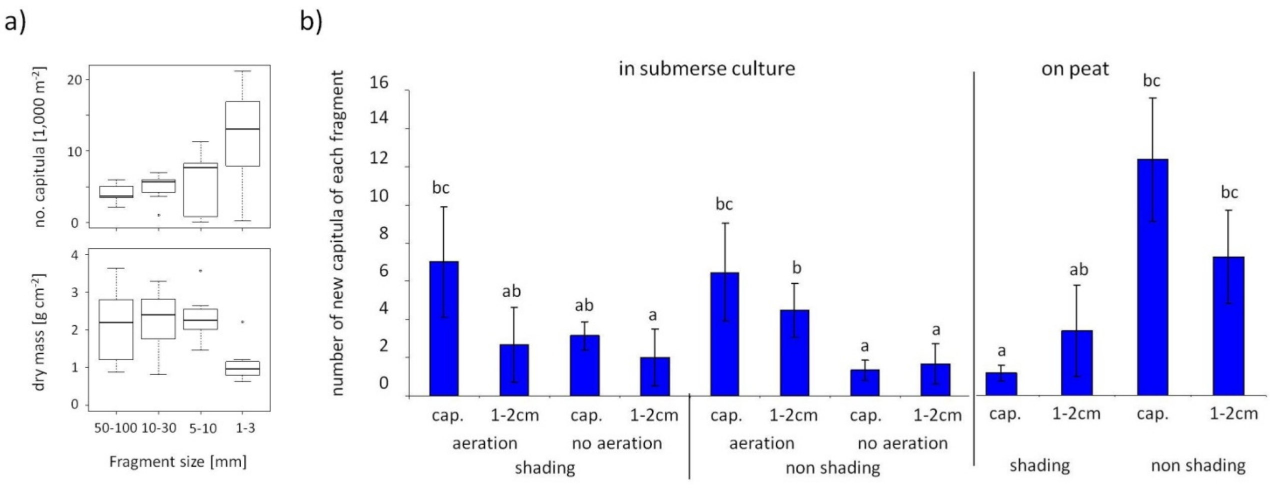

Figure 1. Vegetative reproduction of *Sphagnum palustre*. a) Number of capitula (in 1,000 capitula m^{-2}; n=12) and dry mass (g cm^{-2}; n=7) resulting from moss fragments of different sizes cultivated in a greenhouse, on floating mats and on damp peat with the water level just below the surface, after six months of growth. b) Number of new capitula that had developed ten weeks after inoculation, from fragments of different lengths immersed in a nutrient solution (after Rudolph *et al*. 1988) with aeration (in submerse culture, n=15) or on peat (n=6), with and without shading. Differences between the treatments were tested with the non-parametric Kruskal Wallis test and a multiple comparison test after Siegel & Castellan (1988) using R package pgirmess (Giraudoux 2010). Values with different letters differ significantly (P ≤ 0.05).

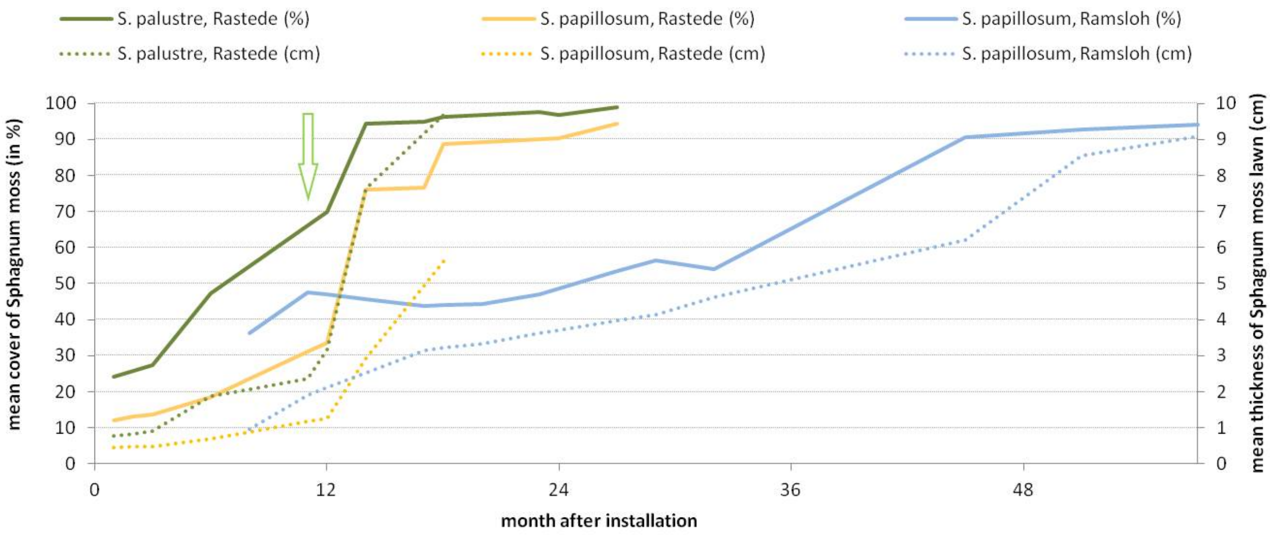

Figure 2. Development of mean moss cover (in %, solid line) and mean moss lawn thickness (in cm, dotted line; five measurements per plot) of *Sphagnum palustre* and *S. papillosum* at Rastede (mechanically spread with manual replenishment of gaps in the developing moss carpets [green arrow]; number of plots for *S. palustre* = 224 and for *S. papillosum* = 96 at start, minus 1/3 of the plots each 12 months for biomass measurements) and of *S. papillosum* at Ramsloh (manually spread, no replenishment of gaps; initial number of plots = 60).

where permanently high water levels (~ 5 ± 10 cm below peat surface) and the replenishment of gaps after one year (by spreading additional peatmoss) led to a thick, dense peatmoss lawn (*S. palustre* 96 % cover 9.7 cm thick, *S. papillosum* 90 % cover 5.6 cm thick) 1.5 years after installation (Figure 2). The data also indicate that installation in spring may favour *Sphagnum* establishment.

Productivity and regeneration

Our greenhouse experiments showed that a high and stable water level is the most decisive factor for *Sphagnum* growth. Fertilisation, on the other hand, has only a minor effect (Gaudig 2008). Productivity mainly ranged between 3 t dry mass (DM) ha^{-1} yr^{-1} and 6 t DM ha^{-1} yr^{-1}. In the field (at Ramsloh), after an initial establishment phase of 3.5 years, the mean productivity of *Sphagnum papillosum* reached a value of 3.6 t DM ha^{-1} yr^{-1}, with the highest productivity (6.9 t DM ha^{-1} yr^{-1}) being attained in locations with permanently high water levels (Figure 3).

Higher productivities ranging from 3.4 t DM ha^{-1} yr^{-1} to 6.8 t DM ha^{-1} yr^{-1} were obtained only one year after inoculation with *Sphagnum palustre* at the continuously wet Rastede plot when the propagules were spread manually. In the parts that were installed using machines, the mean productivity of *S. palustre* reached only 1.85 t DM ha^{-1} yr^{-1}. Because the machines spread *Sphagnum* fragments irregularly, there were gaps in the developing moss carpet, which were replenished by manual spreading of additional *Sphagnum*. A dense, vigorously growing moss lawn established as a result (Figure 2). The productivity of peatmosses growing on floating mats was between 2 t DM ha^{-1} yr^{-1} and 4 t DM ha^{-1} yr^{-1} (mean values for single species), with *Sphagnum palustre* being the most productive species (Figure 3, cf. Joosten 2010). In a harvesting experiment involving removal of the uppermost 2–5 cm of the *Sphagnum* sward, 15 % of the moss plants had generated new capitula after six months (Figure 4). New capitula covered 80 % of the harvested area after a further six months, and almost 100 % after 2.5 years.

Land availability

Land-based cultivation is practiced on bog soils, i.e. on bogs after peat extraction and on bogs used as pasture and meadow (Krebs *et al.* 2012). These soils are widely available (e.g. 145,000 ha of bog grassland in Lower Saxony, NLWKN 2006), but generally require substantial investment in site preparation and irrigation to guarantee the constant high water table that is necessary. Drained bogland loses carbon through a variety of pathways and is a strong emitter of greenhouse gases. Sphagnum farming allows this land to be used in a climate-

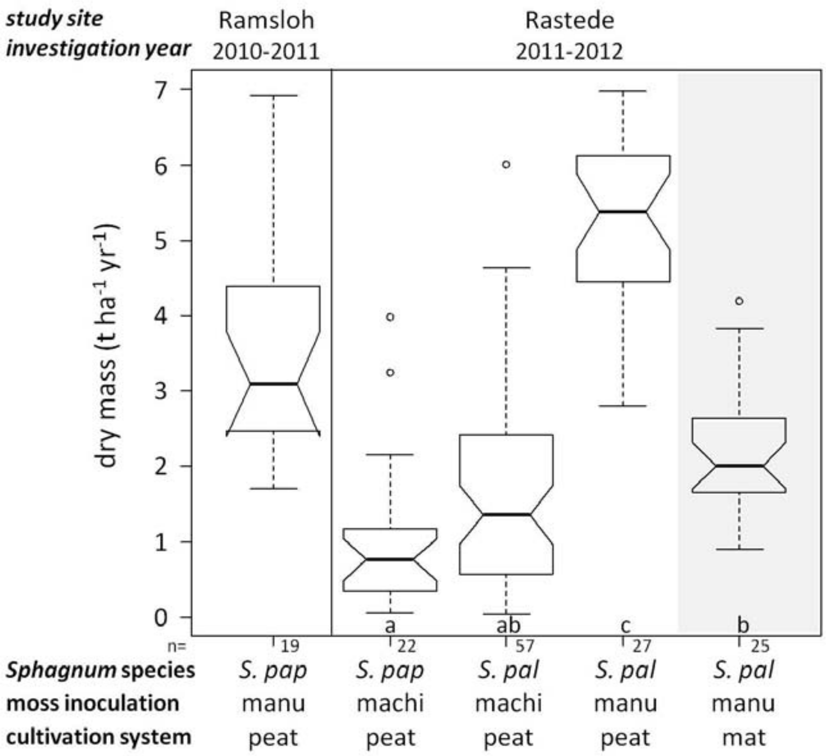

Figure 3. Full-year dry mass increase (in t ha^{-1} yr^{-1}) of *Sphagnum papillosum* and *S. palustre*, growing outdoors in a six-year-old (Ramsloh) and a one-year-old (Rastede) moss lawn on peat (white background) or on floating mats (grey background). Moss inoculation manually (manu) or by machines (machi). Differences between the treatments were tested with the non-parametric Kruskal Wallis test and a multiple comparison test after Siegel & Castellan (1988) using R package pgirmess (Giraudoux 2010). For the Rastede samples, values with different letters differ significantly ($P \leq 0.05$).

friendly, sustainable way and restores some of the original peatland ecosystem services (cf. Barthelmes *et al*. 2012, Wichmann *et al*. 2012).

Water-based *Sphagnum* cultivation on artificial floating mats has been tested at water bodies resulting from the extraction of peat (e.g. Lower Saxony), sand (Lower Saxony) and lignite (Brandenburg, Lausitz) (Blievernicht *et al*. 2011). Although the floating mats guarantee a constant supply of water, water quality may deviate considerably from the ideal (e.g. low pH, high EC levels). Water-based cultivation allows water bodies within bogs to be used not only as water reservoirs for irrigation of cultivated areas during dry periods, but also as additional Sphagnum farming areas. The optimal configuration for Sphagnum farming on re-wetted degraded bogs is likely to be a mosaic of land- and water-based cultivation (Figure 5).

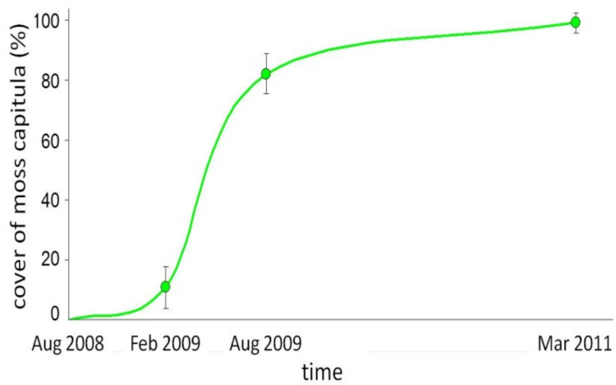

Figure 4. Development of moss capitula cover (%) after removing the uppermost 2–5 cm of the *Sphagnum papillosum* sward (data from Ramsloh, n=30).

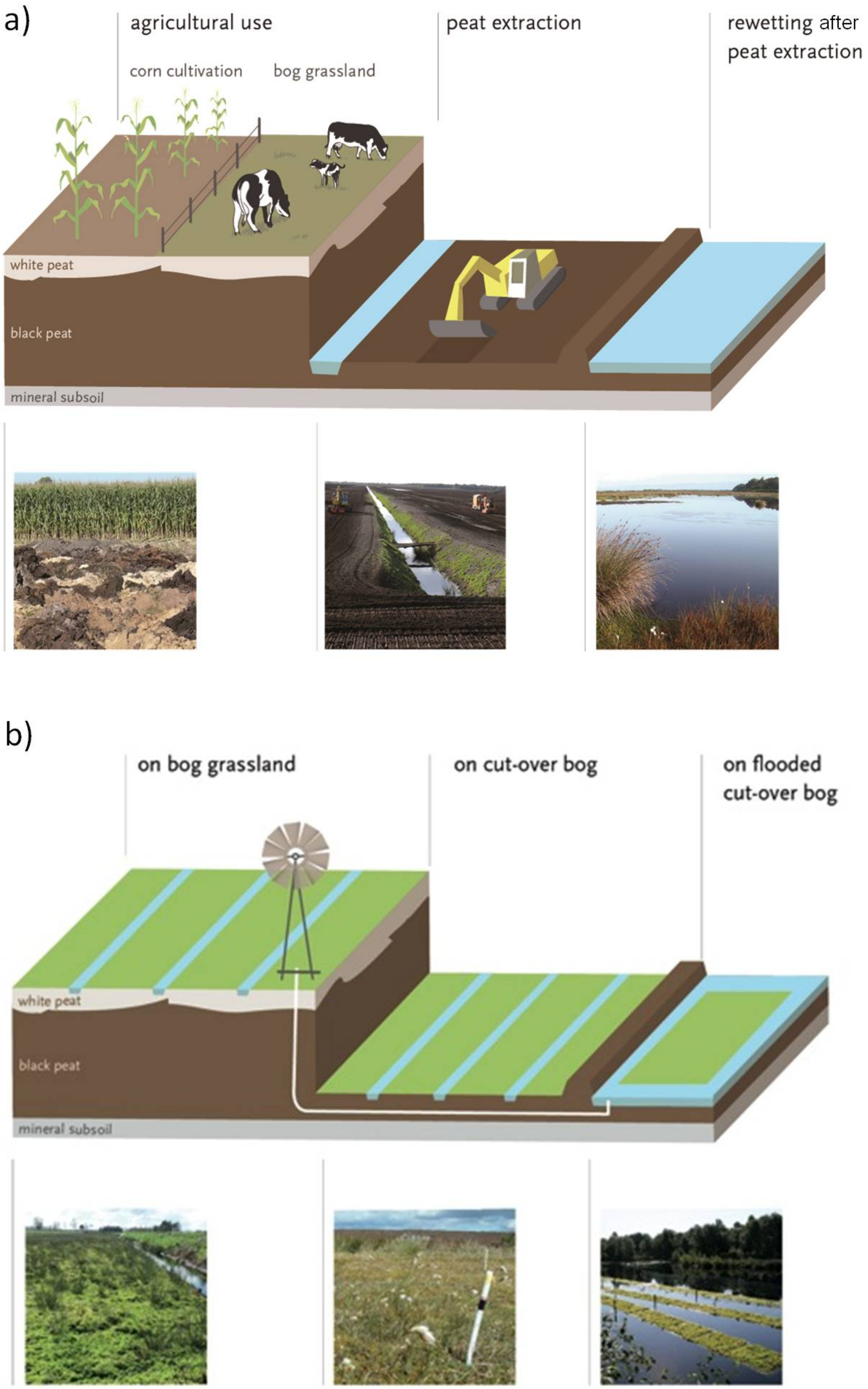

Figure 5. Mosaic of degraded bogs with a) current land use and b) Sphagnum farming options (adapted from Gaudig 2008).

CONCLUSIONS

After a decade of research we know the following:

1) *Sphagnum* biomass is a suitable raw material for horticultural growing media. In the future, new and adapted *Sphagnum*-based growing media should be developed for more applications in horticulture.
2) *Sphagnum palustre* is one of the most promising species for both growing media and Sphagnum farming. So far we have trialled only a small number of peatmoss species originating from just a few locations. Further selection is needed to find more productive species and provenances.
3) *Sphagnum* can be farmed on re-wetted peat areas and deep water, subject to identified risks (e.g. insufficient water availability, as well as expansion of parasitic fungi and vascular plants, in land-based cultivation; birds and waves in water-based cultivation). The next challenge will be to upscale and industrialise the entire production process. The development of machines and methodologies for mass production of *Sphagnum* propagules and for managing and harvesting *Sphagnum* cultures is needed.

Investigations on economic feasibility show that farming *Sphagnum* biomass is already profitable for niche markets with high revenues, but so far cannot compete with low-priced white peat. Nonetheless, the external costs of peat extraction and drainage-based peatland use on the one hand, and the external benefits of Sphagnum farming for society on the other, provide good reasons for developing and encouraging the sustainable production of this promising renewable raw material (cf. Wichmann *et al.* 2012).

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Author for correspondence:
Greta Gaudig, Department of Peatland Studies and Palaeoecology, Institute of Botany and Landscape Ecology, University of Greifswald, Soldmannstraße 15, D-17487 Greifswald, Germany.
Email: gaudig@uni-greifswald.de