Characteristics of Eastern Canadian cultivated Sphagnum and potential use as a substitute for perlite and vermiculite in peat-based horticultural substrates

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SUMMARY

Sphagnum cultivation on harvested peatlands to meet wetland restoration objectives could be an economically feasible activity since cultivated Sphagnum has potential horticultural applications. We compared the characteristics of cultivated Sphagnum from Shippagan (Canada) with those of non-cultivated Sphagnum products from Chile, New Zealand and Canada, and assessed its potential as a perlite and vermiculite substitute in horticultural peat-based substrates. Shippagan cultivated Sphagnum was shorter than the Chilean and New Zealand products with which it was compared, yet more similar to them than to the Canadian product currently on the market. Laboratory tests on physical properties and greenhouse growth trials indicated that 50–100 % of the perlite or vermiculite of a peat-based substrate can be successfully replaced with cultivated Sphagnum. Non-sieved coarsely shredded Sphagnum or the large (> 6.3 mm) fragments of sieved coarsely shredded Sphagnum best replicated the aeration provided by perlite and vermiculite in the substrates that were tested. Decomposition tests and comparisons of changes in physical properties of substrates containing Sphagnum after six weeks of growth trials indicated that Sphagnum degradation leading to reduced substrate performance is not likely to be an issue. Therefore, cultivated Sphagnum has great potential as a substitute for perlite and vermiculite.

KEY WORDS: air porosity; plant growth; Sphagnum fragment size; substrate component; water retention

INTRODUCTION

In Eastern Canada, Sphagnum cultivation is considered a potential second economic use for peatlands from which peat is currently being extracted (Landry & Rochefort 2010), in accordance with the International Peat Society *Strategy for Responsible Peatland Management* (Clarke & Rieley 2010). The reasoning is that commercial Sphagnum cultivation on peatlands harvested for peat could provide livelihoods for people and communities engaged in peat extraction once the peat deposits are exhausted, while respecting Canadian wetland conservation objectives and regulations. The re-introduction of Sphagnum on harvested peatlands is commonly practised as part of restoration procedures developed and applied over the last 20 years in Canada (Campeau & Rochefort 2002, Quinty & Rochefort 2003). Sphagnum cultivation for commercial production purposes, however, is still at the experimental stage in Canada (Campeau & Rochefort 2002, St-Arnaud *et al.* 2008, Pouliot *et al.* 2012) as well as in Europe (Gaudig 2008, Krebs 2008, Reinikainen *et al.* 2012, Gaudig *et al.* 2014). In Eastern Canada, experimental Sphagnum cultivation on harvested peatlands was first attempted in 2004 on a small scale in Shippagan, New Brunswick. Over time, this small experimental site has shown promising results, warranting the creation of larger scale experiments (Pouliot *et al.* 2012). Thus, in order to encourage and justify continued efforts to improve production methods, we found it pertinent to investigate potential uses for cultivated Sphagnum from an Eastern Canadian perspective. Note that, throughout this article, "Sphagnum" refers to non-decomposed mosses of the *Sphagnum* genus and "peat" to partly decomposed plant parts, mostly of Sphagnum, that slowly accumulate under the live layer of vegetation in Eastern Canadian peatlands.

Generally, dried Sphagnum is used as-is in various horticultural applications. The best-known use is as a substrate for the cultivation of orchids (Emmel 2008). Other applications include: as a liner for planted hanging baskets, as a growth substrate in living or green walls, as a mulch for potted plants, as packaging for storing and shipping plants, and as a component of horticultural substrates. Water retention is paramount in these applications, but Sphagnum stem length is also an important characteristic for orchid cultivation and plant packaging applications involving root wrapping. Yet it is the combination of water retention and aeration capacity of Sphagnum that makes it so interesting for horticultural applications. The coarse size and elongated shape of Sphagnum are favourable to the creation of macropores that effectively enable gas diffusivity (Caron *et al.* 2005), whether the moss is used as-is or as a component of a horticultural substrate. Hypothesising that the capacity of Sphagnum to provide aeration could be similar to that of perlite and vermiculite, we investigated how Sphagnum could be used, once shredded and sieved, as a perlite and vermiculite substitute in peat-based horticultural substrates. Perlite and vermiculite are commonly used in such substrates to maintain optimal aeration and drainage; yet they are expensive, non-renewable imported resources. Having the option to replace them in part, or entirely, with a locally produced renewable resource would be of great interest to the horticultural peat industry.

Much of the Sphagnum sold on the market today comes from New Zealand, Australia, Chile, China or the United States of America (USA) and is not cultivated in the sense that we intend, i.e. grown in controlled hydraulic conditions, but harvested from “natural” bogs (Buxton *et al.* 1996, Whinam & Buxton 1997, Esposito 2000, Diaz *et al*. 2008, Diaz & Silva 2012, TDPPWE 2013). Therefore, we also investigated how cultivated Sphagnum from Shippagan compares to Sphagnum products that are already found on the market.

METHODS

Cultivated Sphagnum harvesting and processing

We harvested Sphagnum in December 2012 from a field at the Shippagan experimental Sphagnum farm that was sown in 2004. The ground was partially frozen and we scraped off a 5–15 cm layer of live Sphagnum from a layer of ice with shovels and rakes (Figure 1, top row). The Shippagan farm is located in north-eastern New Brunswick, Canada (47° 40′ N, 64° 43′ W). The sowing process used at the farm was that generally used for peatland restoration in Eastern Canada and is described in Quinty & Rochefort (2003), St-Arnaud *et al.* (2008), Landry & Rochefort (2010) and Pouliot *et al.* (2012). The field contains a variety of Sphagnum species, but *Sphagnum rubellum* and *Sphagnum magellanicum* are the dominant species, contributing more than 85 % of the yearly biomass production (Landry & Rochefort 2010). Any herbaceous vegetation present, mostly leaves and stems of *Eriophorum virginicum*, was harvested along with the Sphagnum. The Sphagnum was spread out indoors on wooden pallets covered with fine mesh screens and left to dry in ambient air conditions (Figure 1, middle row).

Sphagnum for the perlite and vermiculite replacement experiment was shredded with a Worx WG430 13 amp electric leaf mulcher/shredder designed for household use (Figure 1, bottom row). Shredded Sphagnum was then sieved in batches in a sieve shaker with mesh size 150 µm, 2.36 mm, 3.35 mm, 4.75 mm, 6.3 mm, 9.5 mm and 19 mm sieves (Figure 1, bottom row). Note that, because of their elongated shape, Sphagnum fragments can pass through a sieve even if they are longer than the width of the openings. Mesh size is, therefore, not a good indication of the length of the fragments trapped within the sieve. Sieve contents were combined to create three classes of fragment size: small (collecting pan and 150 µm), medium (2.36, 3.35 and 4.75 mm) and large (6.3, 9.5 and 19 mm). The non-Sphagnum fragments were left in with the Sphagnum.

Comparison of cultivated Sphagnum with existing Sphagnum products

We compared cultivated Sphagnum from Shippagan with five retail products available on the Canadian market (Table 1) according to length, proportion of non-Sphagnum plant debris, water retention, pH and electrical conductivity. Sphagnum products, including Shippagan cultivated Sphagnum, were re-hydrated with distilled water. For length estimation, three small samples of each product were taken. Non-Sphagnum material was sorted from Sphagnum fragments, counted and weighed as a whole. Sphagnum fragments were individually counted and measured then weighed as a whole, except for “Lambert floral moss”, from which it was impossible to separate the Sphagnum as individual strands. Three more samples of each product were taken to estimate water holding capacity. These were loosely packed in 7.7 cm diameter cylinders with mesh screen bottoms and submitted to a 72/48 hours saturation cycle. The cylinders were slowly submersed to the brim in a bath of distilled water, from the bottom up, and left to soak for 72 hours, after which they were removed from the bath and left to drain for two hours, returned to the bath and left to soak for another 48 hours, then weighed after draining freely for two hours to determine wet mass M_w. The samples were then dried at 60 °C for 24 hours and weighed again (dry mass M_d). Water holding capacity WHC (g g^{-1}) was calculated as the mass of water retained per unit dry mass:

Figure 1. Top row: cultivated Sphagnum harvesting at the Shippagan experimental farm; middle row: air drying of cultivated Sphagnum; bottom row: shredder and sieves used for Sphagnum processing.

Table 1. Sphagnum products with which Shippagan cultivated Sphagnum was compared.

Product	Brand name	Distributor
Grade A Chilean Sphagnum Moss 150 g	Millenniumsoils Coir Division of Vgrove Inc.	AgroGreen Canada
Floral moss 11 litres	Tourbières Lambert Inc.	Home Hardware
Premium New Zealand Highly Compressed Sphagnum Moss 100 g	Spagmoss (Besgrow)	Lee Valley
Brick Pack Premium New Zealand Sphagnum Moss 150 g	Spagmoss (Besgrow)	Just Moss Canada
New Zealand Sphagnum Moss 1.31 litres	Zoo Med	Pets and Ponds.Com (Critter Cove Pet Centre Inc.)

$$WHC = \frac{M_W - M_d}{M_d} \qquad [1]$$

Finally, another three samples were taken to estimate pH and electrical conductivity. One-way analyses of variance and Dunnett's *t*-tests were conducted on water retention, pH and electrical conductivity data at alpha = 0.05 using IBM SPSS Statistics 21.

Sphagnum as a replacement for perlite and vermiculite in peat-based horticultural substrates

Sphagnum decomposition rate

In order to ascertain whether Sphagnum was likely to decompose over time in a substrate, thus potentially affecting its water retention and aeration properties (Prasad & O'Shea 1999, Prasad & Maher 2004, Prasad & Maher 2008, Nieminen & Reinikainen 2011), we conducted a decomposition trial (Lemaire 1997). The decomposition rate of Sphagnum in a peat-based substrate under greenhouse growth conditions was assessed according to fragment size. Four classes of fragment were tested: small (< 2.36 mm), medium (2.36–6.3 mm), large (> 6.3 mm) and non-sieved. Mesh bags measuring 5 × 6 cm and containing approximately one gram of cultivated Sphagnum from each of the above fragment classes were dried for 24 hours at 60 °C and weighed. They were then buried in six-inch (15.2 cm diameter) pots of commercial all-purpose peat-based substrate (Rochefort *et al.* 1990, Johnson & Damman 1991, Waddington *et al.* 2003) (Figure 2). There were twelve bags of each fragment class, for a total of 48 pots. The pots were positioned randomly on a growth table in six rows of eight pots. They were hand watered as needed, but not fertilised. Six bags of each fragment class were removed, dried and weighed again after six weeks, then replaced in their pots. All bags were removed, dried and weighed after 12 weeks. Decomposition values were expressed as percent of mass lost (Rochefort *et al.* 1990, Waddington *et al.* 2003). Data were compared through a one-way analysis of variance at alpha = 0.05.

Optimal Sphagnum size and amount

Twelve variants of the all-purpose substrate "TH-1" from Theriault & Hachey Peat Moss Ltd. (Baie Ste-Anne, NB) (Table 2) were assessed, as well as eight variants of the high porosity substrate "Mix 4" from Sungro Horticulture Canada Ltd. (Lamèque, NB) (Table 3), in order to select two promising variants of each product for growth trials. The main component of these commercially produced substrates is peat but they also contain perlite (and vermiculite in the case of "TH-1"), lime, wetting agent and fertiliser. Batches of "TH-1" and "Mix 4" were prepared replacing none, half or all of the usual amount of perlite and/or vermiculite with cultivated Sphagnum. Variants of "TH-1" were prepared with perlite and vermiculite replaced with cultivated Sphagnum to the following extents:

(1) 100 % perlite, 0 % vermiculite;
(2) 50 % perlite, 0 % vermiculite; and
(3) 100 % perlite, 100 % vermiculite.

As "Mix 4" does not contain vermiculite, the replacement amounts in this case were:

(1) 100 % perlite; and
(2) 50 % perlite.

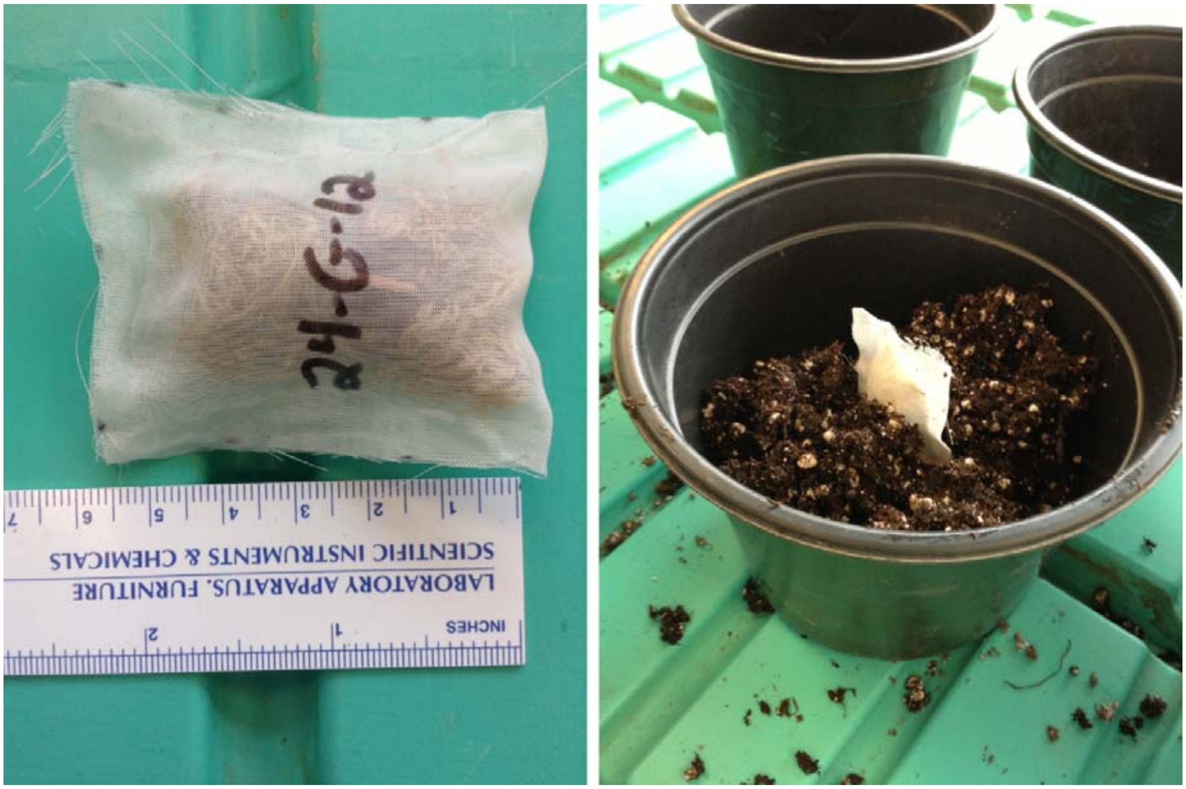

Figure 2. Mesh bags of Sphagnum buried in all-purpose peat-based substrate for the decomposition trial.

Table 2. Substrates tested in the perlite and vermiculite substitution by Sphagnum experiment on the all-purpose peat-based horticultural substrate "TH-1". The substrate labelled #13 is "TH-1" and is used as the control.

Substrate	**Sphagnum fragment**	**Perlite replacement by Sphagnum (%)**	**Vermiculite replacement by Sphagnum (%)**
1	small	100	0
2	small	50	0
3	small	100	100
4	medium	100	0
5	medium	50	0
6	medium	100	100
7	large	100	0
8	large	50	0
9	large	100	100
10	non-sieved	100	0
11	non-sieved	50	0
12	non-sieved	100	100
13	-	0	0

Table 3. Substrates tested in the perlite substitution by Sphagnum experiment on the high-porosity peat-based horticultural substrate "Mix 4". The substrate labelled # 9 is "Mix 4" and is used as the control.

Substrate	Sphagnum fragment	Perlite replacement by Sphagnum (%)
1	small	100
2	small	50
3	medium	100
4	medium	50
5	large	100
6	large	50
7	non-sieved	100
8	non-sieved	50
9	-	0

Furthermore, four Sphagnum fragment size classes were used in the experiment: small (< 2.36 mm), medium (2.36–6.3 mm), large (> 6.3 mm) and non-sieved. The proportion of lime was adjusted to reach target pH, but the amounts of all other components were the same as in the unmodified products.

The following characteristics of each variant were compared to those of the original product: saturated hydraulic conductivity, container capacity, total porosity, air porosity, available water and easily available water. Hydraulic conductivity is a measure of the capacity of the substrate to let water flow through (Fonteno 1993, Bures *et al.* 1997). Container capacity is the maximum amount of water that the substrate can hold within a specific container (White & Mastalerz 1966). Total porosity is the proportion of the substrate that is comprised of pores. Air porosity is the amount of air that the substrate can hold at container capacity (Fonteno & Harden 2003). Available water refers to the proportion of water in a substrate that can be extracted by a plant. Easily available water is the amount of water that is readily extractable (de Boodt & Verdonck 1972).

Three samples of each substrate were placed in four-inch (10.2 cm diameter) horticultural pots and saturated according to the following procedure. Pots were carefully filled to the inside lip (6 cm depth) with the same amount of substrate (± 1 g) between pots of the same substrate, without compacting the substrate. They were then slowly immersed from the bottom up to the brim in a bath of distilled water and left to soak for 24 hours, after which they were removed from the bath and left to drain for two hours. Pots were carefully topped up to the inside lip to compensate for shrinkage, then replaced in the bath and left to soak for another 72 hours to ensure complete saturation of the substrate. They were taken directly from the saturation bath to undergo saturated hydraulic conductivity (K_{sat}) measurements.

K_{sat} was estimated by measuring the flow of water running through the potted samples under steady-state conditions. Samples were placed on a permeable platform in a container of distilled water with an overflow located below the top of the sample (Figure 3) as described by Caron *et al.* (1997). A steady flow of water was applied to the top of the sample and this flow was adjusted until the level of water above the substrate became stable. Once steady-state conditions were attained, water pouring from the overflow of the enclosing container was collected with a graduated cylinder. The volume of water collected during ten seconds was recorded until five consecutive identical measures were obtained.

As derived from Darcy's law (Allaire *et al.* 1994),

$$K_{sat} = \frac{Q}{S} * \frac{dz}{dH} \qquad [2]$$

where K_{sat} is the saturated hydraulic conductivity (cm s^{-1}), Q is the flow rate (cm^3 s^{-1}), S is the cross-sectional area of the pot (cm^2) and dH/dz is the hydraulic gradient (cm cm^{-1}) (Figure 3). Results were not corrected for container geometry or restriction from the pot base, as only relative values were required. Precision was ensured through careful sample preparation, as already described.

After the K_{sat} measurements, the pots were left to drain for two hours, weighed, and placed on tension tables for volumetric water content measurements based on mass at 10, 20, 50 and 100 cm of water suction following general procedures described by Topp *et al.* (1993) and Caron *et al.* (1997). The pots were weighed and shrinkage measured after each stabilisation period: 24 hours at 10 cm of suction, 24 hours at 20 cm, 48 hours at 50 cm and 48 hours at 100 cm. Afterwards, the contents were dried at 105 °C for 24 hours, weighed again to determine dry mass M_d, incinerated at 550 °C for 16 hours and re-weighed to determine the mass of residual ashes M_a. Container capacity (Θ_{cc}) (cm^3 cm^{-3}) and volumetric water content Θ_h (cm^3 cm^{-3}) at 10, 20, 50 and 100 cm of water suction (Θ_{-10}, Θ_{-20}, Θ_{-30}, Θ_{-50}, Θ_{-100}) were calculated according to the following formulae adapted from Caron *et al.* (1997):

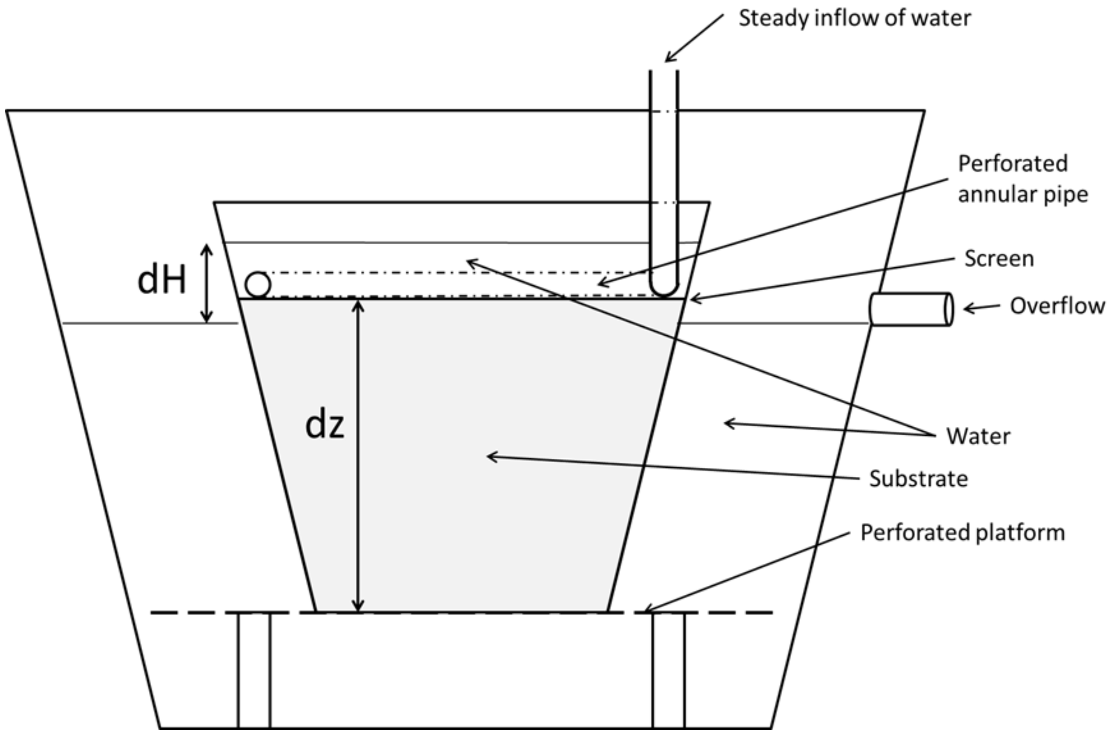

Figure 3. Set-up for saturated hydraulic conductivity measurements.

$$\theta_{cc} = \frac{M_{wd} - M_d}{\rho_{water} * V_t} \quad [3]$$

$$\theta_h = \frac{M_{wh} - M_d}{\rho_{water} * V_t} \quad [4]$$

where M_{wd} is wet sample mass (g) after two hours of free drainage following saturation, M_{wh} is wet sample mass at a given water column height (suction) h (cm), ρ_{water} is the density of water (g cm^{-3}) and V_t (cm^3) is total sample volume. Total porosity (Θ_d) (cm^3 cm^{-3}), as determined by incineration, was calculated from bulk density ρ_{bd} and solid density ρ_{sd} (both in g cm^{-3}) (Caron *et al.* 1997, Parent 2001) as follows:

$$\theta_d = 1 - \frac{\rho_{bd}}{\rho_{sd}} \quad [5]$$

where

$$\rho_{bd} = \frac{M_d}{V_t} \quad [6]$$

and

$$\rho_{sd} = \frac{1}{\frac{F}{\rho_{peat}} + \frac{(1-F)}{\rho_{rock}}} \quad [7]$$

with ρ_{peat} = 1.55 g cm^{-3}, ρ_{rock} = 2.65 g cm^{-3} and the organic matter fraction F (g g^{-1}) calculated as:

$$F = \frac{M_d - M_a}{M_d} \quad [8]$$

Air porosity is the difference between total porosity and container capacity (Θ_d - Θ_{cc}) (cm^3 cm^{-3}). Available water is the difference between container capacity and an assumed permanent wilting point of 100 cm of suction (Θ_{cc} - Θ_{-100}) (cm^3 cm^{-3}) (de Boodt & Verdonck 1972, Caron *et al.* 1997), and easily available water is the difference between container capacity and an assumed temporary wilting point of 50 cm of suction (Θ_{cc} - Θ_{-50}) (cm^3 cm^{-3}) (de Boodt & Verdonck 1972). One-way analyses of variance and Dunnett's *t*-tests were conducted on saturated hydraulic conductivity, container capacity, total porosity, air porosity, available water and easily available water at alpha = 0.05.

Growth trials

Petunias (*Petunia* × *hybrida*) were used in the trial of the two selected variants of "TH-1", whereas *Impatiens walleriana* plants were used for the "Mix 4" trial. Plantlets were purchased from a commercial grower and transplanted into four-inch horticultural pots. For each trial, the pots were randomly positioned in 20 rows of five pots. There were three pots per tested substrate variant, six repetitions, 18 control pots of the commercial substrate and 46 border pots, giving a total of 100 pots. Plants were manually watered as needed. To produce good growth, petunia plants were fed weekly with a 24N : 8P : 16K fertiliser solution of 1 ml L^{-1}, while impatiens plants were fed with a 20N: 8P: 20K fertiliser solution of 1 ml L^{-1} one and three weeks after planting. Growth was monitored for a period of six weeks. After this time, the above-ground biomass was harvested and dried at 105 °C for 24 hours for dry mass determination. Container capacity, total porosity, air porosity, available water and easily available water were determined for all experimental pots according to the previously described procedure, with roots left intact in the pots. One-way analyses of variance were conducted on above-ground biomass dry mass data and after-trial container capacity, available water, easily available water, total porosity and air porosity. Before-trial and after-trial container capacity, available water, easily available water, total porosity and air porosity were compared using paired *t*-tests, two-way within-between analyses of variance on means and one-way analyses of variance on change at alpha = 0.05.

RESULTS

Characteristics of cultivated Sphagnum compared to existing Sphagnum products

Cultivated Sphagnum from Shippagan was shorter than other products, with 75 % of fragments from 0.5 to 5 cm, 21 % from 5.5 to 10 cm, and 4 % from 10.5 to 15 cm (Figure 4). Note that the length of "Lambert floral moss" was not quantified because it was impossible to separate as individual strands. The length distribution of Shippagan farm Sphagnum was most similar to that of New Zealand "Spagmoss100" and Chilean "Milleniumsoils" (Figure 4).

Shippagan farm Sphagnum retained 25 times its dry mass of water. This is significantly more than "Lambert floral moss" and not significantly different from "Millenniumsoils" and "Spagmoss150". It is, however, significantly less than "Zoo med" and "Spagmoss100" (Figure 5a).

The proportion of non-Sphagnum material was higher in Shippagan farm Sphagnum compared to other products at 3 % saturated mass, except for "Lambert floral moss" (Figure 5b). Finally, Shippagan farm Sphagnum had an average pH of 4.2, which is lower than other tested products except for "Lambert floral moss" (Figure 5c), and an average electrical conductivity of 145 µS cm^{-1}, higher than that of the other products (Figure 5d).

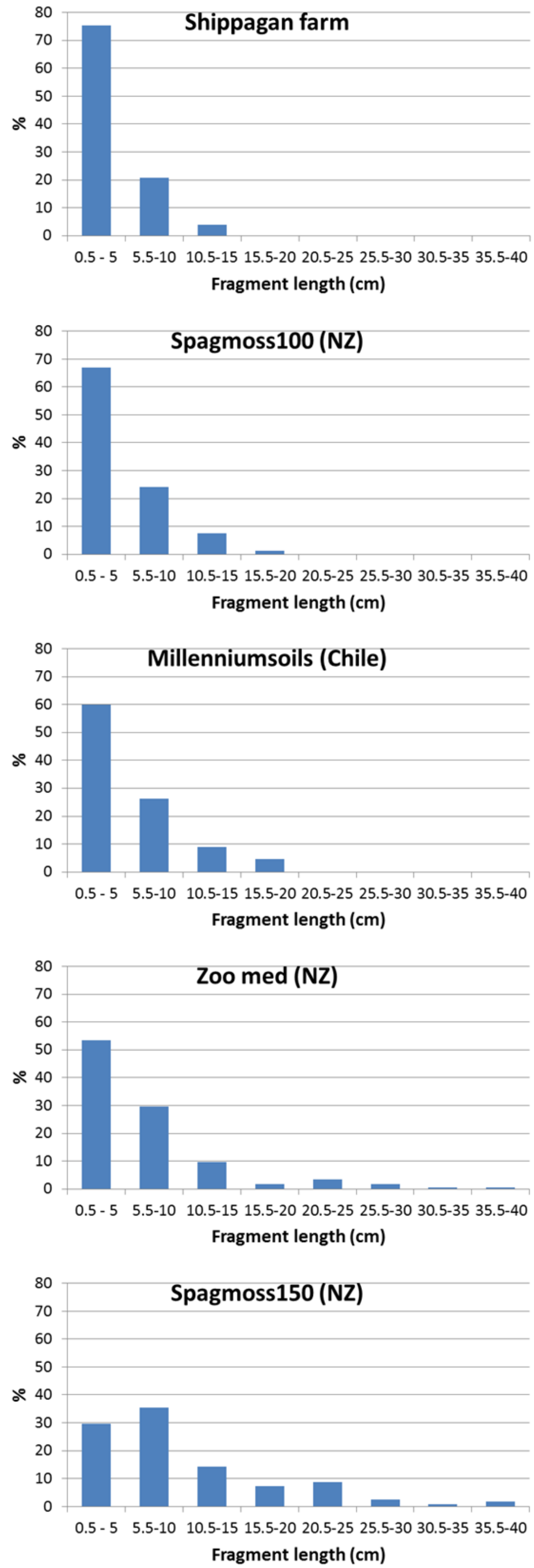

Figure 4. Estimated fragment length distributions of four Sphagnum products and Shippagan farm Sphagnum.

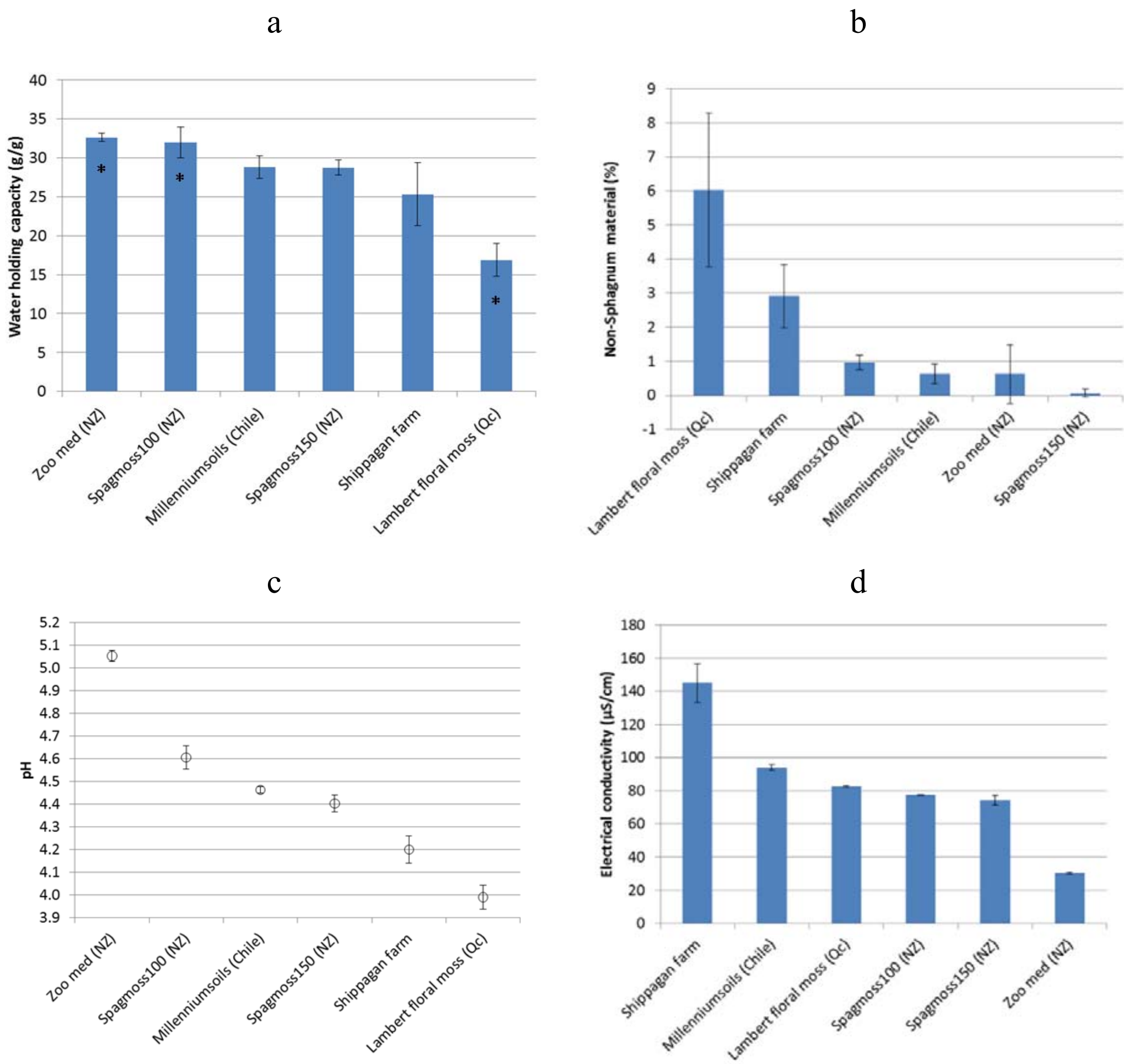

Figure 5. Comparison of five Sphagnum products (Table 1) and Shippagan farm Sphagnum with regard to: (a) water holding capacity (water mass/Sphagnum dry mass), * denotes significantly different from Shippagan farm (Anova, Dunnett's t-test, alpha 0.05); (b) estimated proportion of non-Sphagnum material based on weight at saturation; (c) estimated pH; and (d) estimated electrical conductivity. Error bars show ± standard deviation, $n = 3$.

Performance of Sphagnum as a replacement for perlite and vermiculite in peat-based substrates

Sphagnum decomposition over time under greenhouse growth conditions

The decomposition of the Sphagnum buried in peat-based substrate and exposed to greenhouse growth conditions for 12 weeks was low with an average mass loss of 4 %. No significant differences were observed between fragment types for the samples tested after six weeks and 12 weeks (Figure 6).

Effect of Sphagnum size and amount on physical properties of substrates

Replacing the perlite and vermiculite in "TH-1" with Sphagnum tended to reduce saturated hydraulic conductivity, especially with the small and medium Sphagnum fragments (Figure 7). It tended to increase total porosity, but only substrate #12 (100 % perlite and 100 % vermiculite replacement with non-sieved fragments) had a total porosity that was significantly higher than that of the control (#13). Air porosity was seemingly reduced, although substrate #1 (100 %

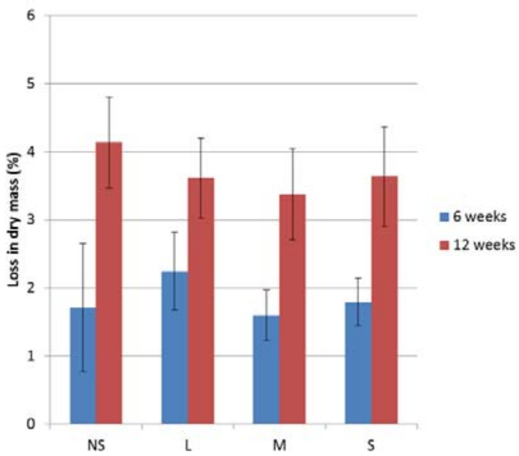

Figure 6. Decomposition of Sphagnum over time according to fragment type (NS = non-sieved, L = large (> 6.3 mm), M = medium (2.36–6.3 mm), S = small (< 2.36 mm)). The left-hand bar of each pair is for six weeks and the right-hand bar for 12 weeks. Error bars show ± standard deviation, $n = 6$ at six weeks and $n = 12$ at 12 weeks.

perlite and 0 % vermiculite replacement with small fragments) was the only substrate to exhibit a significantly lower air porosity than the control. Large and non-sieved fragments provided better air porosity than other fragment types. The replacement of perlite and vermiculite with Sphagnum tended to increase container capacity, although only substrate #1's container capacity was significantly higher than that of the control. It also tended to increase available water and easily available water (Figure 7). Substrates #5 (50 % perlite and 0 % vermiculite replacement with medium fragments), #7 (100 % perlite and 0 % vermiculite replacement with large fragments) and #10 (100 % and 0 % replacement with non-sieved fragments) were the only treatments to exhibit no significant differences from the control for all variables measured (Figure 7). Based on physical characteristics, large and non-sieved Sphagnum fragments seemed a better option than small and medium fragments. Although 100 % perlite and 0 % vermiculite replacement may best reproduce the properties of the original recipe, we opted for testing 100 % perlite and 100 % vermiculite replacement. Therefore, substrates #9 (100 % perlite and 100 % vermiculite replacement with large fragments) and #12 were selected for the "TH-1" growth trial.

Variants of "Mix 4" tended to have a higher saturated hydraulic conductivity, total porosity, container capacity, available water and easily available water than the original recipe (#9), but lower air porosity (Figure 8). Large and non-sieved fragments seemed to provide better air porosity than other fragment types in this case as well. Only substrates #2 (50 % perlite replacement with small fragments), #4 (50 % perlite replacement with medium fragments) and #6 (50 % perlite replacement with large fragments) were not significantly different from the control for all measured variables (Figure 8). We opted for testing substrates #6 and #8 (50 % perlite replacement with non-sieved fragments) in growth trials because of the performance of large and non-sieved fragments and because 100 % replacement of perlite overly modified physical properties as compared to the control.

Greenhouse performance of selected substrate variants containing cultivated Sphagnum

Based on dry mass of above-ground biomass of plants harvested after six weeks, substrates with Sphagnum seemed to perform better than the "TH-1" and "Mix 4" controls, but the differences were not statistically significant (Figures 9 and 10). In addition, there was no significant difference in biomass gain of petunias or impatiens between large and non-sieved Sphagnum fragments.

After six weeks of use, no significant differences in container capacity, available water, easily available water, total porosity and air porosity were observed between the "TH-1" control, "TH-1" with 100 % perlite and 100 % vermiculite replacement with large Sphagnum fragments (TH-1-L), and "TH-1" with 100 % perlite and 100 % vermiculite replacement with non-sieved Sphagnum fragments (TH-1-NS), nor between the "Mix 4" control, "Mix 4" with 50 % perlite replacement with large Sphagnum fragments (Mix 4-L), and "Mix 4" with 50 % perlite replacement with non-sieved Sphagnum fragments (Mix 4-NS).

Within substrates, available water, easily available water and total porosity tended to decrease after six weeks. For "TH-1" substrates, before and after differences were only significant for available water of TH-1-L and TH-1-NS, easily available water of TH-1 and TH-1-L, and total porosity of TH-1-L and TH-1-NS (Figure 11). For all "Mix 4" substrates, total porosity was the only variable that significantly decreased within substrates after six weeks of use (Figure 12). Generally, substrates did not behave differently over time. Differences in changes were not detected between "TH-1" substrates, except for easily available water of TH-1-NS decreasing less than did that of the "TH-1" control. No differences in changes were detected between "Mix 4" substrates for any of the measured water retention and porosity indicators.

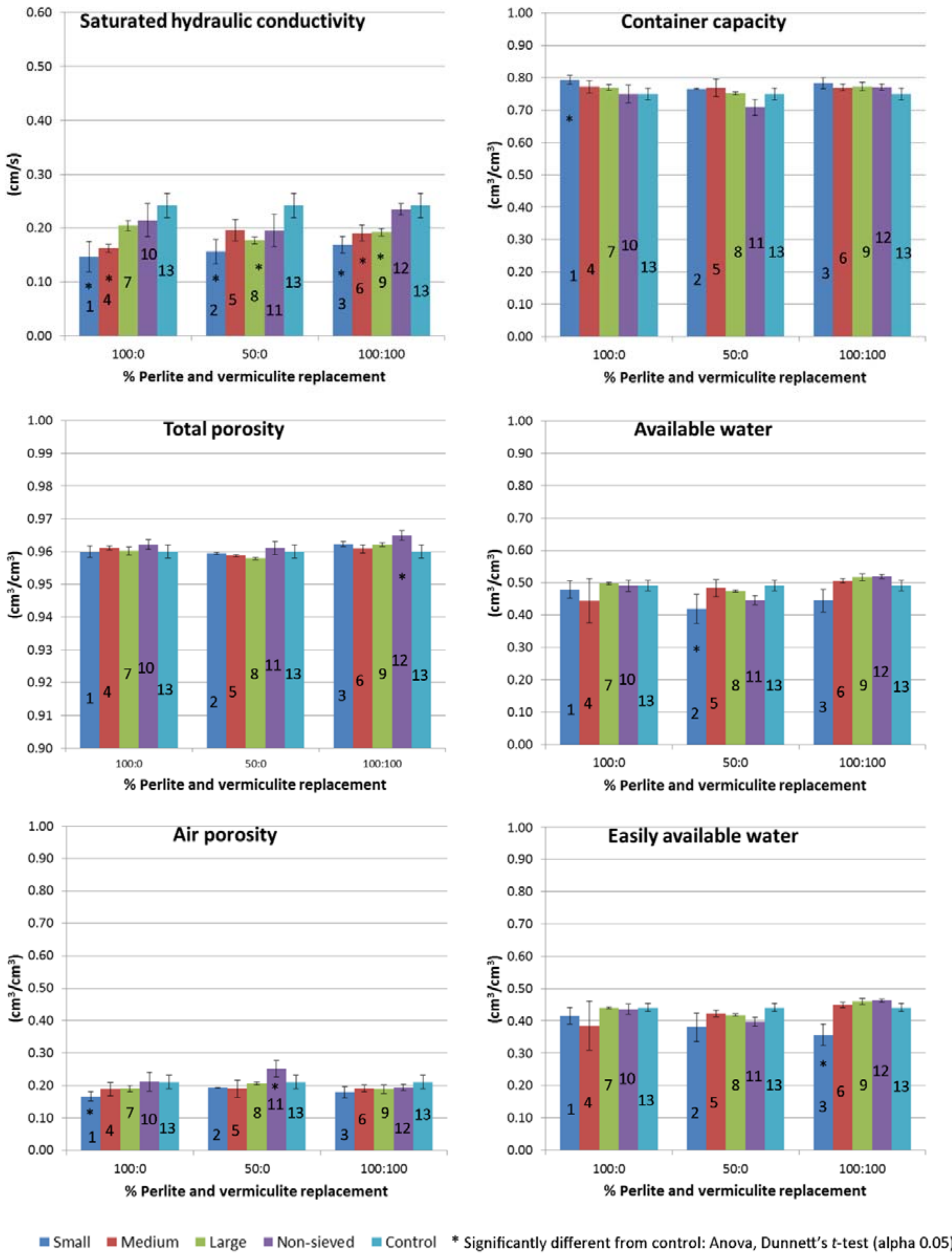

Figure 7. Estimated hydraulic conductivity, total porosity, air porosity, container capacity, available water and easily available water of 12 variants (three ratios of perlite and vermiculite replacement and four types of Sphagnum fragments) as listed in Table 2 and original TH-1 substrate (control) in four-inch pots. Note that the zero on the vertical axis for total porosity is suppressed. Bars show ± standard deviation, $n = 3$.

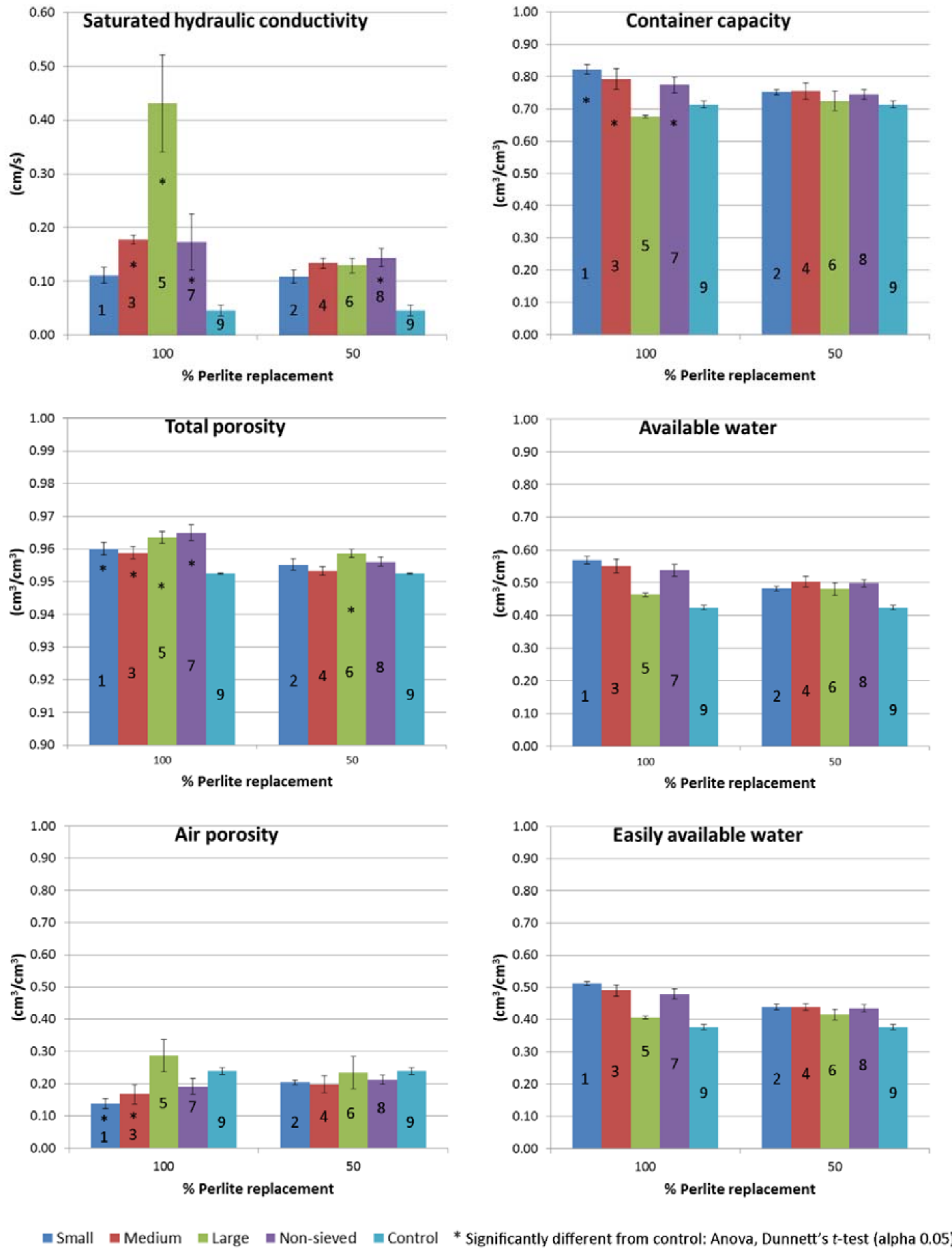

Figure 8. Estimated hydraulic conductivity, total porosity, air porosity, container capacity, available water and easily available water of eight variants (two proportions of perlite replacement and four types of Sphagnum fragments) as listed in Table 3 and original Mix 4 substrate (control) in four-inch pots. Note that the zero on the vertical axis for total porosity is suppressed. Bars show ± standard deviation, $n = 3$.

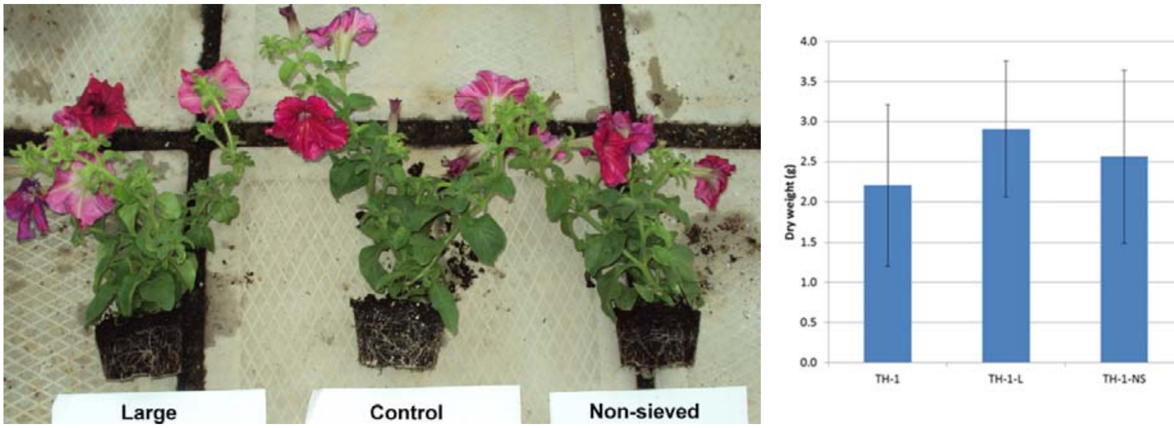

Figure 9. Growth (left) and above-ground dry mass (right) of petunia plants after six weeks in TH-1 (Control), TH-1 with 100:100 % perlite and vermiculite replacement with large Sphagnum fragments (Large/TH1-L), and TH-1 with 100:100 % perlite and vermiculite replacement with non-sieved Sphagnum fragments (Non-sieved/TH-1-NS). Error bars show ± standard deviation, n = 18.

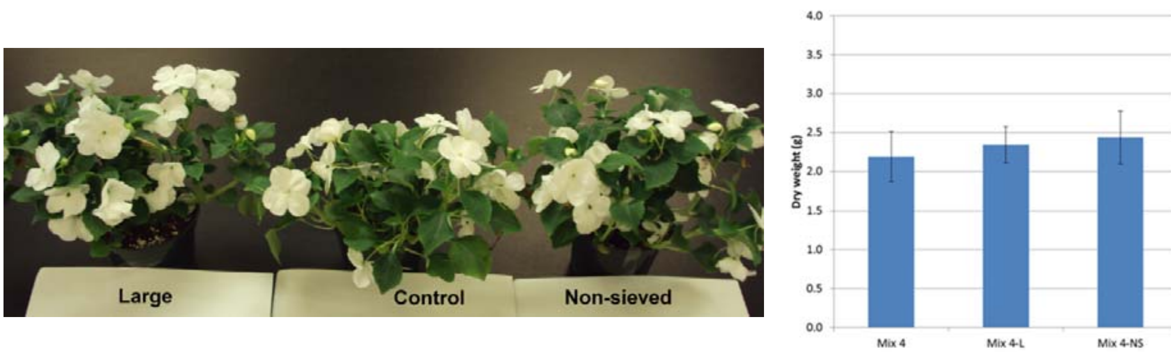

Figure 10. Growth (left) and above-ground dry mass (right) of impatiens plants after six weeks in Mix 4 (Control), Mix 4 with 50 % perlite replacement with large Sphagnum fragments (Large/Mix 4-L), and Mix 4 with 50 % perlite replacement with non-sieved Sphagnum fragments (Non-sieved/Mix 4-NS).

DISCUSSION

As harvested and processed for the experiment, Shippagan farm Sphagnum was of a lower grade than the Chilean and New Zealand products to which it was compared, because of its relatively short length and high non-Sphagnum material content. Harvesting during warmer weather, when there was no ice layer under the Sphagnum, would probably have resulted in a lower proportion of shorter strands in the product. Non-Sphagnum material content could be minimised through improved cultivation methods and practices, selective harvesting and sorting during processing. Chilean and New Zealand Sphagnum are selectively harvested and their processing includes a sorting and cleaning step. Nevertheless, Shippagan farm Sphagnum was more similar to the Chilean and New Zealand products than to the Canadian product currently on the market. Its pH and electrical conductivity, although respectively lower and higher than for the Chilean and New Zealand products, were acceptable and similar to values observed for peat (Lemaire *et al.* 2003, Caron *et al.* 2010). Finally, Shippagan farm Sphagnum has excellent water retention properties. Therefore, we believe it could be used as it is, like Chilean and New Zealand Sphagnum, in applications for which extra- long strands are not required.

Regarding the use of cultivated Sphagnum as a component of peat-based substrates, based on measurements of physical properties and growth trials, 50–100 % of the perlite or vermiculite of a

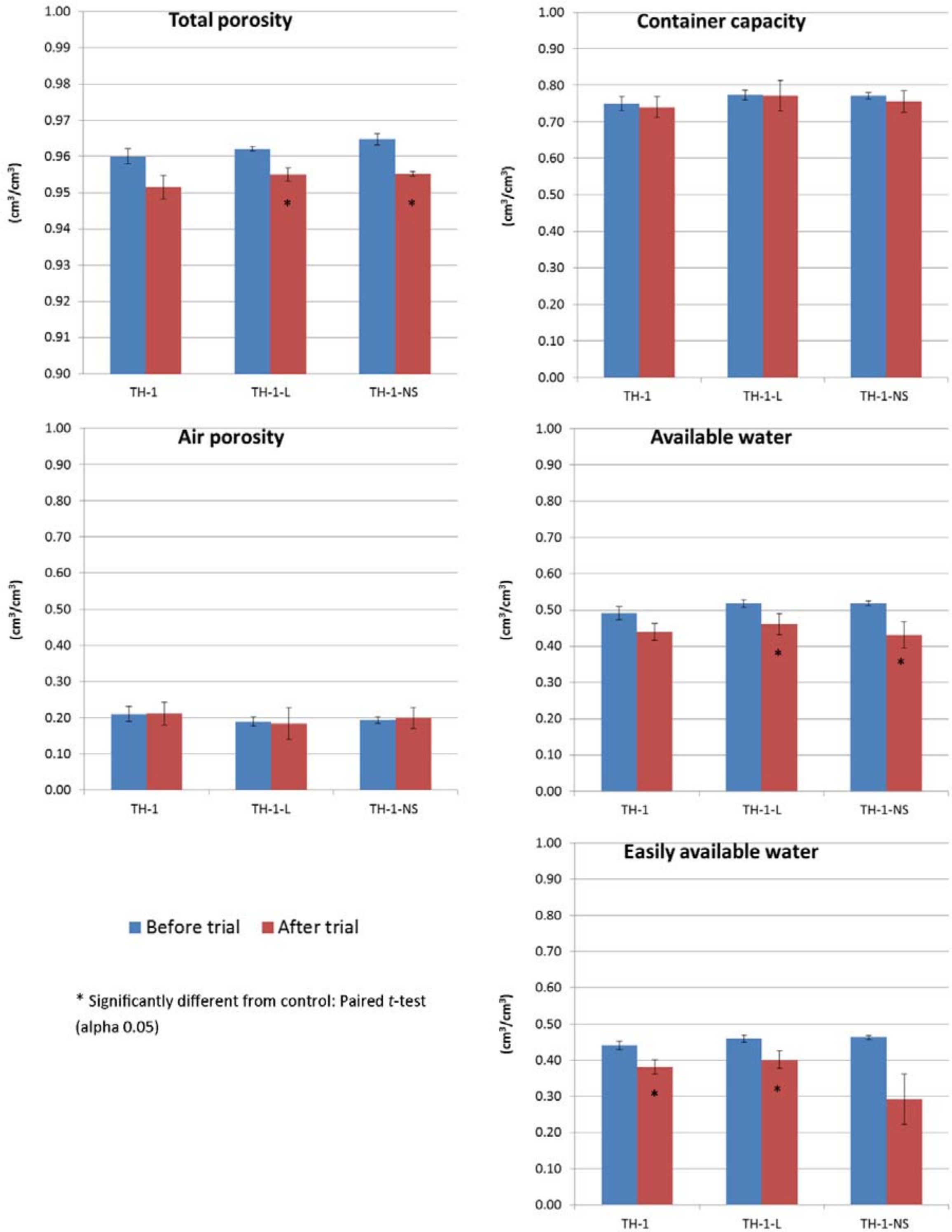

Figure 11. Before and after growth trial estimates of container capacity, total porosity, air porosity, available water and easily available water for control (TH-1), TH-1 with 100:100 % perlite and vermiculite replacement with large Sphagnum fragments (TH-1-L), and TH-1 with 100:100 % perlite and vermiculite replacement with non-sieved Sphagnum fragments (TH-1-NS) in four-inch pots. Note that the zero on the vertical axis for total porosity is suppressed. The left-hand bar of each pair is before trial and the right-hand bar after trial. Error bars show ± standard deviation, $n = 3$.

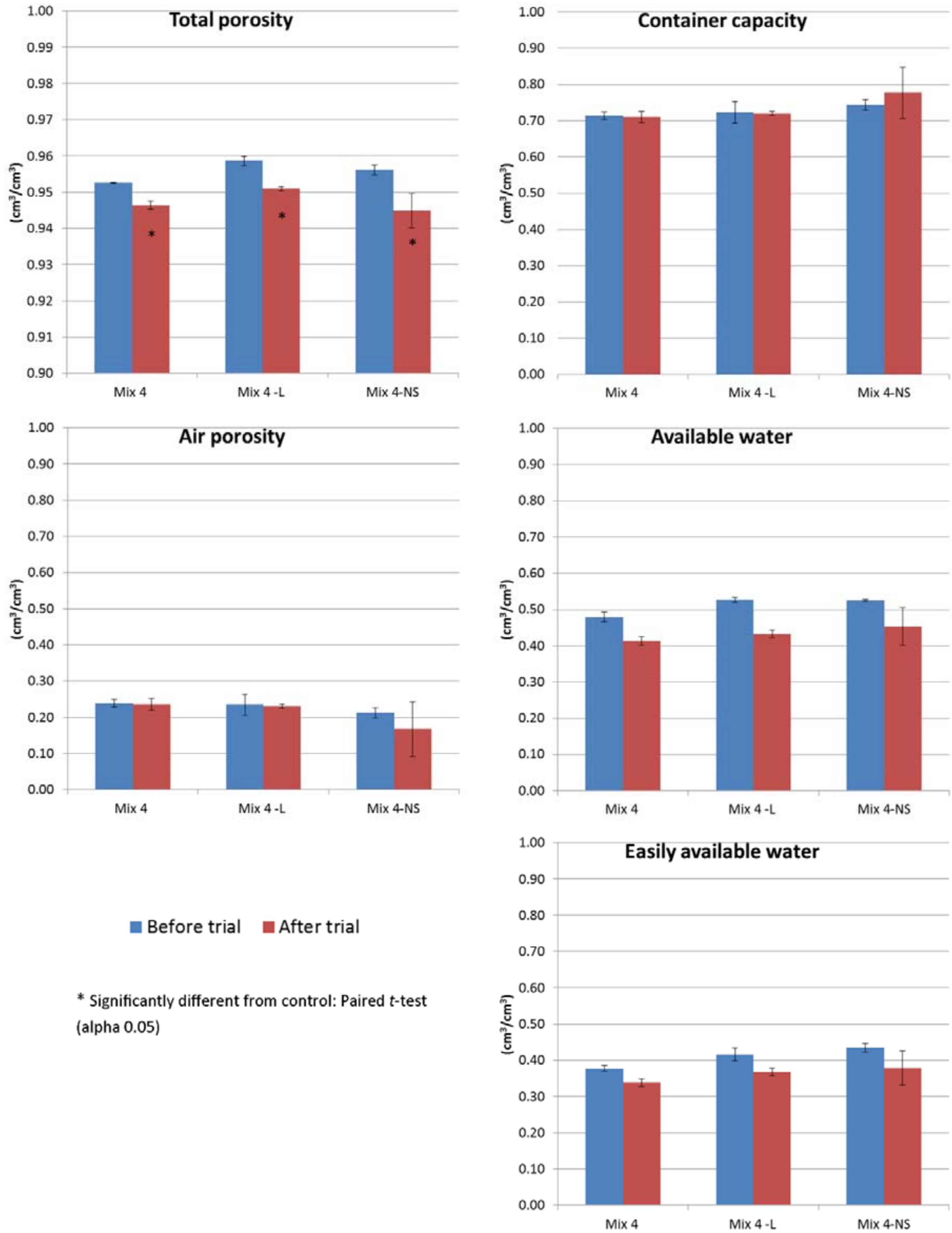

Figure 12. Before and after growth trial estimates of container capacity, total porosity, air porosity, available water and easily available water for control (Mix 4), Mix 4 with 50 % perlite replacement with large Sphagnum fragments (Mix 4-L), and Mix 4 with 50 % perlite replacement with non-sieved Sphagnum fragments (Mix 4-NS) in four-inch pots. Note that the zero on the vertical axis for total porosity is suppressed. The left-hand bar of each pair is before trial and the right-hand bar after trial. Error bars show ± standard deviation, $n = 3$.

peat-based substrate can be successfully replaced with Sphagnum. The aeration properties of perlite and vermiculite are best replicated by non-sieved coarsely shredded Sphagnum or the large (> 6.3 mm) fragments of sieved coarsely shredded Sphagnum. Both fragment types performed well, indicating that sieving may not be essential from a substrate performance point of view. In addition, the water retention and porosity results indicate that water holding capacity can be increased, while maintaining the desired air porosity, by replacing perlite or vermiculite with Sphagnum. Furthermore, decomposition tests and comparisons of changes in physical properties of substrates containing Sphagnum after six weeks of growth trials indicate that Sphagnum degradation leading to reduced substrate performance is not likely to be an issue. Although less stable than coconut coir (Lemaire 1997), Sphagnum may be as stable as some peats. Indeed, in a similar experiment, Lemaire (1997) found that peat could lose 4–7 % of its mass after 12 weeks of being subjected to greenhouse growth conditions.

Depending on plant needs and cultivation methods, Sphagnum could possibly replace a proportion of the peat in a substrate, or even replace the peat entirely. For instance, according to Blievernicht *et al.* (2012), poinsettias (*Euphorbia pulcherrima*) can be grown successfully in a 50–70 % Sphagnum substrate. Reinikainen *et al.* (2012) successfully grew cucumber, tomato and lettuce seedlings in pure Sphagnum, while Oberpaur *et al.* (2010) found that lettuce can be grown in a substrate constituted of 60 % Sphagnum and 40 % compost or humus. Emmel (2008) successfully grew marigolds (*Tagetes patula*) in pure Sphagnum and Chinese cabbage (*Brassica napus*) in a substrate containing 50 % Sphagnum.

From a performance point of view, Eastern Canadian cultivated Sphagnum has great potential as a replacement for perlite and vermiculite in peat-based substrates. It also has the potential to be used in other applications for which non-cultivated Sphagnum is currently used. For applications as a growth substrate or substrate component, size and proportion of Sphagnum fragments can be varied depending on the desired hydraulic conductivity, water retention and air porosity. Small Sphagnum fragments provide higher water holding capacity than large fragments, whereas large fragments provide higher air porosity. Further research is needed on Sphagnum applications, as well as on production methods, to render cultivated Sphagnum use feasible and cost effective from a commercial viewpoint.

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REFERENCES

Allaire, S., Caron, J. & Gallichand, J. (1994) Measuring the saturated hydraulic conductivity of peat substrates in nursery containers. *Canadian Journal of Soil Science*, 74, 431–437.

Blievernicht, A., Irrgang, S., Zander, M. & Ulrichs, C. (2012) The youngest peat - sustainable production of peat moss and its use as growing medium in professional horticulture. *Proceedings of the 14th International Peat Congress* (Stockholm, Sweden), No. 247, International Peat Society, Jyväskylä, 7 pp.

Bures, S., Marfa, O., Perez, T., Tebar, J.A. & Lloret, A. (1997) Measure of substrates unsaturated hydraulic conductivity. *Actae Horticultura,* 450, 297–403.

Buxton, R.P., Johnson, P.N. & Espie, P.R. (1996) *Sphagnum Research Programme: the Ecological Effects of Commercial Harvesting*. Science for Conservation 25, Department of Conservation, Wellington, New Zealand, 34 pp.

Campeau, S. & Rochefort, L. (2002) Possibilities and limits to *Sphagnum* farming. In: Schmilewski, G. & Rochefort, L. (eds.) *Proceedings of the International Peat Symposium: Peat in Horticulture - Quality and Environmental Challenges* (Pärnu, Estonia), International Peat Society, Jyväskylä, 264–269.

Caron, J., Blanchet, L., Richard, G., Tardif, P. & Daigle, J.-Y. (1997) Méthodes d'analyse des propriétés physiques des milieux artificiels, des tourbes et des sols organiques (Methods for analysing physical properties of artificial media, peats and organic soils). In: CPVQ (ed.) *Méthodes d'Analyse des Sols, des Fumiers et des Tissus Végétaux, 2e Mise à Jour (Methods for Analysing Soils, Manures and Plant Tissues, Second Edition)*, Conseil des Productions Végétales du Québec Inc., Québec, 1–30 (in French).

Caron, J., Morel, P., Rivière, L.-M. & Guillemain, G. (2010) Identifying appropriate methodology to diagnose aeration limitations with large peat and bark particles in growing media. *Canadian Journal of Soil Science,* 90, 481–494.

Caron, J., Rivière, L.-M. & Guillemain, G. (2005) Gas diffusion and air-filled porosity: effect of some oversize fragments in growing media. *Canadian Journal of Soil Science,* 85, 57–65.

Clarke, D. & Rieley, J. (eds.) (2010) *Strategy for Responsible Peatland Management*. Second edition, International Peat Society, Jyväskylä, 39 pp.

de Boodt, M. & Verdonck, O. (1972) The physical properties of the substrates in horticulture. *Acta Horticulturae,* 26, 37–44.

Diaz, M.F. & Silva, W. (2012) Improving harvesting techniques to ensure *Sphagnum* regeneration in Chilean peatlands. *Chilean Journal of Agricultural Research*, 72(2), 296–300.

Diaz, M.F., Tapia, C. & Armesto, J.J. (2008) Sphagnum moss harvesting in southern Chile: Capacity building for peatland management and conservation. Archived Abstracts, 93rd ESA Annual meeting (Milwaukee, Wisconsin), Ecological Society of America, Washington. Online at: http://esameetings.allenpress.com/2008/P11946.HTM, accessed 21 Jan 2015.

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

Esposito, K. (2000) Bringing in nature's bounty. *Wisconsin Natural Resources Magazine,* Wisconsin Department of Natural Resources, Madison, April Issue. Online at: http://dnr.wi.gov/wnrmag/html/stories/2000/apr00/mossy.htm, accessed 21 Jan 2015.

Fonteno, W.C. (1993) Problems and considerations in determining physical properties of horticultural substrates. *Acta Horticulturae*, 342, 197–204.

Fonteno, W.C. & Harden, C.T. (2003) *Procedures for Determining Physical Properties of Horticultural Substrates Using the NCSU Porometer*. Horticultural Substrates Laboratory, Department of Horticultural Science, North Carolina State University, Raleigh, 27 pp. Online at: http://www.ncsu.edu/project/hortsublab/pdf/porometer_manual.pdf, accessed 21 Jan 2015.

Gaudig, G. (2008) *Sphagnum* farming in progress - experiences and perspectives. In: Farrell, C. & Freehand, J. (eds.) *After Wise Use: the Future of Peatlands*, *Proceedings of the 13th International Peat Congress* (Tullamore, Ireland), International Peat Society, Jyväskylä, 168–171.

Gaudig, G., Fengler, M., Krebs, M., Prager, J., Schulz, S., Wichmann, S. & Joosten, H. (2014) *Sphagnum* farming in Germany: a review of progress. *Mires and Peat*, 13(8), 1–11.

Johnson, L.C. & Damman, A.W.H. (1991) Species-controlled *Sphagnum* decay on a South Swedish raised bog. *Oikos,* 61(2), 234–242.

Krebs, M. (2008) Perspectives of *Sphagnum* farming in the Kolkheti lowland (Georgia): first results. In: Farrell, C. & Freehand, J. (eds.) *After Wise Use: the Future of Peatlands*, *Proceedings of the 13th International Peat Congress* (Tullamore, Ireland), International Peat Society, Jyväskylä, 172–174.

Landry, J. & Rochefort, L. (2010) *Site Expérimental de Culture de Sphaigne, Shippagan, Nouveau-Brunswick, Rapport d'Activités 2003–2009 (Experimental Sphagnum Farming Station, Shippagan, New Brunswick, Activity Report 2003–2009)*. Groupe de Recherche en Écologie des Tourbières, Université Laval, Québec, 56 pp. (in French).

Lemaire, F. (1997) The problem of the biostability in organic substrates. *Acta Horticulturae,* 450, 63–70.

Lemaire, F., Dartigues, A., Rivière, L.-M., Charpentier, S. & Morel, P. (2003) *Cultures en Pots et Conteneurs, Principes Agronomiques et Applications (Pot and Container Cultivation, Agronomic Principles and Applications)*. Institut National de la Recherche Agronomique, Paris, 210 pp. (in French).

Nieminen, P. & Reinikainen, O. (2011) Influence of peat decomposition on the structure and water behaviour in growing media. *Acta Horticulturae,* 891, 209–214.

Oberpaur, C., Puebla, V., Vaccarezza, F. & Arévalo, M. (2010) Preliminary substrate mixtures including peat moss (*Sphagnum magellanicum*) for vegetable crop nurseries. *Ciencia e Investigacion Agraria,* 37(1), 123–132.

Parent, L.-É. (2001) Classification des sols, pédogénèse et dégradation des sols organiques (Classification, pedogenesis and degradation of organic soils). In: Payette, S. & Rochefort, L. (eds.) *Écologie des Tourbières du Québec-Labrador* (*Ecology of Quebec-Labrador Peatlands*), Les presses de l'Université Laval, Québec, 241–255 (in French).

Pouliot, R., Hogue-Hugron, S. & Rochefort, L. (2012) *Site Expérimental de Culture de Sphaigne,* *Shippagan, Nouveau-Brunswick, Rapport d'Activités 2003–2011 (Experimental Sphagnum farming Station, Shippagan, New Brunswick, Activity Report 2003–2011)*. Groupe de Recherche en Écologie des Tourbières, Université Laval, Québec, 57pp. (in French).

Prasad, M. & Maher, M.J. (2004) Stability of peat alternatives and use of moderately decomposed peat as a structure builder in growing media. *Acta Horticulturae,* 648, 145–151.

Prasad, M. & Maher, M.J. (2008) Moderately decomposed peat as a structure builder for younger peats in growing media. *Acta Horticulturae,* 779, 185–189.

Prasad, M. & O'Shea, J. (1999) Relative breakdown of peat and non-peat growing media. *Acta Horticulturae,* 481, 121–128.

Quinty, F. & Rochefort, L. (2003) *Peatland Restoration Guide*. Second edition, Canadian Peat Moss Association and New Brunswick Department of Natural Resources and Energy, Québec, 120 pp.

Reinikainen, O., Korpi, J., Tahvonen, R., Nakkila, 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. 201/137, International Peat Society, Jyväskylä, 6 pp.

Rochefort, L., Vitt, D.H. & Bayley, S.E. (1990) Growth, production, and decomposition dynamics of *Sphagnum* under natural and experimentally acidified conditions. *Ecology,* 71(5), 1986–2000.

St-Arnaud, C., Rochefort, L., Poulin, M. & Landry, T. (2008) The farming of *Sphagnum* and of aquatic and semi-aquatic plants for peatland restoration. In: Farrell, C. & Freehand, J. (eds.) *After Wise Use: the Future of Peatlands, Proceeding of the 13th International Peat Congress* (Tullamore, Ireland). International Peat Society, Jyväskylä, 179–183.

TDPPWE. (2013) Sphagnum moss - Sustainable use and management. Tasmania Department of Primary Industries, Parks, Water and Environment. Online at: http://www.dpiw.tas.gov.au/inter.nsf/WebPages/BHAN-54A8CA?open#top, accessed 21 Jan 2014.

Topp, G.C., Galganov, Y.T., Ball, B.C. & Carter, M.R. (1993) Soil water desorption curves. In: Carter, M.R. (ed.) *Soil Sampling and Methods of Analysis*, Lewis Publishers, Florida, 569–579.

Waddington, J.M., Rochefort, L. & Campeau, S. (2003) *Sphagnum* production and decomposition in a restored cutover peatland. *Wetlands Ecology and Management,* 11, 85–95.

Whinam, J. & Buxton, R. (1997) *Sphagnum* peatlands of Australasia: an assessment of harvesting sustainability. *Biological Conservation,* 82, 21–29.

White, J.W. & Mastalerz, J.W. (1966) Soil moisture as related to container capacity. *Proceedings of the American Society for Horticultural Science,* 89, 758–765.

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