Ecological Engineering 74 (2015) 135–147

Contents lists available at ScienceDirect

Ecological Engineering

journal homepage: www.elsevier.com/locate/ecoleng

Sphagnum farming: A long-term study on producing peat moss biomass sustainably

Rémy Pouliot [a,*], Sandrine Hugron [a], Line Rochefort [a]

[a] Peatland Ecology Research Group and Centre d'Études Nordiques, Université Laval, 2425 Rue de l'Agriculture, Quebec City, Québec, G1 V 0A6, Canada [1]

ARTICLE INFO

Article history:
Received 9 April 2014
Received in revised form 25 September 2014
Accepted 6 October 2014
Available online 29 October 2014

Keywords:
Cutover bog
Horticultural substrate
Hydrology
Paludiculture
Peatland
Reclamation

ABSTRACT

Sphagnum farming refers to the cultivation of *Sphagnum* mosses to produce *Sphagnum* biomass sustainably. Some possible uses of these fibers are as ingredients in growing substrates, as floral moss, as plant packaging during transport, or as moss reintroduction material for peatland restoration projects. Because this biomass production is sustainable, *Sphagnum* farming should reduce human impacts on natural peatlands. Despite its various benefits, research on *Sphagnum* farming is limited. To determine if *Sphagnum* farming is feasible on a large-scale basis (on the order of 900–1500 m^2 size basin), 6 yearly production cycles were implemented in trenches of former block-cut peatland in eastern Canada. These sites were monitored over seven growing seasons. *Sphagnum* cover (67%) and accumulated biomass (787 $g\,m^{-2}$) from the culture basins were similar or superior to surveys from restored peatlands. However, cover and biomass values differed greatly among production cycles when comparing the time elapsed since the creation of the basins. Differences in productivity during different cycles were largely coupled with variations of water table levels compared to intrinsic properties of plant interactions. We believe that the optimization of water access (for example through automated of irrigation systems) for *Sphagnum* mosses would greatly improve the productivity of *Sphagnum* farming.

1. General introduction

Peat will continue to be a major component of growing substrates over the next decades because of its unique qualities, low cost, and availability (Caron and Rochefort, 2013). *Sphagnum* farming is the cultivation of *Sphagnum* mosses to produce biomass of non-decomposed *Sphagnum* fibers on a cyclic and renewable basis. If a certain quantity of these *Sphagnum* fibers is used in conventional peat products, it would reduce the impact of peat extraction or of simple harvesting in the wild, while having the potential to maintain the quality of growing substrate mixes. *Sphagnum* can be farmed on various degraded and drained peatlands of former lands used for agriculture, forestry, roads, oil pad, energy, or horticultural substrates. Non-decomposed *Sphagnum* fibers thus produced would have the advantage to be harvested on a cyclic and renewable basis in comparison to peat moss conventionally harvested from natural peatlands. The establishment of a *Sphagnum* moss paludiculture (production under wet conditions) would reduce the negative environmental impacts of drainage such as peat oxidation, soil subsidence and CO_2 emissions (Joosten, 1998; Joosten et al., 2012).

Sphagnum fibers have multiple end uses that are environmentally sound. These fibers are currently sold as floral moss used in orchid propagation (largely for *Phalaenopsis* species), for roof greening (popular in South Asia), in miniature models, for urban yard landscaping, to top dress containers and flower beds, for lining wire framed hanging baskets, on lawn wire sculpture or for making wreath. These fibers could also successfully substitute peat in growing substrates (Emmel, 2008; Reinikainen et al., 2012), consequently lengthening the life time of a given peat deposit and reducing the expansion of peat harvesting, and can replace perlite or vermiculite in horticultural growing mixes (Jobin et al. submitted). In addition, *Sphagnum* fibers could be used to manufacture compostable plant pots, thus contributing to a substantial reduction of plastic. Further uses of these fibers include packaging seedling plants for transport and for cellar storing of root vegetables, protecting them against spoiling, mice, insects and other potential invaders. Finally, the *Sphagnum* fibers could be reintroduction material for ecological restoration of

* Corresponding author. Tel.: +1 418 656 2131x7058; fax: +1 418 656 7856.
E-mail address: remy.pouliot.1@ulaval.ca (R. Pouliot).
[1] (PERG, http://www.gret-perg.ulaval.ca).

http://dx.doi.org/10.1016/j.ecoleng.2014.10.007
0925-8574/

cutover bog when using the moss layer transfer technique (Graf et al., 2012 or Rochefort and Lode, 2006 for the method description), especially in regions where natural peatlands are scarce and should be preserved.

Despite the multiple environmental benefits of *Sphagnum* farming, research, literature and ongoing projects are limited. Small scale trials have been conducted in many countries, such as Canada, Germany, Chile, Ireland, Finland, Korea, New Zealand and Japan in the last 10 years. With the exception of Gaudig et al. (2014), results from these trials were mostly presented in reports, which were not in English (see for example: Blievernicht et al., 2011; Joosten, 2010; Pouliot et al., 2012; Silvan, 2008), in conferences proceedings (see for example: Campeau and Rochefort, 2002; Gaudig et al., 2012; Krebs, 2008; Pouliot et al., 2013) or in journals without peer review (as Peatlands International, see for example: Joosten et al., 2013 or Landry et al., 2011b).

The general aim of this article is to review the main drivers favoring *Sphagnum* growth in cultivation and to present the results from a field experiment where 6 production cycles (on the order of 900–1500 m^2 size basin) were installed over 7 years in trenches of a block-cut peatland after cessation of peat harvest activities. In this experiment we wanted to determine if *Sphagnum* farming is feasible (logistically and for *Sphagnum* growth) on a large scale basis. More specifically, our goals were to determine (1) if large-scale mechanized *Sphagnum* farming will allow dense moss carpet to establish and develop quickly (within 5 years) and (2) whether an optimal hydrology for *Sphagnum* species could be maintained in the basins through an open ditch and overflow controls.

2. Drivers favoring *Sphagnum* growth in cultivation

Among drivers influencing *Sphagnum* growth, the more important are the intrinsic properties of *Sphagnum* species, plant interactions (among *Sphagnum* species and between *Sphagnum* and other moss or vascular plant species), and water level. All these factors can modify the yield rates in *Sphagnum* farming basins.

The intrinsic properties of *Sphagnum* species are generally similar within a main subgenus (*Acutifolia*,*Cuspidata* or *Sphagnum*) (Clymo and Hayward, 1982; Coulson and Butterfield, 1978; Johnson and Damman, 1993; Rochefort et al., 1990; Rydin, 1993; Rydin et al., 2006). These properties will affect the accumulation rate and the quality of biomass accumulating in *Sphagnum* farming basins. Species within the *Acutifolia* subgenus generally have higher stem densities and greater abilities to transport water by capillarity, enabling them to form carpet and cushion well above the water table. They have the lowest growth rates among all subgenera, but also the lowest decomposition rates (Johnson and Damman, 1993; Rochefort et al., 1990), with a result they can be interesting in *Sphagnum* farming. As a result, they often form the bulk of peat deposits in North America. Intrinsic properties of species from the *Sphagnum* subgenus can confer great porous and structuring quality to growing media due to their large hyaline cells and pores (Malcolm, 1996). Due to their size, these species generally have lower stem densities than species for the *Acutifolia* subgenus, but biomass per surface unit is still high. They also have low decomposition rates, but they do not have a great ability to transport water which can hamper their growing time during a field season (McCarter and Price, 2012). The generally wet species of the *Cuspidata* subgenus have the highest growth rates, but are also associated with low stem densities and high decomposition rates, quickly leaving only bundle of stem with poor porous quality. They also have the worst abilities to transport water. For all these reasons, the *Sphagnum* species from *Acutifolia* and *Sphagnum* subgenus should be targeted in the context of *Sphagnum* farming.

Competition or facilitation events in peatlands have a significant effect on *Sphagnum* growth and interactions between species are closely related to the distance from the water table. In fact, competition between *Sphagnum* species will be the limiting factor in the wetter part, closer to the water table level, while physiological tolerance to water stress will be more important in the driest part, farther of the water table level (see for example: Andrus et al., 1983; Rydin, 1993; Rydin and McDonald, 1985). In the context of large-scale reintroduction of *Sphagnum* diaspores in culture basins, donor material contains diaspores of species from all subgenera with a dominance of *Acutifolia*and *Sphagnum* subgenera. As competitive abilities of *Sphagnum* species will differ according to their position along the water table gradient, the control of the water table level in the basins can help to increase the growth of targeted species, while preventing the establishment of others. *Sphagnum* species can also interact positively with others. Experimentation in the field upon an earlier idea which pioneer species from *Cuspidata* subgenus (as *Sphagnum fallax* (Klinggr.) Klinggr.) can rapidly colonize humid areas and then prepare the substrate for the targeted species and facilitate their implantation speed (Grosvernier et al., 1997), was proved wrong. Indeed, under controlled water table level, no gain of biomass was observed for *Sphagnum magellanicum* Brid. or *Sphagnum papillosum* Lindb. when grown with *S. fallax* (Picard, 2010). On the other hand, the establishment and growth of species from the *Sphagnum* subgenus improve when mixed with species from the *Acutifolia* subgenus (Chirino et al., 2006). These species allow a better transport of water by capillarity to surrounding stems of *Sphagnum* subgenus when the water stress increases, reinforcing the choice of species from these subgenera for the *Sphagnum* farming. In addition, the presence of vascular plants can increase *Sphagnum* growth by creating adequate microclimates, by providing physical supports and by stabilizing the water table and the soil surface (Malmer et al., 1994, 2003). These effects are more important when the relative humidity is low, such as under continental temperate climate than under hyperoceanic climate where high rates of relative humidity prevails (Andrus, 1986; Kleinebecker et al., 2007; Pouliot et al., 2011). Moreover, the climate during the year when *Sphagnum* species were reintroduced affects the plant establishment speed, whereas the climate during subsequent years does not influence the development of *Sphagnum* carpet (Chirino et al., 2006). A better control of water table near the surface via irrigation, at least during the first year after basin creation, could overcome the limitation of the climatic effect, making the presence of vascular plants unnecessary. Finally, in greenhouse experiments, it was possible to control fungi infection in *Sphagnum* carpets by a fungicide application without any effects on *Sphagnum* growth (Landry et al., 2011a), giving us an option if this problem appears in *Sphagnum* farming basins. The control of algal proliferation should be also easier under a controlled water table level. Controlling the water table level is thus essential In *Sphagnum* farming because the right water level will positively affect the growth of target *Sphagnum* species and reduce the competition effects of undesirable ones.

Farming *Sphagnum* mosses in flat topography into basins helps to retain more water during dry summers as basins are lower than the surrounding lands and the presence overflow wooden devices avoids prolonged periods of flooding. Indeed, cultivating *Sphagnum* mosses in formerly peat block-cut trenches allows for a better development of the moss carpet during dry years, while having no effect during wet years (Campeau et al., 2004). While blocking drainage ditches can be enough to promote *Sphagnum* growth in old block-cut cutover peatlands (González et al., 2013), such trenches require an overflow outlet to prevent flooding. Flooding can harm *Sphagnum* establishment because newly introduced material can be displaced, peat erosion can bury the established material (Rochefort and Lode, 2006), and prolonged floods cause elongation of *Sphagnum* stems without any gain of biomass (Campeau et al., 2004).

Water availability for *Sphagnum* growth can be improved through the installation of irrigation systems. As surface irrigation with sprinklers or by a gravity distribution of water into culture basins with a system of perforated PVC pipes did not significantly increase *Sphagnum* growth, the investment was considered too high (Rochefort, 2001; Rochefort and Bastien, 1998). However, an experiment where water was pumped into a ditch to keep adjacent *Sphagnum* culture basins wet over three growing seasons, showed a net improvement in *Sphagnum* growth (Rochefort, 2001), strongly indicating that irrigation through open ditches surrounding culture basins or by subsurface drains could prove to be an efficient water management options (Gaudig et al., 2014; Querner et al., 2012). Assuring an adequate and stable water table level in basins could thus be the key factor to maximize the yield of *Sphagnum* farming by increasing biomass accumulation.

3. Material and methods

3.1. Study site

The *Sphagnum* farming experimental site was established in a cutover bog located in Shippagan, in the northeastern part of the Acadian Peninsula, New Brunswick, Canada (47°40′ N, 64°43′ W). The region is subjected to the Atlantic maritime climate, characterized by relatively cool (average temperature 4.4 °C) and humid (1097 mm average annual precipitation) temperatures (Environment Canada, 2013a). In that peatland, peat was harvested by the manual block-cut method from 1941 to 1971, leaving a topography characterized by alternating baulks and trenches. Since the cessation of peat harvesting activities, trenches were colonized by a relatively uniform cover of *Sphagnum* mosses, while the vegetation on the bulks was dominated by ericaceous species and trees (Poulin et al., 2005; Robert et al., 1999).

3.2. Establishment of production cycles

A production cycle refers to the year where a given basin was created, so the moment where the *Sphagnum* biomass production started. The establishment of the *Sphagnum* farming cycles was performed mechanically with a method adapted from the moss layer transfer technique (see Graf et al., 2012 or Quinty and Rochefort, 2003 for a method description), currently used for the large-scale ecological restoration of industrial harvested bogs in North America. Each cycle was established in a basin located in a former trench with an approximate width of 15 m and a length ranging from 60 to 100 m (Fig. 1A). The depth of the residual peat layer after block-cut harvesting is around ~1.5 m in trenches (Campeau et al., 2004) and the residual peat is

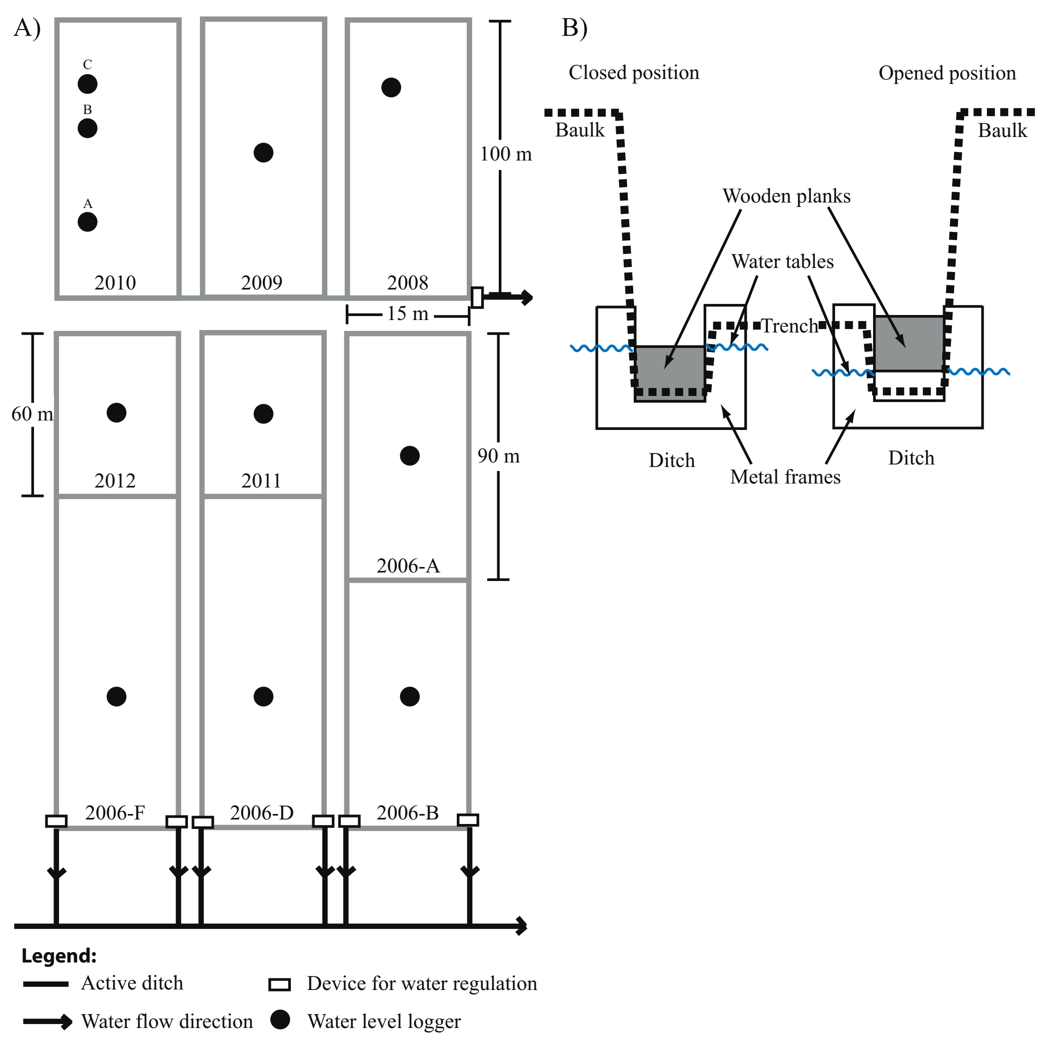

Fig. 1. (A) Plan of the *Sphagnum* farming experimental site in 2013, including the localization of the automated water level loggers. (B) Sketch of the wooden device for outflow water regulation in opened and closed positions. The 2011 production cycle was put in place on the 2006-C and the 2012 cycle on the 2006-E.

composed of *Sphagnum* mosses still relatively undecomposed (pH 3.7, electrical conductivity = 62 μS and bulk density = 0.09 g cm^{-3}; Robert et al., 1999). All vegetation that colonized spontaneously the trenches was removed with an excavator down to the more decomposed residual peat to create a basin (depending of the trench, around 10–30 cm were removed). The peat surface was leveled and small drainage ditches of around 30 cm width by 30 cm deep were dug around the basins with the same equipment. The top 10 cm of the *Sphagnum* carpet (mainly species of the *Acutifolia* subgenus: *Sphagnum flavicomans* (Cardot) Warnst., *Sphagnum fuscum* (Schimp,) Klinggr. and *Sphagnum* rubellum Wilson with *S. magellanicum* from the *Sphagnum* subgenus) were collected with a rototiller or an excavator in nearby undisturbed trenches. Plant material was spread in the basins with a lateral manure spreader which circulated on the bulks. The ratio of introduction was 1:10, which means that 1 m^2 of diaspores (moss carpet 10 cm thick on average) coming from donor trenches was spread over a basin surface of 10 m^2. The plant fragments covered the peat surface with a thin layer of 1–3 cm. Plant material was then covered with straw (3000 kg/ha), using a lateral straw spreader. Finally, the water level in the basins was controlled manually with a wooden device for water regulation, where the position could be adjusted to maintain a maximum height of the water level at approximately 5–10 cm below the surface (Fig. 1B). This water control device prevented flooding, but did not prevent the water level from dropping to greater depths during summer droughts. In total, 11 production cycles (each in a different basin) were established between 2006 and 2012 (6 in 2006: 2006-A to 2006-F, and 1 per year between 2008 and 2012; Fig. 1A). The basins of 2011 and 2012 were set in place in the top two drier parts among the 2006 production cycles (2006-C and 2006-E, respectively), with a low *Sphagnum* cover (mean ± SE of 32 ± 3%, comparatively to 53 ± 3% in other parts of the 2006 cycle after 4 growing seasons). The surface level was leveled lower than it was originally to allow the water table to be closer to the surface. The total area under cultivation was around 12,600 m^2. Basins were all created during the snowmelt period (end of April or beginning of May), to enable the machines to drive in the peatland and to limit disturbances.

3.3. Vegetation monitoring

To assess vegetation establishment, cover was estimated annually for the following plant categories: *Sphagnum* mosses, true mosses (other than *Sphagnum*) and hepatics, ericaceous species, herbs and straw. All bryophytes (*Sphagnum*, true mosses, and hepatics) were also grouped together. Vegetation cover was recorded along transects perpendicular to the length of the trenches set every 10 m and evaluated in 25 cm × 25 cm quadrats distributed systematically along each transects. A variation in sampling efforts from year to year and between basins was present and was due to human resource constraints, basin size, or the use of some space in basins for other experiments (see Table 1 for details). In all cases, the percent cover of each plant species was visually estimated. *Sphagnum* biomass accumulated since plant reintroduction was assessed annually in June (see Table 1 for sampling efforts). Biomass samples were collected in 25 cm × 25 cm quadrats systematically distributed in each basin adjacent to the location of vegetation cover transects. *Sphagnum* fibers were then separated out from remaining straw or cleaned from other plant material, dried at 70 °C and weighted. As for cover, *Sphagnum* mosses, true mosses (other than *Sphagnum*), and hepatics, ericaceous species, herbs and remaining straw were considered separately.

In addition, productivity for the three 2006 basins (B, D and F) which had complete *Sphagnum* carpets was assessed during the 2012 growing season. *Sphagnum* moss annual net productivity (MAPP, in g m^2 yr^{-1}) was estimated with the following equation (adapted from Vitt and Pakarinen, 1977): $MAAP = AI \times D \times W \times C$ where AI = mean annual increment of moss (cm), D = density of *Sphagnum* mosses (stem m^{-2}), W = dry weight for one centimeter of *Sphagnum* stem (g cm^{-1} $stem^{-1}$) and C = cover of *Sphagnum* mosses (%). Mean annual increment was measured with the white mark technique (Ilomets, 1982; Pouliot et al., 2010). At the beginning of the growing season (April 2012), 14 *Sphagnum* small bunches (∼10 × 10 cm) comprising a mix of *S. rubellum*, *S. fuscum*, and *S. magellanicum* were carefully collected. In each carpet, around 30 *Sphagnum* stems (coming from the different species, proportionally to their abundance) in the sample were marked with insoluble white paint one centimeter below the capitulum. Bunches were then replaced in their initial position with the capitula at the same level than the surrounding mosses. One year later (April 2013), bunches were retrieved and *Sphagnum* elongation was recorded by measuring the distance between the mark and the capitulum and subtracting one centimeter from the result (AI in the equation). The density of *Sphagnum* stems (D) was estimated by counting each capitulum in a 0.0082 m^2 sample cored near the *Sphagnum* bunches of marked stems. 40 *Sphagnum* stems were then taken in each sample, capitulum was removed and the first 3 cm was cut, dried and weighted (divided by 3, for W in the equation). As we were dealing with complete *Sphagnum* carpets, percent cover of *Sphagnum* mosses was equal to 100% (C = 1 in the equation).

3.4. Hydrological monitoring

The position of the water table was automatically recorded by 11 water level loggers (Onset HOBO® U20) located in each basins during the 2013 growing season (Fig. 1A). Water table position was recorded once per hour between May 29th and October 11th for eight level loggers (until August 13th for other ones). From 2007 to 2013, water table levels were also recorded manually in wells. The number of measurements through the summer and the number of wells in each basin differ (Table 2).

3.5. Climate monitoring

The mean monthly temperature (°C), the total monthly precipitation (mm) and the monthly number of days with effective rainfall (superior to 2 mm, see Price et al., 1998) were extracted from the Bas-Caraquet meteorological station (47°48″ N 64°50″ W; Environment Canada, 2013a). This station is the closest of the *Sphagnum* farming experimental site (∼13 km). Those data were compared to the climate norms and averages between 1981 and 2010 (Environment Canada, 2013b) for the station of Haut-Shippagan (47°45″ N; 64°46″ W, at ∼6 km of the station) to detect if some years were significantly rainier, dryer, hotter, or colder than normal. The station of Haut-Shippagan was used for climate norms and averages rather than the one of Bas-Caraquet as more years were used to calculate the averages (from 1987 to 2005 vs. 1983 to 1993). No data are available for the station of Haut-Shippagan from 2006 to 2011.

3.6. Statistical analyses

One-way ANOVAs were performed to compare the differences among production cycles (basin) with equal time since their creation in terms of *Sphagnum* cover and biomass. Analyses were done separately for each year (1–7 years after the establishment of production cycles). Each basin of the production cycles of 2006 were considered separately in the analyses. Then, to give a decision tool to estimate where *Sphagnum* biomass could be

Table 1
Comparisons of selected data of *Sphagnum* cover (%) and biomass ($g\,m^{-2}$) in the *Sphagnum* farming basins at the experimental station of Shippagan (47°43′36″ N; 64°42′06″ W) and in restored peatlands of eastern Canada. A dot indicates that no biomass sample was harvested or no cover was estimated for that production cycle for a given number of growing season(s) after the creation of a basin. Numbers in parenthesis refer to number of missing values mainly due to water inundation.

			Number of growing season(s) after the creation of a basin													
			1		2		3		4		5		6		7	
			Mean ± SE	*n*	Mean ± SE	*n*	Mean ± SE	*n*	Mean ± SE	*n*	Mean ± SE	*n*	Mean ± SE	*n*	Mean ± SE	*n*
Sphagnum cover (%)	*Sphagnum* farming basins, production cycle of:	2006-A	10 ± 1	52 (4)	27 ± 3	56	20 ± 3	24	42 ± 6	24	57 ± 7	24	39 ± 7	24	34 ± 7	24
		2006-B	17 ± 3	32 (24)	22 ± 3	55 (1)	31 ± 6	24	41 ± 6	24	64 ± 7	24	62 ± 6	24	69 ± 9	16 (8)
		2006-C	7 ± 1	55 (1)	13 ± 2	56	20 ± 4	24	25 ± 5	24	.		.		.	.
		2006-D	21 ± 3	49 (7)	34 ± 4	56	50 ± 6	24	69 ± 6	24	85 ± 5	24	86 ± 5	24	92 ± 5	16
		2006-E	6 ± 1	55 (1)	23 ± 3	56	20 ± 3	24	33 ± 6	24	47 ± 7	24	.		.	.
		2006-F	15 ± 2	45 (11)	36 ± 4	56	43 ± 6	24	55 ± 5	24	73 ± 7	24	73 ± 5	24	89 ± 4	16
		2008	2 ± 0	53 (3)	15 ± 2	56	45 ± 4	56	34 ± 4	55 (1)	33 ± 4	56	.		.	
		2009	.		11 ± 1	50 (6)	5 ± 1	56	7 ± 2	56	.		.		.	
		2010	.		48 ± 4	53 (3)	47 ± 5	56	.		.	.	.	.	.	
		2011	.		30 ± 4	34 (1)		.	.	.	.	.	.		.	
		2012	39 ± 6	34 (1)				.	.	.	.	.	.		.	
		All cycles	13 ± 1	375	26 ± 1	528	31 ± 2	312	34 ± 2	255	55 ± 3	176	65 ± 3	96	67 ± 4	72
	Restored peatlands of:	Bois-des-Bel	11 ± 3	22	10 ± 2	32	15 ± 3	32	32 ± 4	32	47 ± 4	31	55 ± 3	32	63 ± 3	32
		Chemin-du-Lac	2 ± 1	9	10 ± 4	11	14 ± 3	23	25 ± 6	8	16 ± 4	29	19 ± 7	8	19 ± 3	29
		Kent	.		8 ± 1	5	15 ± 3	22	16 ± 5	4	40 ± 13	5	.		42 ± 11	5
		Maisonnette	.		.		5 ± 1	32	17 ± 4	6	12 ± 2	32	.		22 ± 3	26
		Pokesudie	.		.		8 ± 2	9	21 ± 6	5	29 ± 7	5	.		.	
		St-Charles	2 ± 0	3	5 ± 4	3	16 ± 7	3	.		27 ± 19	3	.		37 ± 21	2
		Ste-Marguerite	1 ± 0	3	1 ± 0	7	9 ± 2	13	11 ± 3	16	13 ± 2	31	44 ± 5	4	21 ± 3	36
		St-Modeste	.		.		6 ± 3	6	.		18 ± 11	6	.		30 ± 15	6
		Verbois	.		8 ± 3	6	16 ± 4	10	.		27 ± 6	10	.		.	
		All sites	7 ± 2	37	8 ± 1	64	11 ± 1	150	23 ± 2	71	23 ± 2	152	48 ± 3	44	32 ± 2	136
Sphagnum biomas ($g\,m^{-2}$)	*Sphagnum* farming basins, production cycle of:	2006-A	11 ± 7	4	76 ± 41	4	355 ± 169	4	205 ± 98	5	350 ± 59	5	220 ± 173	4 (1)	500 ±228	5 (1)
		2006-B	66 ± 50	4	91 ± 47	4	126 ± 17	4	338 ± 65	5	279 ± 60	5	608 ± 75	5	572 ± 134	5 (1)
		2006-C	13 ± 4	4	44 ± 23	4	126 ± 44	4	344 ± 88	5	.		.		.	
		2006-D	23 ± 18	4	41 ± 14	4	262 ± 79	4	726 ± 175	5	976 ± 226	5	1044 ± 122	5	1076 ± 141	6
		2006-E	13 ± 4	4	48 ± 17	4	105 ± 47	4	209 ± 51	5	280 ± 55	5	.		.	
		2006-F	.		77 ± 35	4	136 ± 66	3 (1)	508 ± 167	5	470 ± 57	5	552 ± 211	5	917 ± 82	6
		2008	.		49 ± 23	5	177 ± 40	5	273 ± 63	6	220 ± 50	6	.		.	
		2009	24 ± 18	5	93 ± 40	5	63 ± 27	6	41 ± 14	6	.		.		.	
		2010	.		.		63 ± 27	6	.		.		.		.	
		2011	89 ± 28	6	99 ± 42	6	.		.		.		.		.	
		2012	66 ± 13	6	.		.	.	.		.		.		.	
		All cycles	42 ± 9	37	70 ± 11	40	149 ± 24	40	322 ± 44	42	422 ± 60	31	626 ± 97	19	787 ± 86	22
	Restored	Bois-des-Bel	8 ± 2	54	32 ± 4	58	44 ± 6	62	70 ± 14	60	339 ± 40	58	428 ± 65	46	.	

Coordinates of restored peatlands: Bois-des-Bel: 47°58′01″ N; 69°25′44″ W, Chemin-du-Lac: 47°45′50″ N; 69°31′32″ W, Kent: 46°18′40″ N; 65°08′32″ W, Maisonnette: 47°49′37″ N; 65°01′39″ W, Pokesudie: 47°48′48″ N; 64°46′20″ W, St-Charles: 46°44′53″ N; 70°59′44″ W, Ste-Marguerite: 48°48′16″ N; 72°10′24″ W, St-Modeste: 47°50′02″ N; 69°27′49″ W, Verbois: 47°50′28″ N; 69°26′37″ W.

harvested in basins, regressions were run to quantify the evolution of the *Sphagnum* biomass in function of the number of growing season(s) since the creation of basins. In that case, data coming from all production cycles and for all number of growing seasons were pooled together. Finally, one-way ANOVA were performed to compare the water table position in each production cycles (each basin) during the growing seasons of 2013 (using daily mean value). Following the ANOVAs, protected LSDs were run when a significant difference between production cycles was found. The GLM procedure in SAS software was used (SAS Statistical System software, v. 9.2, SAS Institute Inc., Cary, NC, USA). We have used a Bonferroni correction to set the α at 0.007 as 7 statistical tests have been performed simultaneously on a single data set for cover and biomass values and the α was set at 0.05 for the comparison of water table positions. All Cover of *Sphagnum* mosses after 1–4 year(s) and *Sphagnum* biomass after 1, 3 and 5 year(s) were square-root transformed prior to analyses.

Table 2
Mean ± SE annual water table position under *Sphagnum* moss surface in wells where water table was manually recorded. n represents the number of well in each production cycle. Numbers in parentheses represent the number of field visits for water table measurements for a given year. Mean was calculated for each well before doing a general annual mean. Gray fillings indicate that the production cycles didn't exist for a given year (cycle of 2001 was built in the 2006-C one and cycle of 2012 was built in the 2006-E one). A dot indicates that no water table measurements were made for after a given production cycle for a given year.

Production cycle	In 2007 (7) Mean ± SE	In 2008 (5) Mean ± SE	In 2009 (5) Mean ± SE	In 2010 (7) Mean ± SE	In 2011 (7) Mean ± SE	In 2012 (11) Mean ± SE	In 2013 (6) Mean ± SE	*n*
2006-A	−17 ± 3	4 ± 12	−12 ± 3	−26 ± 3	−8 ± 2	−20 ± 1	−13 ± 1	4
2006-B	−11 ± 2	−2 ± 4	2 ± 3	−9 ± 3	−2 ± 4	−3 ± 1	−1 ± 1	4
2006-C	−16 ± 4	−10 ± 3	−8 ± 5	−26 ± 5				4
2006-D	−8 ± 3	−5 ± 1	1 ± 3	−8 ± 2	0 ± 5	−5 ± 2	−5 ± 2	4
2006-E	−24 ± 2	−11 ± 3	−7 ± 3	−28 ± 4	−3 ± 5			4
2006-F	−17 ± 3	−4 ± 3	−2 ± 2	−10±2	3 ± 4	−5 ± 3	−6 ± 2	4
2008		.	.	−13±3	−7 ± 5	−9 ± 3	−6 ± 3	6
2009			.	−11±2	−9 ± 4	−5 ± 1	−3 ± 1	6
2010				.	6 ± 5	−8 ± 4	−5 ± 5	6
2011					−12 ± 5	−16 ± 2	−14 ± 2	4
2012						−15 ± 4	−16 ± 4	4

In 2007: one measurement was missing in one well for 2006-B, 2006-E cycles and all wells for 2006-F cycle.
In 2009: one measurement was missing in one well for 2006-B cycle.
In 2010: one measurement was missing in one well for 2009 cycle and in three wells for 2008 cycle.
In 2011: one measurement was missing in one well for 2008, 2009 and 2011 cycles and in all wells for 2010 cycle.

4. Results

4.1. Vegetation cover, biomass and productivity: all production cycles pooled by the number of years since the establishment

Sphagnum carpets developed from 13 ± 1% (mean cover ± SE everywhere) after one growing season to 67 ± 5%, after seven growing seasons, a mean increase of 9% per year (Fig. 2A). True mosses other than *Sphagnum* (mainly *Polytrichum strictum* Brid.) covered between 1 and 5%, depending of the number of growing seasons. In all cases, *Sphagnum* species from the *Acutifolia* subgenus (mainly *S. flavicomans*, *S. fuscum* and *S. rubellum*) composed the majority of the *Sphagnum* carpet (Fig. 3), followed by species of the *Sphagnum* subgenus (mainly *S. magellanicum* and *S. papillosum*). Species from the *Cuspidata* subgenus remained scarce. Likewise, *Sphagnum* biomass accumulated since the creation of *Sphagnum* basins augmented from 42 ± 9 g m^{-2} after one growing season to 787 ± 86 g m^{-2} after seven growing seasons

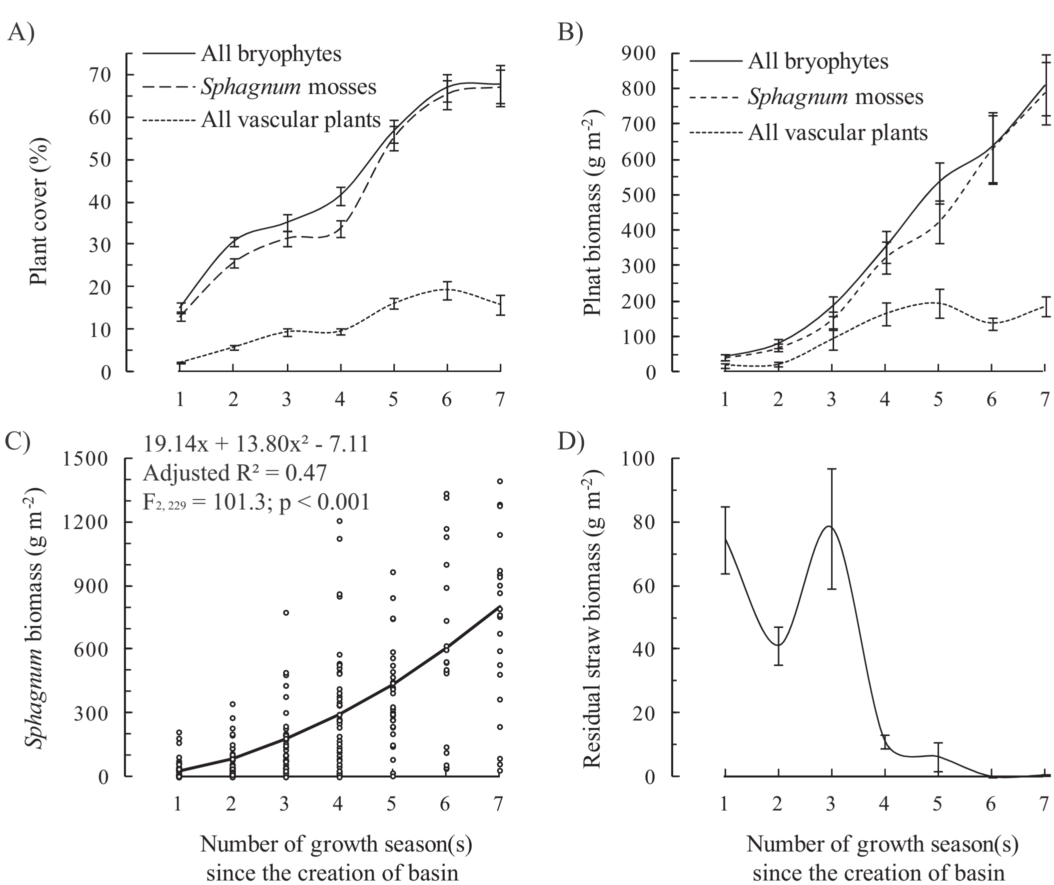

Fig. 2. The evolution of plant cover (%) and biomass (g m^2) accumulated since the creation of culture basins (A and B). The regression representing the relation between *Sphagnum* biomass (g m^{-2}) accumulated since the creation of culture basins in function of the number of growing seasons are represented in (C). Changes for the residual straw used for the protection of plant fragments at the reintroduction time (in g m^{-2}) are represented in (D). All values are expressed as mean ± SE. See Table 1 for *n* values.

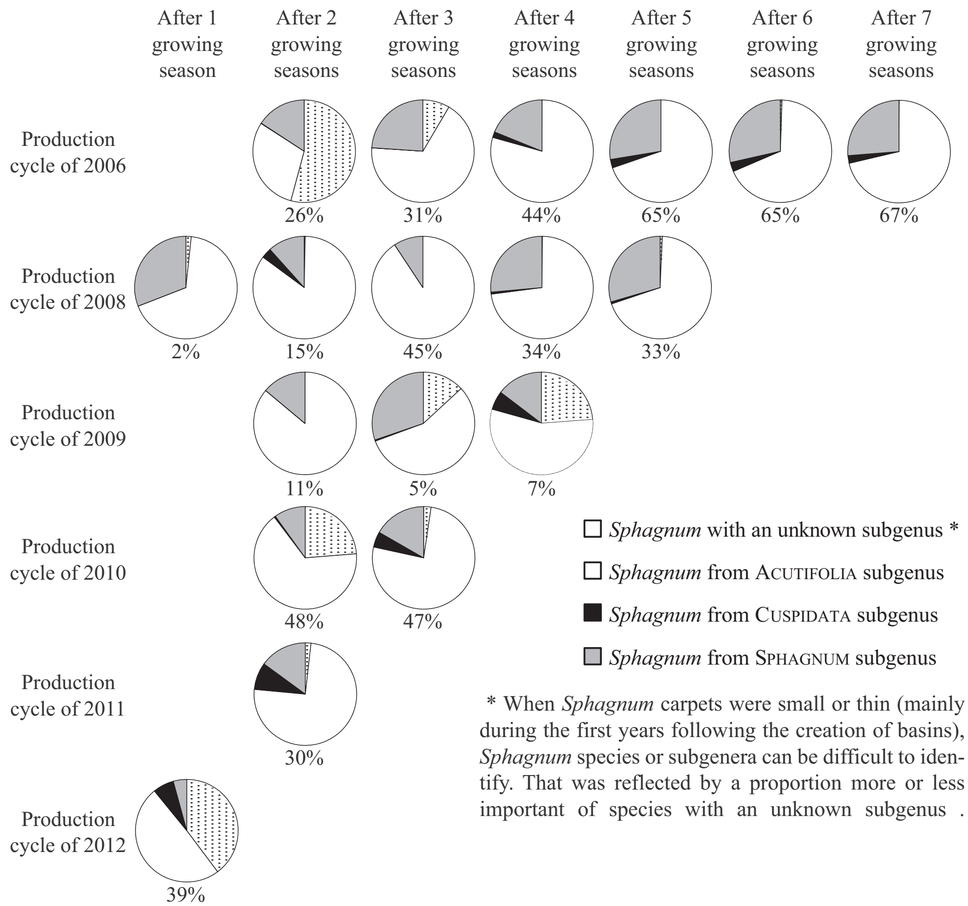

Fig. 3. Changes of the cover composition of the different subgenera of *Sphagnum* mosses through time since the creation of basins. Numbers under each circles represent the mean *Sphagnum* cover estimated for a given production basin after a given number of growing season(s). See Table 1 for *n* values.

(Fig. 2B) with an annual gain of biomass between 28 and 204 g m^{-2} depending of the year. The equation representing the best fit to quantify the evolution of *Sphagnum* biomass in function of number of growing seasons was: $y = 19.14x + 13.80x^2 - 7.11$ (adjusted $R^2 = 0.47$; $F_{1,229} = 101.3$; $p < 0.001$; Fig. 2C). *Sphagnum* productivity in the 2006 production cycles after six growing seasons was estimated at 155 ± 28 g m^{-2} yr^{-1}.

The abundance of the non-targeted vascular plants stayed relatively low during the first 7 growing seasons, passing from 2 ± 0% after 1 growing seasons to 16 ± 2% after seven growing seasons (Fig. 2A). Herbs, mainly *Eriophorum* and few *Carex* species, counted for the majority of vascular plant with a cover of 14 ± 2% after seven growing seasons. Ericaceous species counted for the rest (2 ± 0% after seven growing seasons). Vascular plant biomass increased from 20 ± 6 g m^{-2} after 1 growing season to 186 ± 29 g m^{-2} after seven growing seasons (Fig. 2B). Again, herb biomass was the most important (155 ± 29 g m^{-2} after 7 growing seasons). Finally, residual straw used to protect plant fragments during the first years following the creation of basins rapidly decreased over the years, passing from 74 ± 10 g m^{-2} after 1 growing season to almost zero (1 ± 0 g m^{-2}) after 7 growing seasons (Fig. 2D).

4.2. Vegetation cover and biomass: comparison of production cycles (basins) with equal time since the establishment

Cover values were significantly different between the production cycles after a given number of growing seasons since the basin creation, but biomass values were significantly different between cycles only after 4 and 5 growing seasons (Fig. 4, Table 1). After 3 growing seasons, *Sphagnum* cover and biomass differences between production cycles became more evident and some cycles performed better than others. The production cycle of 2009 was the worst compared to other cycles. The production cycle of 2006 had the best results with a constant augmentation of cover and biomass. However, cover and biomass of the 2006 production cycle varied among basins, indicating intra production cycle variability depending on the configuration (the leveling) of the basin. After 7 growing seasons, cycles 2006-D and 2006-F had a cover respectively 2.7 and 1.3 times higher than cycle 2006-A and cycle 2006-B (Fig. 4a, Table 1, see Fig. 1 for cycle location). Moreover, cycle 2006-D accumulated two times more biomass since the creation of basins than cycles 2006-A and 2006-B (Fig. 4b, Table 1).

4.3. Hydrology

The record of water table levels showed that water table depths were not similar between and within production cycles (Fig. 5). Level logger B in the cycle of 2010 showed the higher water table throughout the growing season of 2013, with a water table over the peat surface for more than 50% of the time, but differed from the 2 other level loggers in the 2010 cycle. Cycles of 2006-B, 2006-F, 2009 and level logger A in the 2010 cycle had similar trends of water table level variations (more than 50% of the time between 0 and −10 cm). Cycles of 2006-A, 2011 and 2012 formed another group with mean water table level around −15 cm. Cycle of 2006-D was the driest one (mean of −18 cm), but we suspect a trouble with the level logger as annual mean water table level recorded manually was similar to production cycles of 2006-B and 2006-F

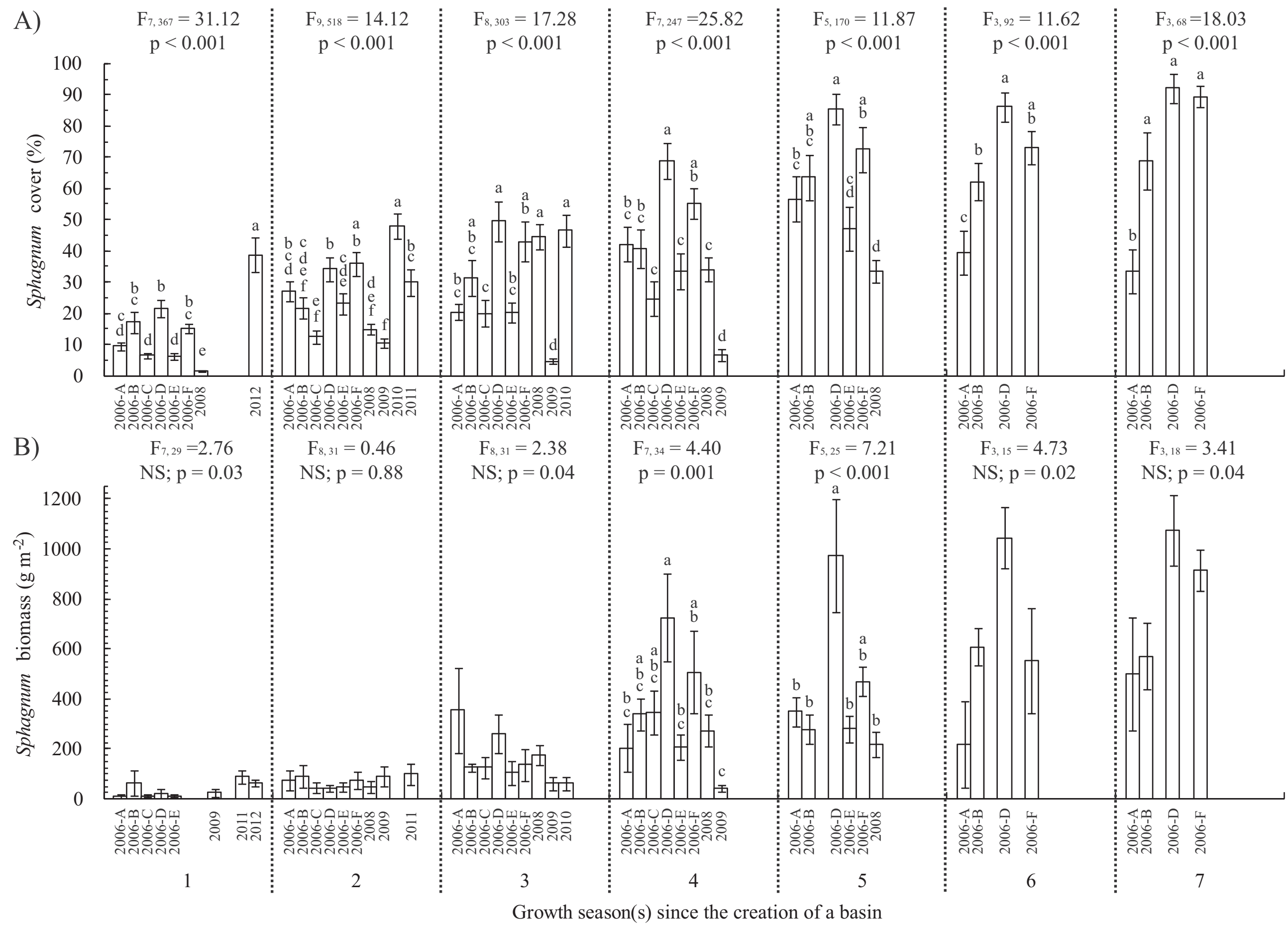

Fig. 4. Comparison of (A) *Sphagnum* covers (%) and (B) biomass (g m^{-2}) since the creation of culture basins after the same number of growing season(s). All values are expressed as mean ± SE. See Table 1 for *n* values. Letters indicate significant difference following a protected LSD tests (done for each number of growing season(s) separately). NS = not significant.

(see Table 2). In some cases, particularly for the production cycles of 2006-A, 2006-D and level logger A for 2010 cycle, water table was not really stable during the growing season (approximately equal frequency of water table level for many classes). Finally, water tables responded well to the precipitation as showed by a diminution of the water table depth following important rain events (showed for production cycles of 2006; Fig. 6), but variations of water table in the cycles of 2006-A and 2006-D were more important. Trends were similar for annual mean water table levels that were measured manually (Table 2). Production cycles of 2006-B, 2006-D, 2006-F and 2009 had the highest water tables year after year whereas cycles of 2006-A, 2006-C, 2006-E, 2011 and 2012 had the lowest ones.

4.4. Climate

When compared to norms and averages from 1981 to 2010, all the years studied fell within normal range for average temperatures over the growing seasons (between 14.2 and 15.9 °C vs. a norm of 14.9 ± 1.1 °C; Table 3). However, the first part of the growing season in 2006 (May–July) was 2.1 °C hotter than the norm (mean for the three months of 16.3 vs. 14.2 °C for the norm). The growing seasons 2011 and 2013 were significantly rainier than normal with respectively 168 and 242 mm more precipitation than average, all the other years except 2006 fit within the norm (±18 to 25 mm with the norm). The growing season of 2006 was slightly drier than the norm (44 mm less). Looking more specifically at the average precipitation values for the months of May and June, which corresponds to the most critical period for diaspores survival that were just introduced, we observed that months of May 2006, 2009, 2011, 2013 and June 2011, 2012 were especially rainy with over 110 mm of precipitation (between 30 and 72 mm more than normal) and were well distributed during the month as seen by the number of days with effective rainfall (>2 mm).

5. Discussion

Even if many small-scale experiments, at a scale where machines are not needed to reintroduce the moss material, showed that *Sphagnum* farming is a promising option in degraded peatlands (see for example Campeau and Rochefort, 2002 or Campeau et al., 2004 for Canada; Salinas and Cartes, 2009 for Chile; Gaudig, 2008 for Germany and Krebs, 2008 for Georgia), our *Sphagnum* experimental farm, established in eastern Canada, gave some insight that *Sphagnum* farming can be performed on large-scale and be operated mechanically in block-cut cutover bog after the cessation of peat harvesting activities. These results were comparable in terms of feasibility at large-scale basins done elsewhere (for example: Gaudig et al., 2012, 2014 for Germany).

5.1. Productivity in Sphagnum *farming basins: a comparison with ecological restoration options or natural peatlands*

In our studies, *Sphagnum* establishment and the development of *Sphagnum* carpet were faster than in mechanically restored sites (mean cover of 67% with a maximum of 92% at the farmed basins

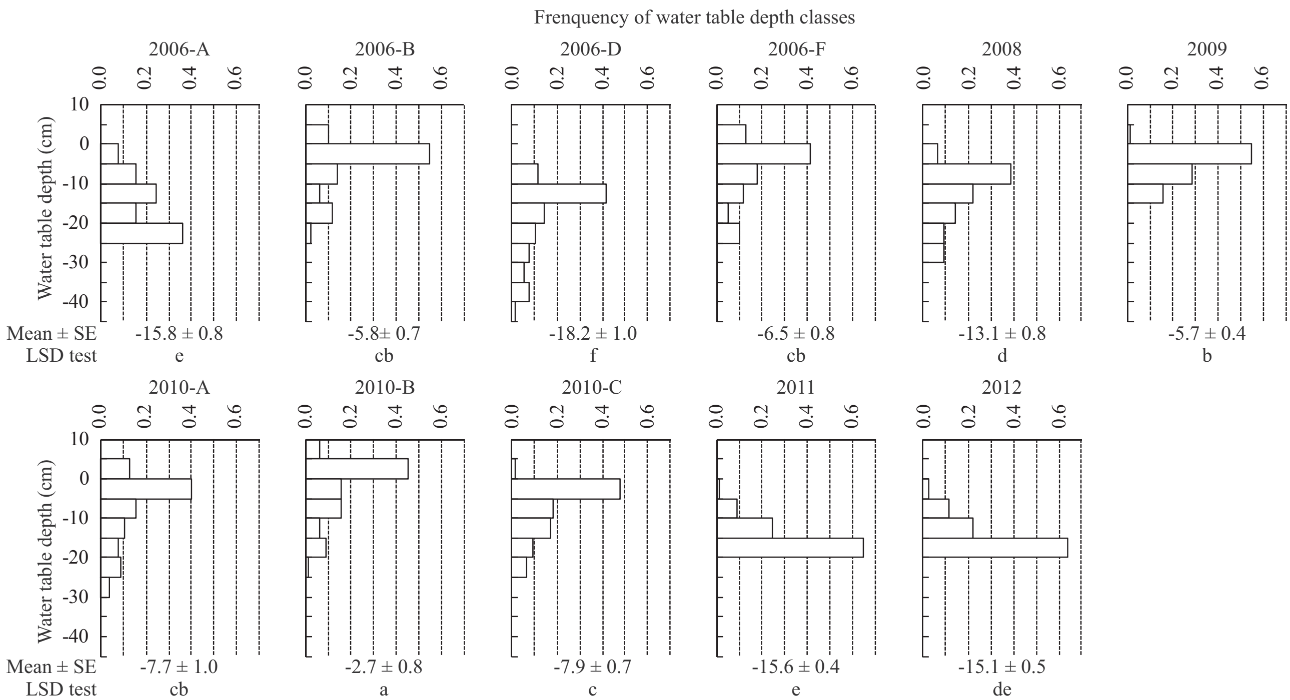

Fig. 5. Frequency distribution of water table during the 2013 growing seasons (from May 29th to August 13th). Water table values were recorded by automated level loggers. From one value recorded per hour, daily mean were calculated before analyses. Water table values were grouped into classes of 5 cm. $n = 77$ in all cases. Water table depths were significantly different among cycles ($p < 0.001$). Different letters indicate significant differences following a protected LSD tests done on mean values of water table depth.

vs. 32% with a maximum of 63% from different restored projects when compared after 7 seven growth seasons, see Table 1). This is slightly lower than the *Sphagnum* cover in natural bog (close to 80% in Rochefort et al., 2013). As for *Sphagnum* cover, the accumulation of biomass in culture basins was greater than in restored peatlands (mean of 626 vs. 428 g m^{-2} after 6 growing seasons, see Table 1). The estimation of *Sphagnum* productivity in the 2006 production cycles during a normal summer in terms of temperature and precipitation (see Table 3 for 2012) was similar to other estimation done at our whole-ecosystem field experiment of a restored cutover bog (155 g m^{-2} vs. a range of 105–179 g m^{-2} depending of the year; Andersen et al., 2013; Lucchese et al., 2010; PERG, unpublished data). Results in the *Sphagnum* farming experimental site included production cycles with poor performances in terms of *Sphagnum* cover and accumulated biomass since the creation of basins (as the 2009 cycle), but conditions seemed clearly better in some cases (as the 2006-D and 2006-F cycles), where *Sphagnum* mosses reached a cover of more than 90% after seven growing seasons with around 10 t/ha of dry *Sphagnum* biomass. This is probably due to a more constant and uniform input of water. As *Sphagnum* farming gave higher *Sphagnum* cover, biomass and similar productivity than peatland restoration projects and that *Sphagnum* biomass increased years after years in many production cycles all done mechanically, it can thus be considered as a potential option for reclamation in degraded peatlands. That is especially true if opportunities for the transformation for *Sphagnum* biomass can be generated in the region around *Sphagnum* farming basins.

In the context of *Sphagnum* farming, an invasion by flowering plants is not desirable, because *Sphagnum* biomass should not be contaminate by vascular plant seeds to ensure the quality of the final product. On the other hand, the colonization by certain vascular plants can be beneficial. Ericaceous species covers are similar in culture basins and in the restored peatland of Bois-des-Bel (cover of 14–15% after seven growing seasons; Rochefort et al., 2013). *Sphagnum* mosses benefit from a sparse canopy of ericaceous species (better microclimates and scaffolding to grow; Malmer et al., 1994, 2003; Pouliot et al., 2011). Furthermore, ericaceous shrubs are low growing species that can be easily clipped and removed just prior to *Sphagnum* harvest. However, high covers of herbs are not desirable in *Sphagnum* farming as they can produce a considerable amount of seeds and contaminate the *Sphagnum* biomass. Even if herbs can also be easily mowed periodically, their growth forms (many individual stems or tussocks) can be difficult to remove before *Sphagnum* harvest. Their growth must be overseen but, fortunately, herb cover after seven growing season was considerably lower in culture basins compared to the restored peatland of Bois-des-Bel (14% vs. 45%; Rochefort et al., 2013). Thus, even if after seven growing seasons, vascular plants were not a serious problem in *Sphagnum* farming, strategies to efficiently eradicate herbs from basins should be further investigated.

The performance of the *Sphagnum* farming basins in eastern Canada was slightly lower than similar experiments in Germany (average of 7.87 t ha^{-1} of dry *Sphagnum* biomass after seven growing seasons, mean of 1.12 t ha^{-1} yr^{-1} with an annual biomass gain between 0.08 and 2.01 t ha^{-1}). In *Sphagnum* farming basins similar to ours, also with a mechanical spreading of *Sphagnum* fragments but with a controlled irrigation, one and a half year after its establishment, *Sphagnum* mosses shown a cover of more than 90% with an average biomass accumulation of 0.80–1.85 t of dry mass ha^{-1} yr^{-1} depending of species (Joosten et al., 2013; Gaudig et al., 2014). On floating mats, *Sphagnum* biomass was between 2 and 4 t of dry mass ha^{-1} yr^{-1} depending of species (Joosten, 2010). In all cases, the access of water was better than in our basins. To optimize *Sphagnum* growth, these German *Sphagnum* farming sites were automated irrigated to a constant and chosen water table depth (close to the surface) or directly on an open water body for the floating mats. Consequently, the German team chose *Sphagnum* species with high growth rates but requiring a high water table (*S.*

Table 3
Average monthly temperatures (*T*), total monthly precipitation (Prec.) and monthly number of days with effective rainfall (more than 2 mm; days > 2 mm) for the growing seasons (May–September) during the years since the first production cycle was put in place (in 2006). The climate norms and averages (1981–2010) for those variables are also presented. The meteorological station used was the one at Bas-Caraquet (47°48″ N; 64°50″ W) for values at the Sphagnum farming experimental site and at Haut-Shippagan (47°45″ N; 64°46″ W) for climate norms and averages (Environment Canada, 2013a,b,b)

Year	Variable	May	June	July	August	Sept.	May-Sept.
2006	*T* (°C)	10.9	17.9	20.2	16.8	13.8	15.9
	Prec. (mm)	110	71	102	36	79	398
	Days > 2 mm	10	9	11	4	7	41
2007	*T* (°C)	8.7	14.0	18.9	17.0	13.6	14.4
	Prec. (mm)	50	75	106	109	96	433
	Days > 2 mm	5	6	10	10	6	37
2008	*T* (°C)	8.1	13.6	19.6	17.2	13.6	14.4
	Prec. (mm)	88	90	73	101	108	460
	Days > 2 mm	10	13	8	5	7	43
2009	*T* (°C)	8.7	14.1	16.9	19.2	13.9	14.6
	Prec. (mm)	140	85	107	41	50	423
	Days > 2 mm	10	9	12	8	6	45
2010	*T* (°C)	8.5[a]	14.3	20.0	18.1	13.6	15.0
	Prec. (mm)	84	100	51	18	164	417
	Days > 2 mm	11	12	8	4	9	44
2011	*T* (°C)	8.1	13.1	18.0	17.8	14.2	14.2
	Prec. (mm)	152	123	136	93	106	610
	Days > 2 mm	11	10	6	11	5	43
2012	*T* (°C)	9.8	14.5	18.9	19.9	14.4	15.5
	Prec. (mm)	78	110	70	114	93	466
	Days > 2 mm	7	8	6	14	6	41
2013	*T* (°C)	9.5	14.0	19.2	17.9	13.8	14.9
	Prec. (mm)	143	97	157	81	207	684
	Days > 2 mm	11	8	8	7	10	44
1981–2010	*T* (°C)	8.8 ± 1.5	15.0 ± 1.2	18.7 ± 1.0	18.0 ± 0.8	14.2 ± 1.2	14.9 ± 1.1
	Prec. (mm)	80	77	92	121	73	442
	Days > 2 mm	–	–	–	–	–	–

[a] Data were missing for 10 days in the month. For the calculation of the average temperature for the growing season, the data was replaced by the historical average (1981–2010) of the month with missing data (1981–2010).

fallax (Klinggr.) Klinggr., *S. palustre* L. and *S. papillosum*) contrary to us (mainly species from *Acutifolia* subgenus with low growth rates but able to grow with lower water tables). Also, in this region, *Sphagnum* mosses can grow all year long as the snow cover is almost inexistent, contrary to eastern Canada, where growing season lasts around eight months. Thus, in the eastern Canada context (presence of cold and snowy winter) *Sphagnum* farming gave encouraging results after seven growing seasons in terms of *Sphagnum* carpet development and biomass accumulation. However, improvements can definitively be obtained by a better control of hydrology.

5.2. The control of the hydrology: a step forward

The variation among production cycles despite using identical techniques could be explained by the passive control of water availability. Although excess water was drained from the basin, water was not pumped into basins in case of water deficit. That means that water table levels varied according to weather and were not stable throughout the growing season as is necessary to maximize *Sphagnum* growth. Climatic conditions were within norms during the study interval and probably did not have a great influence on the final results in these *Sphagnum* basins. Notwithstanding, during a year without water limitations, such as 2013, water table levels measured between and within basins were significantly different. In some cases, basins with high cover and biomass accumulation (as the 2006-B and 2006-F) and another with bad cover and biomass (cycle of 2009) showed similar water table fluctuations. Another one (cycle of 2012) had a low water table level most of the time and the cover after one year, taken after a normal year in terms of temperature and precipitation, gave promising results. Water table levels in *Sphagnum* farming basins were thus extremely variables, but other factors than the water table levels could influence the yields in *Sphagnum* farming basins.

5.3. Other factors influencing the Sphagnum biomass accumulation

Residual peat and plant fragment quality as well as the basin leveling could all affect the water tables levels and the *Sphagnum* biomass accumulation. First, the residual peat properties (such as bulk density, decomposition level or fiber content) or the level of peat compaction in basins considerably alter the pore structure in peat, resulting with changes in water storage capacity and hydraulic conductivity of peat (Price et al., 2003). That, as well as the ditch condition, can influence the water table level by altering the water movement within production cycles and explain a part of the differences between production cycles. Secondly, the quality of plant fragments (length of *Sphagnum* stems and depth of collection) can have an effect on *Sphagnum* establishment (Campeau and Rochefort, 1996). So, the choice of the donor site for each production cycle as well as the reintroduced layer of plant fragments (Quinty and Rochefort, 2003) can potentially have changed the establishment rates of *Sphagnum* mosses. Even if we have tried to have similar donor site for each production cycle, small differences in the species composition in the reintroduction plant material can also have an influence on the basin yields.

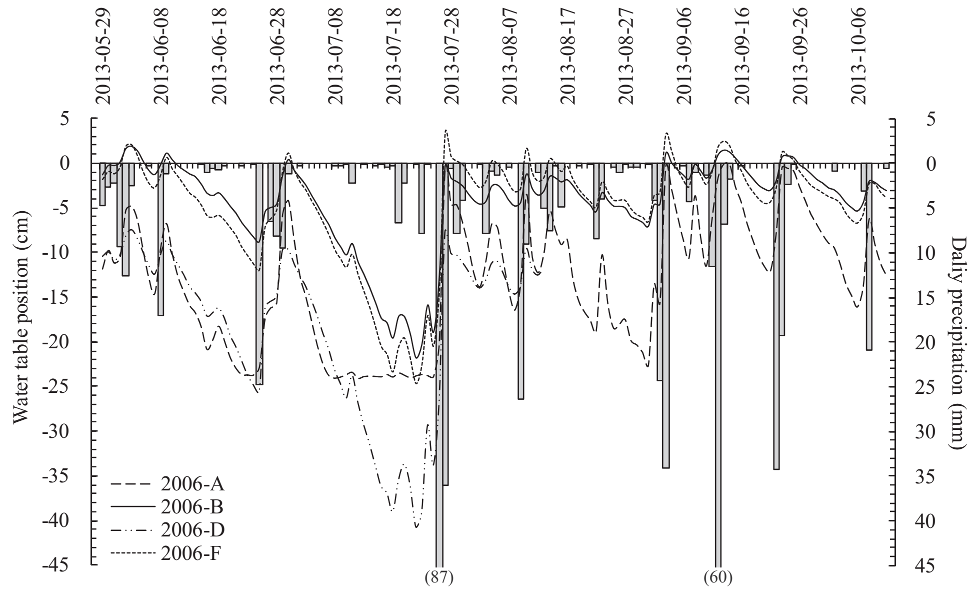

Fig. 6. Changes of water table depth during the 2013 growing season in the remaining production cycles started in 2006. Water table values were recorded by automated level loggers. From the one value recorded per hour, the daily mean was calculated before analyses. Data were recorded from May 29th to October 11th excepted for the 2006-D cycle (until August 13th). For two days, the daily precipitation exceeded 45 mm and the real amount was noted in parenthesis.

Thirdly, basins were often leveled when the soil surface is still frozen to support the weight of the machinery. As the ice melted, some depressions may have been formed depending on the remaining frost depth at the time of basin creation. These depressions created a microtopography inside basins with slightly different water table level which thus affected *Sphagnum* growth. The control of all these factors associated with an automated control of water table level is thus needed to diminish the variation of water accessibility for *Sphagnum* mosses between and within production cycles.

5.4. What are the options to favor for the future of Sphagnum *farming?*

Some challenges have to be considered before scaling up to an operational level of a *Sphagnum* farm. The first and most important challenge is the improvement of water table level control. The success or failure of a *Sphagnum* farming basin is closely linked to climate during the first years after *Sphagnum* moss introduction and that can permanently influence *Sphagnum* growth (Chirino et al., 2006). The worst results among all production cycles seen for the 2009 cycle can be explained by this reason as the summers of 2009 and 2010 had lower summer precipitation than the mean for 1981–2010 (see Table 3) and the annual water table level in 2010 was the lowest for this cycle (see Table 2). The inclusion of an automated irrigation system in a *Sphagnum* farming site would allow the addition or the removal of water in the basins depending on weather conditions (flooding or droughts) and thus, overcome a potential climatic effect. The water table level could thus be maintained at an optimal growth level for monocultures of a particular *Sphagnum* species or *Sphagnum* subgenus and to avoid invasion by vascular plants or algae. A second challenge is in the design of the basins as to allow mechanical *Sphagnum* harvesting, drainage ditch maintenance and sufficient water supply for optimal *Sphagnum* growth. The idea of designing a basin with a central ditch would make the *Sphagnum* harvest easier as it would be possible to scrape the *Sphagnum* biomass from the center to the edges of the basin without risk of ditch filling. On the other hand, peripheral edge ditches appears easier to maintain. Another design to supply water within the basins could be by underground pipes connected to the pumping system. This would both facilitate ditch maintenance and the *Sphagnum* biomass harvest. A third challenge is in the flat leveling of basins as to reduce the water table level variation within a given basin (for example with a surveyor optical level). Improving the design of the basins should increase the biomass yields closer to the values obtained in other *Sphagnum* farming systems where water supply and distribution is better controlled (as in Germany: Blievernicht et al., 2011; Joosten et al., 2013) and will allow a more constant production of *Sphagnum* biomass, which is imperative in a commercial context.

At the moment, the prediction of the ideal number of years after which the *Sphagnum* biomass should be harvested is difficult. However, our results indicate that after seven years, the biomass accumulation (mainly from the *Acutifolia* subgenus) still showed a steady increment. This indicates that the decomposition of the newly formed *Sphagnum* fibers could be still limited. Eventually, the estimation of the time needed to reach a condition where the formation of new fibers will significantly slowed down by the loss of material by decomposition (when a plateau will be present in the biomass accumulation curve) will be crucial to determine the interval between the biomass harvests. In addition, tests are needed with different *Sphagnum* species from subgenera of interest for *Sphagnum* farming (*Acutifolia* and *Sphagnum* subgenera) in a way to increase yields into basins.

6. Conclusion

Sphagnum farming is still at its beginning and the continuity of research in this area is crucial for several reasons. First, *Sphagnum* farming reduces the human pressure on the remaining natural peatlands in the surroundings areas by providing renewable *Sphagnum* biomass with multiple possible uses. Second, the development of partnerships with local companies able to transform the raw material coming for *Sphagnum* farming basins into other products such as pots and growing substrate or with companies using *Sphagnum* biomass as shipping material would create new niche markets. Finally, the *Sphagnum* farming could diversify the activities and incomes of peat companies.

Our research demonstrated that *Sphagnum* farming is feasible on a large-scale basis even without active irrigation control in block-cut cutover bog after the cessation of peat harvesting activities. However, even if abandoned block-cut sites are common in regions where peat harvesting activities are located, the feasibility of *Sphagnum* farms in post vacuum-harvesting sites have to be considered and small scale trials are in progress (APTHQ, pers. comm.). Also, studies on the synergy between better water supply through irrigated *Sphagnum* culture basins and composition or structure of the moss carpet as well as with emissions of greenhouse gas or vascular plant presence and abundance are warranted in this new field of research.

Acknowledgments

Financial support was provided by the Natural Sciences and Engineering Research Council of Canada, the Ministry of Natural Resources and Energy of New Brunswick, the Canadian Sphagnum Peat Moss Association and its members. We thank all the field assistants that helped at the *Sphagnum* farming experimental site, but also in the laboratory as well as all members of the Peatland Ecology Research Group. Special thanks to Martha D. Graf for her constructive comments and English revision on earlier drafts of the manuscript. Special thanks also goes to Mathieu Quenum, scientific director for Peat, Peatlands & Sustainable Development in the Coastal Zones Research Institute Inc. and other members of this institute for their help on the field.

References

Andersen, R., Pouliot, R., Rochefort, L., 2013. Above-ground net primary production from vascular plants shifts the balance towards organic matter accumulation in restored *Sphagnum* bogs. Wetlands 33, 811–821.

Andrus, R.E., Wagner, D.J., Titus, J.E., 1983. Vertical zonation of *Sphagnum* mosses along hummock-hollow gradients. Can. J. Bot. 61, 3128–3139.

Andrus, R.E., 1986. Some aspects of *Sphagnum* ecology. Can. J. Bot. 64, 416–426.

Blievernicht, A., Irrgang, S., Zander, M., Ulrichs, C., 2011. Produktion von torfmoosen (*Sphagnum* sp.) als torfersatz im erwerbsgartenbau. Gesunde Pflanze 62, 125–131 (In German).

Campeau, S., Rochefort, L., 1996. Sphagnum regeneration on bare peat surfaces: field and greenhouse experiments. J. Appl. Ecol. 33, 599–608.

Campeau S., Rochefort L., 2002. Possibilities and limits to Sphagnum farming. In: Schmilewski G., et Rochefort, L. (eds.). Proceedings of the International Peat Symposium: Peat in horticulture-Quality and environmental challenges. A joint symposium of Commission II (Industrial utilization of peat and peatlands) and Commission V (After-use of cut-over peatlands) of the International Peat Society. Pärnu, Estonia, 3–6 September 2002. Jyväskylä, Finland: International Peat Society, 2002. p. 264–269.

Campeau S., L. Miousse, F. Quinty, 2004. Caractérisation du site expérimental de Shippagan et techniques suggérées dans un but de recherche sur la production de fibre de sphaigne. Bryophyta Techonologie Inc. Saint-Charles-de-Bellechasse, Québec, Avril 2004. Campeau S., Rochefort L., Price J.S, 2004. On the use of shallow basins to restore cutover peatlands: Plant establishment. Restoration Ecology 12: 471482.

Caron, J., Rochefort, L., 2013. Use of peat in growing media: state of art on the industrial and scientific effort envisioning sustainability. ISHS Acta HorticultureProceedings of the International Symposium on Responsible Peatland Management and Growing Media Production, 982. , pp. 15–22.

Chirino, C.C., Campeau, S., Rochefort, L., 2006. *Sphagnum* establishment on bare peat: the importance of climatic variability and *Sphagnum* species richness. Appl. Veg. Sci. 9, 285–294.

Clymo, R.S., Hayward, P.M., 1982. The ecology of Sphagnum. In: Smith, A.J.E. (Ed.), Bryophyte Ecology. Chapman and Hall, London, UK, pp. 229–289.

Coulson, J.C., Butterfield, J., 1978. An investigation of the biotic factors determining the rates of plant decomposition on blanket bog. J. Ecol. 66, 631–650.

Emmel, M., 2008. Growing ornamental plants in Sphagnum biomass. ISHS Acta HorticultureProceedings of the International Symposium on Growing Media, 779. , pp. 173–178.

Environment Canada. 2013. Daily Data for Bas-Caraquet meteo station. Available at http://climate.weather.gc.ca/advanceSearch/searchHistoricDataStations_e.html?searchType=stnName&timeframe=1&txtStationName=bas-caraquet&searchMethod=contains&optLimit =yearRange&StartYear=1840&EndYear=2013&Year=2013=yearRange&StartYear=ps2#EndYear=&Year=2013&Month=8&Day=11&selRowPerPage=25&cmdStnSubmit=Recherche (accessed on September 13.09.13).

Environment Canada. 2013. Canadian climate normals 1981–2010 Available at http://climate.weather.gc.ca/climate_normals/index_e.html (Accessed on 13.09.13).

Gaudig, G., 2008. Sphagnum farming in progress–experiences and perspective. The 13th International Peat Congress: After Wise Use – The Future of Peatlands, Tullamore, Ireland, June, pp. 168–171.

Gaudig, G., Gahlert, F., Krebs, M., Prager, A., Schulz, J., Wichmann, S., Joosten, H., 2012. Sphagnum farming in Germany – 10 years on the road to sustainable growing media. The 14th International Peat Congress: Peatlands in Balance, Stockholm, Sweden, June Extended abstract No. 374.

Gaudig, G., Fengler, F., Krebs, M., Prager, A., Schulz, J., Wichmann, S., Joosten, H., 2014. *Sphagnum* farming in Germany – a review of progressMires and Peat 13. . Art. 8 http://mires-and-peat.net/pages/volumes/map13/map1308php.

González, E., Henstra, S.W., Rochefort, L., Bradfield, G.E., Poulin, M., 2013. Is rewetting enough to recover Sphagnum and associated peat-accumulating species in traditionally exploited bogs? Wetlands Ecol. Manage doi:http://dx.doi.org/10.1007/s11273-013-9322-6.

Graf, M.D., Bérubé, V., Rochefort, L., 2012. Restoration of peatlands after peat extraction: impacts, restoration goals, and techniques. In: Vitt, D.H., Bhatti, J.S. (Eds.), Restoration and Reclamation of Boreal Ecosystems. Cambridge University Press, Cambridge, United-Kingdom, pp. 259–280.

Grosvernier, P., Matthey, Y., Buttler, A., 1997. Growth potential of three *Sphagnum* species in relation to water level and peat properties with implications for their restoration in cut-over bogs. J. Appl. Ecol. 34, 471–483.

Ilomets, M., 1982. The productivity of Sphagnum communities and the rate of peat accumulation in Estonian bogs. In: Masing, V. (Ed.), Peatland Ecosystems. Estonian Contribution to the International Biological Programme, Tallinn, pp. 102–116 No 9.

Jobin, P., Caron, J., Rochefort, L., 2014. Developing new substrate with Sphagnum fibers. Can. J. Soil Sci (submitted).

Johnson, L.C., Damman, A.W.H., 1993. Decay and its regulation in *Sphagnum* peatlands. Adv. Bryol. 5, 249–296.

Joosten, H.1998. Peat as a renewable resource: the road to paludiculture. In: Peatland Restoration and Reclamation. Proceedings of the 1998 International Peat Symposium, pp. 56–63.

Joosten H., 2010. Abschlussbericht Verbundprojekt Torfmooskultivierung auf schwimmenden Vegetationsträgern für ein nachhaltiges und umweltfreundliches Torfsubstitut im Erwerbsgartenbau, Teilvorhaben Torfmooskultivierung auf überstauten Hochmoorflächen. Institut für Botanik und Landschaftsökologie, Ernst-Moritz-Arndt Universität Greifswald. 166 p. (In German).

Joosten H., Tapio-Biström M.L., Tol S., 2012. Peatlands-guidance for climate change mitigation through conservation, rehabilitation and sustainable use. Mitigation of climate change in agriculture (MICCA) programme. Food and Agriculture Organization of the United Nations.

Joosten H., Gaudig G., Krebs M. 2013. Peat-free growing media: Sphagnum biomass. Peatlands international 1/2013: 28–31.

Kleinebecker, T., Hölzel, N., Vogel, A., 2007. Gradients of continentality and moisture in South Patagonian ombrotrophic peatland vegetation. Folia Geobotanica 42, 363–382.

Krebs, M., 2008. Perspectives of Sphagnum farming in the Kolkheti lowland (Georgia): first results. The 13th International Peat Congress: After wise use – The future of peatlands, Tullamore, Ireland, June, pp. 172–174.

Landry, J., Martinez, C., Rochefort, L., 2011a. The use of fungicide Nova to mitigate infection of *Sphagnum* by parasitic fungi in the greenhouse. Botany 89, 655–661.

Landry, J., Pouliot, R., Gaudig, G., Wichmann, S., Rochefort, L., 2011b. Sphagnum farming workshop in the Canadian Maritimes: international research efforts and challenges. Peatlands Int. 2, 28–33.

Lucchese, M., Waddington, J.M., Poulin, M., Pouliot, R., Rochefort, L., Strack, M., 2010. Organic matter accumulation in a restored peatland: evaluating restoration success. Ecol. Eng. 36, 482–488.

Malmer, N., Svensson, B.M., Wallén, B., 1994. Interactions between Sphagnum mosses and field layer vascular plants in the development of peat-forming systems. Folia Geobotanica 29, 483–496.

Malcolm, J.E., 1996. Relationships Between Sphagnum Morphology and Absorbency of Commercial Sphagnum board. MSc. Thesis. Department of Botany, University of Alberta, Edmonton, Canada, pp. 199.

Malmer, N., Albinsson, C., Svensson, B.M., Wallén, B., 2003. Interferences between *Sphagnum* and vascular plants: effects on plant community structure and peat formation. Oikos 100, 469–482.

McCarter, C., Price, J.S., 2012. Ecohydrology of Sphagnum moss hummocks: mechanisms of capitula water supply and simulated effects of evaporation. Ecohydrology 7, 33–44.

Picard, H., 2010. Établissement D'espèces de Sphaignes Dans un Contexte de Production de Biomasse. MSc. Thesis. Université Laval, Quebec City, Canada, pp. 124 (in French).

Poulin, M., Rochefort, L., Quinty, F., Lavoie, C., 2005. Spontaneous revegetation of mined peatlands in eastern Canada. Can. J. Bot. 83, 539–557.

Pouliot, R., Marchand-Roy, M., Rochefort, L., Gauthier, G., 2010. Estimating moss growth in arctic conditions: a comparison of three methods. Bryologist 113, 322–332.

Pouliot, R., Rochefort, L., Karofeld, E., Mercier, C., 2011. Initiation of *Sphagnum* moss hummocks in bogs and the presence of vascular plants: is there a link? Acta Oecol. 37, 346–354.

Pouliot, R., Hogue-Hugron, S., Rochefort, L., 2012. Site expérimental de culture de sphaigne à Shippagan au Nouveau-Brunswick: Rapport d'activités 2003–2011. Groupe de recherche en écologie des tourbières, Université Laval, pp. 57 (in French).

Pouliot, R., Hogue-Hugron, S., Rochefort, L. 2013. La culture de sphaignes, une deuxième vie pour les tourbières commerciales. ACFAS, 81st congress (Quebec City) (In French).

Price, J., Rochefort, L., Quinty, F., 1998. Energy and moisture considerations on cutover peatlands: surface microtopography, mulch cover and *Sphagnum* regeneration. Ecol. Eng. 10, 293–312.

Price, J.S., Healthwaite, A.L., Baird, A.J., 2003. Hydrological processes in abandoned and restored peatlands: an overview of management approaches. Wetlands Ecol. Manage. 11, 65–83.

Querner, E.P., Jansen, P.C., van den Akker, J.J.H., Kwakernaak, C., 2012. Analysing water level strategies to reduce soil subsidence in Dutch peat meadows. J. Hydrol. 446–447, 59–69.

Quinty, F., Rochefort, L., 2003. Peatland restoration guide. Canadian *Sphagnum* Peat Moss Association and New-Brunswick. Department of Natural Resources and Energy, Québec, Québec, Canada, pp. 106.

Reinikainen, O., Korpi, J., Tahvonen, R., Näkkilä, J., Silvan, N., Silvan, K., 2012. Harvesting of Sphagnum biomass and its use as a growing medium constituent. Proceedings of The 14th International Peat Congress (Stockholm, Sweden), No. 137, International Peat Society, Jyväskylä, Finland.

Robert, E.C., Rochefort, L., Garneau, M., 1999. Natural revegetation of two block-cut mined peatlands in eastern Canada. Can. J. Bot. 77, 447–459.

Rochefort, L., Vitt, D.H., Bayley, S.E., 1990. Growth, production, and decomposition dynamics of *Sphagnum* under natural and experimentally acidified conditions. Ecology 71, 1986–2000.

Rochefort, L., Bastien, D., 1998. Réintroduction de sphaignes dans une tourbière exploitée et abandonnées: évaluation de divers moyens de protection contre la dessiccation. Écoscience 5, 117–127 (In French).

Rochefort, L., 2001. Restauration écologique. In: Payette, S., Rochefort, L. (Eds.), Écologie des Tourbières du Québec-Labrador. Les presses de l'Université Laval, Quebec City, Canada, pp. 449–504 (In French).

Rochefort L., Lode E., 2006. Restoration of degraded boreal peatlands. In: Wieder R. K., Vitt D.H. (Eds.), Boreal peatland ecosystems, pp. 381–423. Ecological Studies, Vol. 188. Springler-Verlag, Berlin Heidelberg.

Rochefort, L., Isselin-Nondedeu, F., Boudreau, S., Poulin, M., 2013. Comparing survey methods for monitoring vegetation change through time in a restored peatland. Wetlands Ecol. Manage. 21, 71–85.

Rydin, H., McDonald, A.J.S., 1985. Tolerance of *Sphagnum* to water level. J. Bryol. 13, 571–578.

Rydin, H., 1993. Mechanisms of interactions among *Sphagnum* species along water-level gradients. Adv. Bryol. 5, 153–185.

Rydin, H., Gunnarsson, U., Sundberg, S.2006. The role of Sphagnum in peatland development and persistence. In: Wieder, R. K. & Vitt, D. H. (eds.), Boreal peatland ecosystems, pp. 47–65. Ecological Studies, Vol. 188. Springler-Verlag, Berlin Heidelberg.

Salinas M., Cartes F., 2009. Uso manejo y protección del musgo Sphagnum. Proyectos de innovación en la XI región de Aysén. Experiencias de Innovación para el Emprendimiento Agrario. Fundación para la innovación agraria. ISBN N°978-956-328-049-4.

Silvan, N., 2008. Sphagnum biomass production in cut-away peatlands as an after-use alternative, Sphagnum biomass production in cut-away peatlands as an after-use alternative. In: Korhonen, R., Korpela, L., Sarkkola, S. (Eds.), Finland–Fenland. Maahenki Ltd Finnish Peatland Society, Finland, pp. 230–233.

Vitt, D.H., Pakarinen, P., 1977. The bryophyte vegetation, production and organic components of Truelove Lowland. In: Bliss, L.C. (Ed.), Truelove Lowland, Devon Island, Canada: A High Arctic Ecosystem. University of Alberta Press, Edmonton, pp. 225–244.