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RESEARCH

Growth of Nordic container forest tree seedlings in some peatless and peat-reduced growing media

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Abstract

Carbon emissions and environmental concerns have led to the aspiration to reduce peat extraction and its use as a growing medium (GM). In Nordic Forest tree seedling production, Sphagnum peat has been almost exclusively used as a GM in seedling containers due to its good properties and availability. This study examined the feasibility of several peat-reduced and peat-free GM in container tree seedling production of the key tree species in Nordic forestry (Scots pine (*Pinus sylvestris* L.), Norway spruce (*Picea abies* L. Karst.) and silver birch (*Betula pendula* Roth) as well as Russian larch (*Larix archangelica* P. Lawson & C. Lawson ex Trautv.) and common alder (*Alnus glutinosa* (L.) Gaertn.). Pure or mixed GM, consisting of low-humified Sphagnum peat (pure as a control), harvested Sphagnum moss, wood fiber, cow manure digestate from a biogas plant, and a common reed compost were tested. Seedlings were grown in controlled conditions in greenhouse experiments and also in larger-scale commercial tree nurseries. Peat-reduced media containing peat of at least 50 vol% provided growth that is similar to pure Sphagnum peat for the tested species and container types. All the studied alternative media can yield marketable seedlings, although commonly of reduced size and requiring special adjustments in growing management. The studied media have a potential to reduce or replace peat in seedling production, but adjustments of their physical and chemical properties, as well as of seedling fertigation and management procedures, are required. The economic feasibility and environmental sustainability of these GM, as well as the outplanting success of seedlings grown in these media, remain to be studied.

Keywords Digestate · Compost · Peat-free growing media · Reed fibers · Sphagnum Moss · Tree nurseries · Wood fibers

Introduction

Increasing concern about climate change has led to a global drive to minimize carbon (C) emissions and maximize carbon sequestration. For example, the EU has the objective of achieving C neutrality by 2050 and Finland by 2035 (ym.fi/en/climate-neutral-fin-

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Extended author information available on the last page of the article land-2035). These objectives have led to diminishing fossil fuel use and peat extraction, as peatlands are globally seen as a significant C sink, and they regenerate slowly. Meanwhile, C stock changes and greenhouse gas emissions on unmanaged land (including peatlands) are usually unknown because they are not commonly inventoried, as they are not included in the inventory guidelines of the intergovernmental panel on climate change (IPCC) (e.g. Ogle et al. 2018).

Peat is the most used growing medium (GM) in the world today (ca. 40 $\mathrm{Mm}^3\ \mathrm{a}^{-1}$) (Blok et al. 2021), in addition to which about an equal amount of energy peat is used (World Energy Council 2013). Ceasing energy peat extraction with endeavors to reduce the use of peat as a GM has led to an increasing demand for novel peatless GM materials (Barrett et al. 2016; Gruda 2019). For example, Ireland's largest peat company has ended all peat harvesting on its lands (www.bordnamona.ie) and the UK government (Defra) has announced that the sale of peat GM for amateur gardening will be banned by 2024 (www.gov.uk/government/news/sale-of-horticultural-peat-to-be-banned-in-move-to-protect-englands-precious-peatlands). On the other hand, environmental footprint scores (product environmental footprint method, PEF) for peat GM have been shown to be similar to those of non-peat GM constituents (GME 2021).

In the Nordic countries, tree seedlings have almost exclusively and successfully been grown for decades in pure peat in small containers (plugs) with standardized management practices (Heiskanen 1994, 2013; Poteri 2002; Nilsson et al. 2010; Rikala 2012). In Finland, about 2 $\mathrm{Mm}^3\ \mathrm{a}^{-1}$ of peat for GM has been produced, of which half has been used domestically and 15–20 000 $\mathrm{m}^3\ \mathrm{a}^{-1}$ in forest tree nurseries (Heiskanen 1994; Leinonen 2010). In Finland, forest tree seedlings are exclusively raised in pure low-humified Sphagnum peat GM in small hard-plastic containers (plugs) (Heiskanen 1994, 2013; Poteri 2002; Rikala 2012; see also statdb.luke.fi). Sphagnum peat as a GM has shown high and consistent quality for efficient container seedling production and good seedling out-planting success.

Container tree seedling production has specific characteristics which deviate from the greenhouse production of decorative and edible plants. GM used in open field nurseries, landscaping, or in large pots in horticulture may not be feasible for containerized tree seedlings. Nordic tree seedling production is extensive (large bulk production), with a limited cost- bearing capacity and tolerance for deviations in the production chain. Scots pine (*Pinus sylvestris* L.), Norway spruce (*Picea abies* L. Karst.) and silver birch (*Betula pendula* Roth) are the main tree species raised in small containers in tree nurseries (Heiskanen and Rikala 2000; Poteri 2002; Nilsson et al. 2010; see also publication.nordgen.org/Forest-Seeds-and-Plants-Statistics-v2023/overview-of-the-most-important-species-in-each-country.html). These seedlings require e.g. low pH and suppressiveness to seedling pathogens in the GM (Tahvonen 1982; Rikala 2012).

There is an urgent practical need to reduce and replace peat in growing media, and thus testing the alternatives already available to seedling producers is in high demand and justified. The aim of this study was therefore to examine the growing performance and feasibility of some of the most potential and available GM in the peat-reduced and peat-free container seedling production of Scots pine (later referred to as pine) and Norway spruce (spruce) in the Nordic conditions. The GM studied were either pure or mixed, consisting of low-humified Sphagnum peat (pure as a control), harvested Sphagnum moss, wood fiber, cow manure digestate from a biogas plant and a common reed compost (*Phragmites australis* (Cav.) Trin. ex Steud.). The growth of silver birch (birch), Russian larch (*Larix archan-*

gelica P. Lawson & C. Lawson ex Trautv.) (larch) and common alder (*Alnus glutinosa* (L.) Gaertn.) (alder) were also tested in moss and digestate GM mixtures. We hypothesized that some of the tested GM could achieve seedling growth that is comparable to that in pure peat.

Materials and methods

Growing media description

Commonly used pure, light low-humified Sphagnum peat in tree nurseries was used as a control GM treatment in the growing experiment with spruce and pine seedlings (Table 1; Fig. 1). The other GM used were either pure or mixed, consisting of Sphagnum peat, harvested Sphagnum moss (with a minute proportion of other bog biomass), the wood fiber of Scots pine, cow manure digestate and a common reed compost. The used digestate originated from a cow manure sludge (with a little hay) from a farm biogas plant (Luke, Maaninka, Finland), where it was processed and separated (Virkajärvi et al. 2016) and then air-dried. In a parallel experiment with silver birch, Russian larch and common alder, GM mixtures of moss and digestate were used.

Physical analyses

The particle size distribution of GM describes markedly many other physical properties such as water retention characteristics (Dumroese et al. 2011, 2018; Heiskanen 1995). It was

Table 1 Growing media (GM) used in the growing experiments

Code	Volumes %	Specifier	Fertilization*	Producer
P100	100	Light peat (Ctrl), FPM 420 W F6, 4–20 mm	F + L	kekkilaprofessional.com
M100	100	Sphagnum moss, < 25 mm	F + L	novarbo.fi/en
M67D-33	100	Moss 67% + air-dried, non-hygienized digestate 33%	In moss part	Self-made mix
M67D+33	67 + 33	Moss 67% + air-dried, hygienized at 75°C digestate 33%	In moss part	Self-made mix
P75W25c	75 + 25	Fiberboost 420: B-peat 75% +wood fiber 25%, 4–20 mm	F + L	kekkilaprofessional.com
P75W25f	75 + 25	Fiberboost 08: C-peat 75% +wood fiber 25%, 0–8 mm	F + L	kekkilaprofessional.com
P50M25W25	50 + 25 + 25	Ecoboost 08: C-peat 50% +moss 25% +wood 25%, 0–8 mm	F + L	kekkilaprofessional.com
P33M33W33	33 + 33 + 33	Moss mix 1: Peat 33%, moss 33%, wood fiber 33%, < 25 mm	F + L	novarbo.fi/en
M50W50	50 + 50	Moss mix 2: Moss 50%, wood fiber 50%, < 25 mm	F + L	novarbo.fi/en
R100	100	RuokoGrow: Common reed grass compost with MycoStop	F + L	matojamulta.com
M75D25	75 + 25	Moss 75% + air-dried, non-hygienized digestate 25%	In moss part	Self-made mix
M50D50	50 + 50	Moss 50% + air-dried, non-hygienized digestate 50%	In moss part	Self-made mix

*) Base fertilizer in GM: F = fertilizer 0.8–1.2 kg/m^3, L = dolomite lime 1.2–2.0 kg/m^3

Fig. 1 Growing media used in the study (see Table 1 for abbreviations). The diameter of the Petri dish is 9 cm

measured using seven size classes for individual GM components ($n=3$) using dry sieving with a series of sieves (from 20 to 0.1 mm). The bulk density (Db) of each GM was determined as the ratio of dry mass (dried at 105 °C) to near-saturated volume in steel cylinders ($n=3$) (Dumroese et al. 2011, 2018; Heiskanen et al. 2020). The cylinders (height 60 mm, diameter 58 mm) were filled with each media, saturated, and allowed to drain freely (to about −0.3 kPa matric potential).

The particle density (Ds) was estimated using an average density of 2.65 g cm^{-3} for mineral and 1.5 g cm^{-3} for organic components (Blake and Hartge 1986; Heiskanen 1992). Loss on ignition (LOI) at 550 °C for 2 h provided an approximate estimate of the organic matter for each medium ($n=3$). The total porosity (TP) was estimated as ((Ds-Db)/Ds) * 100. Volumetric water retention at decreasing matric potentials (i.e., at desorption) was measured for each medium ($n=3$) using a pressure plate apparatus (Soilmoisture Equipment Corp., Santa Barbara, CA, USA) and standard methods (for details, see Dumroese et al. 2011, 2018; Heiskanen 1995; Heiskanen et al. 2020). Easily available water (EAW) was determined as the water content retained between −1 and −10 kPa matric potential, buffer water retention (BW) as that between −10 and −100 kPa, and air-filled porosity at matric potential −1 kPa (AFP). Electrical conductivity (EC) and pH were measured in water suspension (1 sample+5 water method). EC and acidity (pH) were also measured from the press water extract taken from the GM in seedling growing experiments.

Chemical analyses

GM samples were dried at 60 °C for 96 h and then sieved (<2 mm). Total C and N were measured (ISO 10,694, 1995; ISO 13,878, 1998) from the samples using a Leco TruMac CN Determinator (Leco Corp., St. Joseph, MI, USA). Total C and N for foliage samples of spruce seedlings were measured in the same way. Samples for other total elements in GM (SFS-ISO 11,466, 2007) were digested by the closed wet HNO_3-HCl digestion method in a microwave (CEM MDS-2000; CEM Corp., Matthews, NC, USA) and the extract was analyzed on an iCAP 6500 Duo ICP emission spectrometer (Thermo Scientific Ltd., Cambridge, UK).

To assess extractable sulfur (S), acid ammonium acetate (pH 4.65) extractant was used (Vuorinen and Mäkitie 1955). The quantification was done using an iCAP 6500 Duo ICP emission spectrometer (Thermo Scientific Ltd., Cambridge, UK). Ammonium (NH_4), nitrate (NO_3), and total N in the GM were determined from a KCl extract on a FIA-analyzer (Lachat QuickChem 8000, Lachat Instruments, Milwaukee, WI, USA) (Kalra and Maynard 1991). Using a microwave (CEM MDS-2000, CEM Corporation, USA) and the hot water refluxing method, the easily soluble B was extracted, and then quantified using the ICP-emission spectrometer.

For cation exchange capacity (CEC), GM samples were prepared as for extractable nutrients (ISO 11,260, 2018). We used a 0.1 M $BaCl_2$ solution to extract exchangeable cations, and their total concentrations in the filtrate were determined using the previously described ICP-emission spectrometer. To determine exchangeable acidity, the 0.1 M $BaCl_2$ extract was titrated with a 0.05 M NaOH solution up to pH 7.8. Effective CEC [ECEC(cmol kg^{-1})] was then calculated as ECEC (in cmol kg^{-1}) = Na + K + Ca + Mg + ACI_E, where ACI_E is exchangeable acidity from $BaCl_2$ extract. Percentage base saturation was calculated as the sum of the bases (Na, K, Ca, Mg) divided by ECEC.

Elements in press water extract from different GM in containers were analyzed using a modified ICP-OES-technique (ISO 11,885, 2007) and nitrate and ammonium using flow analysis (SFS-EN ISO 13,395, 1997 and ISO 11,732, 2005; for more details, see Dumroese et al. 2011, 2018; Heiskanen et al. 2020).

Seedling growing experiments in greenhouse

Each GM used was filled into six hard-plastic seedling container trays by hand. A seedling tray consisted of 12 cells, which were cut off from a whole tray of 81 cells (Plantek PL81F, https://bccab.se/products-planting/growing-systems) to achieve a larger experimental setup with a smaller treatment unit size in the greenhouse (Luke, Suonenjoki, Finland). Therefore, 60 trays and 720 containers (10 GM x 6 trays x 12 containers) were filled for both spruce and pine seedlings. Furthermore, 24 trays and 288 containers (4 GM x 6 trays x 12 containers) were filled for birch, alder, and larch seedlings. In total, the experiment consisted of 194 trays (120 + 72) and 2304 containers and seedlings (1440 + 864). The edges of the seedling tray area in the greenhouse were surrounded with empty trays to reduce variability in transpiration. Tray positions were changed every second week to minimize spatial variability. The experiment was organized for each species according to a completely randomized design in the greenhouse.

Seeds (two per cell) were sown in GM in containers in the late fall (Oct. 3, 2022). Genetically improved seeds of central Finnish origin from seed orchards were used for spruce (EY/FIN/T03-21-0508: SV113), pine (EY/FIN/M29-20-0031: SV407), birch (EY/FIN/M29-19-0001: SV460), alder (EY/FIN/M29-19-0018: SV439) and larch (EY/FIN/M29-21-0019: SV309). The laboratory seed germination rates at 21 days were 95, 97, 89, 85, and 73% for pine, spruce, birch, larch and alder. Trays were first mist-irrigated frequently with tap water to ensure germination. After the seedling emergence level was determined at 21 days from sowing, the germinants were thinned or pricked to one in each tray cell. After four weeks, irrigation was done using fertigation (0.1% concentration of Taimi-Superex, NPK 19-4-20, kekkilaprofessional.com). The masses of the trays were monitored by weighing. When the masses of the trays were reduced to about 40% in TP, the trays were irrigated manually so that about 60% water in TP with each GM treatment was achieved. Once every two weeks, the trays were also irrigated so that water flowed somewhat through to reduce variability in GM water contents and avoid overdrying.

The daytime air temperature in the glass greenhouse was set to 20 °C (+ direct light heat), at night to 15 °C, and with a cycle of 18/6 h. During germination, artificial lights (high-pressure sodium lamps) were kept on during the day, providing a radiation intensity of 150–200 µmol m^{-2} s^{-1} (PAR) 20 cm from the surface of the GM. After thinning and pricking, the light intensity was increased to 300–400 µmol m^{-2} s^{-1} (PAR). Due to the scanty natural light during the fall, a low intensity interference light was used at night for two hours to prevent early bud formation and growth cessation. Press water extracts were sampled from the GM on two occasions during the seedling growing.

The seedling emergence level was determined 21 days after sowing. Thereafter, plant vigor and height were measured every second week. The occurrence of liverworts (*Marchantiophyta*) was determined for each tray cell. The experiment was ended, and seedlings harvested three months after sowing (Jan. 4, 2023). The seedlings were measured for final morphological characteristics (height, root collar diameter) and biomass (for details, see Dumroese et al. 2018; Heiskanen et al. 2020, 2022).

Seedling growing in tree nursery

Selected GM P100, M100, M75D25 (mix of moss and unhygienized digestate), W75D25 (a mix of coarse < 20 mm, white unprocessed pine wood fibers from novarbo.fi/en and of the unhygienized digestate described previously), P75W25f, and M50W50 were used in the practical scale growing test for spruce seedlings in a plastic greenhouse at the Suonenjoki nursery (Luke, Suonenjoki, Finland). GM with digestate were applied to three seedlings tray pallets, each containing 18 trays of Plantek 81 F (i.e. 18 × 81 = 1458 seedlings per pallet), while the other GM were applied to six pallets. M100 and M50W50 were also applied so that three pallets received an additional N base fertilization (150 g N m^{-3}, www.kekkila.fi/tuotteet/kukkasipuliravinne), while the other three pallets had GM without additional fertilization. In all, 48,114 spruce seedlings were grown (33 × 18 × 81). Seedling trays were mechanically filled with peat (also M100, M50W50, W75D25 for spruce), while other GM were filled manually due to their smaller amounts and partly due to coarse structures. Seeds were sown mechanically between May 2 and 4, 2023 (filling and sowing machine: Urbinati Beta 65-C; www.urbinati.com). Seed origin was the same as in greenhouse experiments except for pine (EY/FIN MM29-21-0036: SV411). Seedlings were monitored, managed, and measured using practical procedures used in the nursery adjusting e.g., fertigation according to visual and tactile evaluation (Rikala 2012).

In addition, one pallet for each GM of P100, M100, M75D25, M50W50 and R100 was used for growing pine seedlings in Plantek 81 F trays in practical conditions in the Suonenjoki nursery (sown on May 16, 2023). M50W50 received an additional N base fertilization in the GM (150 g N m^{-3}, www.kekkila.fi/tuotteet/kukkasipuliravinne). A total of 7,290 pine seedlings were therefore grown (5 × 18 × 81). Furthermore, P100, M100, and M25D75 were filled into Plantek 81 F trays in three pallets per GM to grow birch seedlings in the nursery (sown May 13, 2023). Thus, 13,122 seedlings were grown (3 × 3 × 18 × 81). In addition, P100, M100, M75D25, and M50W50 were used to grow transplanted spruce seedlings (sown on May 4 and 5, 2023) in practical conditions in the Partaharju nursery (www.partaharju.fi/en/forest-tree-seedlings). One pallet containing 30 seedling trays (PP126 M-plastics) was used for each GM. Thus, 15,120 seedlings were grown (4×30×126). All the practical growings received the otherwise normal handling procedures used in the nursery.

Close to terminal bud formation or growth cessation in September, seedlings were evaluated from random three containers in 10 random trays for each GM type. They were measured for height, collar diameter and, shoot fresh mass, and were assessed for indicative marketability (actual seedling sorting occurred a couple of weeks later because the ending of the growing season was delayed due to a warmer than usual autumn). We considered ungerminated cells and seedlings of poor quality or low height (shorter than 8 cm for spruce and 10 cm for pine and birch) as non-marketable and rejectable. In Finnish tree nurseries, the proportion of seedlings are considered marketable when they meet the official standards (www.finlex.fi/fi/laki/alkup/2002/20021055), and those used in the nursery for visual quality and height.

Statistical analyses

The experimental growing data were analyzed with SAS (Version 9.4). One-way analysis of variance was used to compare the effect of GM on the plant variables (tray means used as replicates). Homogeneity of variance was tested using Levene's test. Analysis of variance for the proportions of non-marketable seedlings was conducted after arcsine square root transformation to comply with the normality assumption. The Bonferroni method at a significance level of $p < 0.05$ was used for post-hoc multi-comparison tests of the differences between the means of different GM. Linear regression analysis was used to identify the relations between variables.

Results

Growing media

Particle size was weighted towards size class 1–5 mm in R100, M100, and M50W50, while P100 and D100 (pure digestate) had relatively uniform distribution over the size classes (Table S1). However, the dry sieving procedure measured not only unattached particles but also particles combined as crumbs, which was the case especially with R100. P75W25f had the highest proportion of particles smaller than 1 mm and least particles greater than 5 mm suggesting increased water retention.

All the GM had a relatively similar loss on ignition, density, and total porosity (Table 2 and S2). On the other hand, easily available water retention (EAW) was highest, at over 10 vol% in P75W25c, P75W25f, P50M25W25, and P100, while it was lowest in R100, at only 2.7 vol%. Buffer water retention (BW) was generally lower and lowest in R100. pH (in 1+5 suspension) was between 4.5 and 5.3 but was 6 or above in GM containing digestate and in R100. EC (in 1+5 suspension) was also highest in GM containing digestate.

The total element concentrations of the GM varied according to the component origin (Table S3). Digestate tended to elevate concentrations of Ca, Mg, K, P, S, B, and Na. R100

Table 2 Mean loss on ignition (LOI), particle (Ds) and bulk densities (Db), total porosity (TP), air-filled porosity (AFP, at -1 kPa matric potential), easily available water retention (EAW, between − 1 and − 10 kPa matric potential), and buffer water retention (BW, between − 10 and − 100 kPa) for the studied growing media ($n=3$), as well as electrical conductivity (EC) and pH in water suspension (1+5 method) ($n=3$)

Medium	LOI, %	Ds, g/cm3	Db, g/cm3	TP, vol%	AFP, vol%	EAW, vol%	BW, vol%	EC, mS/cm	pH
P100	95.9	1.55	0.100	93.5	52.3	10.5	4.4	0.132	4.54
M100	92.7	1.58	0.057	96.4	54.6	9.0	2.5	0.126	4.94
M67D-33	90.1	1.61	0.074	95.4	55.8	7.3	2.8	0.332	6.39
M67D+33	90.5	1.61	0.077	95.2	54.1	6.9	2.6	0.343	6.54
P75W25c	96.6	1.54	0.093	94.0	58.6	10.3	4.2	0.104	5.33
P75W25f	94.2	1.57	0.105	93.3	49.8	13.2	4.1	0.214	4.70
P50M25W25	95.3	1.55	0.101	93.5	49.5	12.0	3.5	0.146	4.72
P33M33W33	94.4	1.56	0.084	94.7	56.9	9.3	4.5	0.176	4.68
M50W50	94.6	1.56	0.072	95.4	61.1	8.0	2.7	0.158	4.96
R100	50.3	2.07	0.146	93.0	55.1	2.7	1.7	0.436	5.95
M75D25	90.4	1.61	0.072	95.5	55.0	7.8	2.5	0.327	6.46
M50D50	89.3	1.62	0.096	94.1	54.7	7.4	2.5	0.628	7.23

showed high concentrations of Al, Fe and Na. Digestate containing media also had high N concentrations and low C/N ratios. R100 had the lowest C and C/N values. Wood fibers containing media P33M33W33 and M50W50 had the lowest N concentrations and highest C/N ratios.

The effective cation exchange capacity was highest in digestate containing GM (>100 cmol kg^{-1}) and lowest in R100 (Table S4). The extractable N concentration was also highest in the digestate GM and in M100. The lowest extractable N concentration was in the order R100, P75W25c, M50W50, and P33M33W33 respectively. The digestate component provided the highest P and K and low Al and Fe concentrations in GM. R100 showed the lowest P and Al but the highest Na concentrations.

EC and acidity (pH) in the press water extract taken from the GM varied markedly (Fig. 2). pH and EC were highest in GM containing digestate. EC was also high in R100. The total N concentration of press water extract was very high in R100 at the end phase of the growing experiment (Fig. 3, Table S5). Despite filtering, the turbidity of the extract of R100 was very high, which suggests that the suspension particles had high N concentration within. R100 also had high concentrations of Al, Ca, Mg and Na (Table S5). P concentration was highest in GM containing digestate, which was also rich in N, Ca, and Mg.

Seedling growing experiments in greenhouse

The seedling emergence level of spruce seeds 21 days after sowing was over 92% in all GM except in M67D+33 and P75W25f, where it was about 86% (data not shown). In pine, the overall seedling emergence level was lower being over 60% except in M67D-33, M67D+33, and M50W50, where it was 42–56%. In birch, larch, and alder, it was relatively uniform among GM being 91–96%, 72–82%, and 61–77%, respectively.

Seedling visual quality and vigor were generally good in all treatments (data not shown). The mortality of spruce and pine seedlings was below 1.4% in all GM except in M67D-33, where the mortality of spruce seedlings was 2.8%. With birch, larch and alder seedlings, mortality was 0%, but in M100 it was 4.2–6.9%. Seedling mortality occurred primarily at

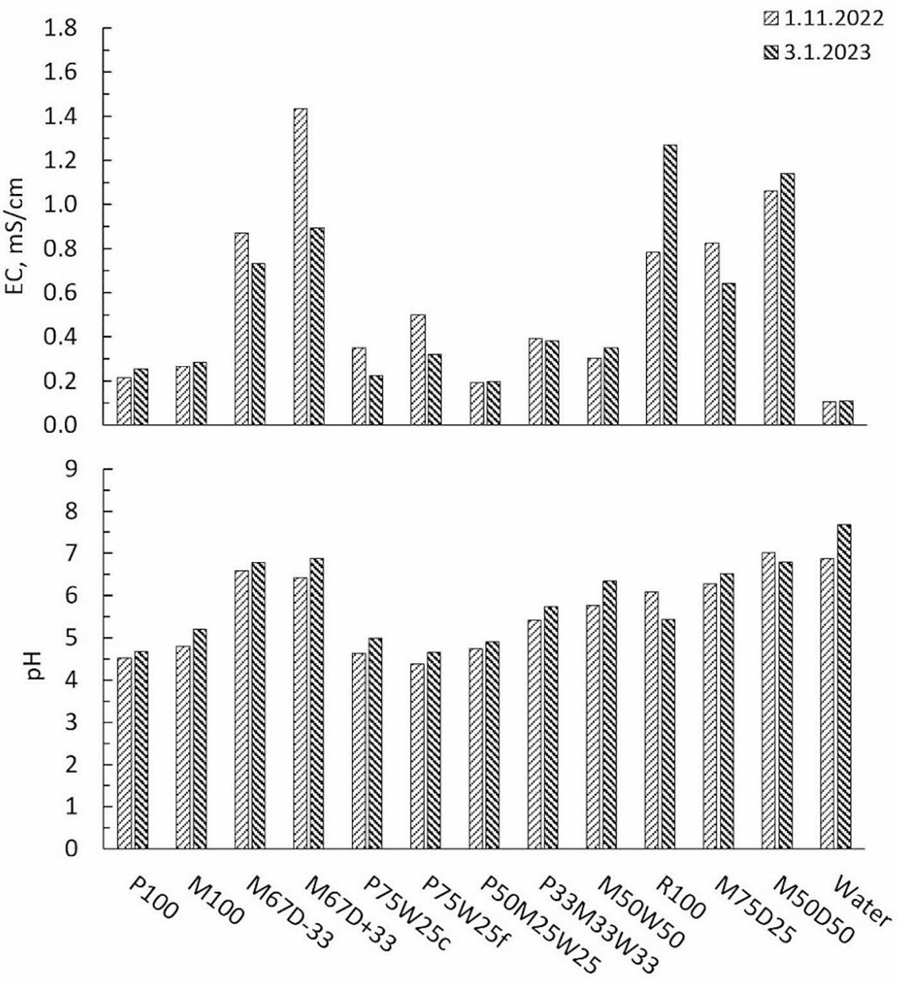

Fig. 2 Electrical conductivity and acidity (pH) of press water extract from different growing media and pure irrigation water at the beginning and end (date as dd.mm.yy) of the growing experiment (from one combined sample per GM)

the edges of the seedling trays, where there was the greatest risk of drying out. GM with digestate also exhibited wetness during growing, as well as surface hardness, at the start when mist irrigation was used. Mainly larch seedlings were observed to have a superficial rooting in GM with digestate, which tended to compact the GM surface structure. No or few (0–4% of tray cells) liverworts (*Marchantiophyta*) were observed on the surfaces of M100, P75W25f, P33M33W33, M50W50 and R100. The highest occurrence of liverworts (30% of cells) was found on the surface of M67D-33 with pine seedlings. The foliar N in spruce seedlings was above 1.4% DM, except in seedlings grown in P33M33W33 and M50W50, where it was 1.04 and 1.28% respectively. The highest foliar N concentration was 2.54 and 1.99% in R100 and P100.

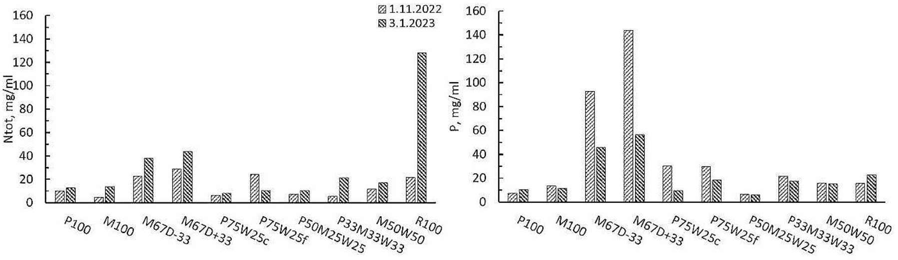

Fig. 3 Concentrations of nitrogen (Ntot) and phosphorous (P) of press water extract from different growing media at the beginning and end (date as dd.mm.yy) of the growing experiment (from one combined sample per GM)

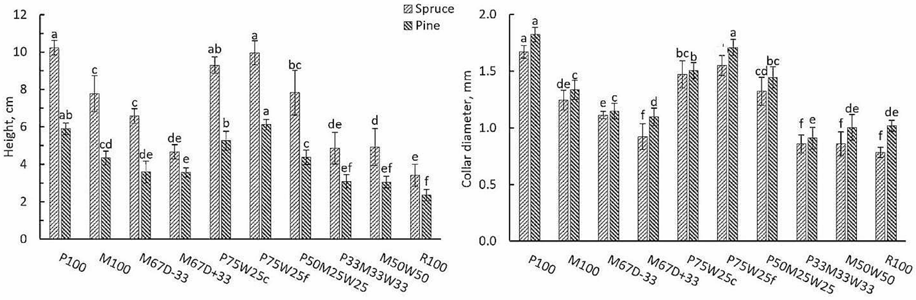

Fig. 4 Final height and collar diameter of spruce and pine seedlings grown in different growing media (arithmetic mean ± Sd, $n = 6$ container trays). The different letters above the bars indicate significant differences between growing media within tree species ($p < 0.05$, Bonferroni test)

The final height of spruce seedlings was over two times taller in the best GM than in the GM with the poorest growth (Fig. 4). The greatest growth was in P100, P75W25f, and P75W25c. The next best growth was in P50M25W25, M100, and M67M-33. Similar but a little less pronounced differences were seen for pine. EAW (water retained between -1 and -10 kPa matric potentials) of GM was found to have a marked positive linear correlation with the mean final height of spruce and pine seedlings in the GM ($R^2 = 0.66$ for both species, Fig. S1). BW (water retained between -10 and -100 kPa) showed a positive linear correlation with the final height of spruce and pine seedlings ($R^2 = 0.44$ and 0.46 respectively).

The final root collar diameter was of the same order of magnitude in both species varying similarly to height in the GM. Biomass in different GM was also largest in P100 and P75W25f (Fig. 5). The shoot and root biomasses in these GM were about three times larger than in the GM with poorly grown seedlings (P33M33W33, M50W50, R100 and, M67D+33). Pine generally gained somewhat greater shoot and root biomass than spruce.

The final height and collar diameter of birch, alder and larch seedlings were largest in P100 (Fig. 6). Alder seedlings grew as well in M100 and M75D25 as in P100. The weakest height and collar diameter growth in all species was in M50D50. Shoot and root biomasses had similar differences among the GM (Fig. 7). However, birch root biomass was as great in M75D25 as in P100. After germination, the primordial root of some larch seedlings tended to remain on the surface of GM for several days. The number of seedlings with this tendency

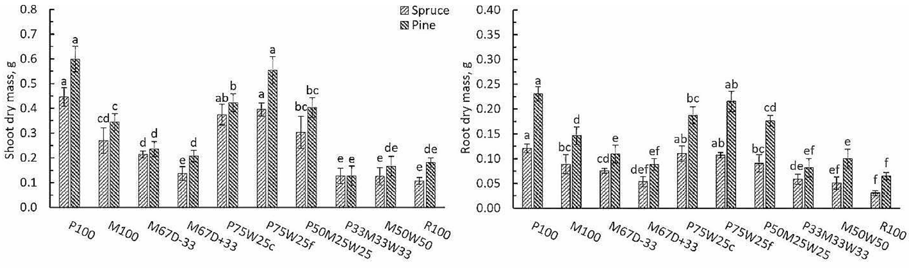

Fig. 5 Final biomasses of shoots and roots of spruce and pine seedlings grown in different growing media (arithmetic mean ± Sd, $n = 6$ container trays). The different letters above the bars indicate significant differences between growing media within tree species ($p < 0.05$, Bonferroni test)

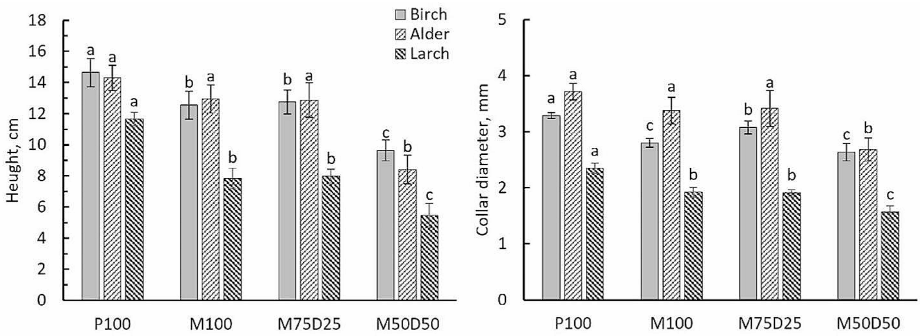

Fig. 6 Final height and collar diameter of birch, alder and larch seedlings grown in different growing media (arithmetic mean ± Sd, $n = 6$ container trays). The different letters above the bars indicate significant differences between growing media within tree species ($p < 0.05$, Bonferroni test)

increased in GM in the order P100, M100, M75D25 and M50D50 being 1.4, 4.2, 15.3, and 58.3% respectively.

Seedling growing in tree nursery

Despite manual tray filling, some partially filled cells with GM in trays (PL81f) were still found in the nursery due to settling. Immediately after the trays in the Suonenjoki nursery were sowed and irrigated, the fresh total masses of trays (in kg) were found to decrease linearly as the maximum vertical height gap (cm) in a cell of a tray increased in relation to the full cell height (7.3 cm) ($R^2 = 0.85$, 10 trays x 9 different GM were measured). The greatest average tray mass was in P100 (6.52 kg) with the lowest maximum filling gap (0.49 cm), while the lowest tray mass (4.23 kg) was associated with the highest filling gap (1.72 cm) in W75D25. Three and half months later at terminal bud formation, the moist tray masses had a similar but less pronounced relation to the maximum height gap in tray cells ($R^2 = 0.26$), because P100 had a very low filling gap (0.31 cm), and R100 a very high gap (1.36 cm) in relation to their tray masses. The highest tray mass (6.16 kg) was in R100, and the lowest mass (3.76 kg) in W75D25, which had the highest filling gap (1.47 cm).

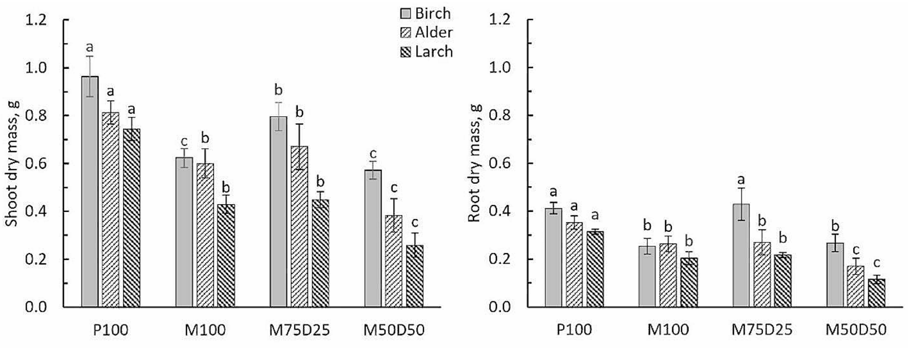

Fig. 7 Final biomasses of shoots and roots of birch, alder and larch seedlings grown in different growing media (arithmetic mean ± Sd, $n = 6$ container trays). The different letters above the bars indicate significant differences between growing media within tree species ($p < 0.05$, Bonferroni test)

At the Suonenjoki nursery, the proportion of spruce seedlings considered non-marketable and rejectable at harvest was highest in W75D25 (76.6%) and was within 4.6–10.7% in other GM (Fig. S2). The shoot terminal height of the marketable spruce seedlings lower in M50W50, M50W50 + N, and especially in W75D25 compared with P100, M100, M100 + N, P75W25f and M75D25. However, the seedling diameter at root collar in relation to height (i.e., sturdiness) was highest (15.7%) in W75D25. At the Partaharju nursery, the proportion of non-marketable rejected spruce seedlings was 3.4, 10.5, 12.4 and 23.9% in P100, M100, M75D25, and M50W50 respectively (Fig. S3). The largest growth was in P100, while it was weakest in M50W50.

At Suonenjoki, most non-marketable pine seedlings (11.2%) were found in R100, while it was below 6.7% in other GM (Fig. S4). The growth of the marketable pine seedlings was weakest in M50W50 + N. Birch seedlings showed a relatively high proportion of non-marketable seedlings (17–28%) due to poor germination and probably unoptimized fertigation (Fig. S5). Birch seedling grew best in P100, while in M100 and M75D25 growth was significantly decreased.

Discussion

In this study, pure Sphagnum peat proved again its good performance as GM in tree seedling production. The dominance of peat as a GM has been based on its good growing performance and long-term development work in practical horticulture and tree seedling production, as well as on its good properties proved by scientific research (Schmilewski 2008; Rikala 2012; Barrett et al. 2016). Peat has been readily available, has good water and nutrient retention properties, and can sustain low pH and suppressiveness to seedling pathogens in the GM and resist seedling damping-off (Tahvonen 1982; Rikala and Jozefek 1990; Rikala 2012; Heiskanen 2014). In Finland and Scandinavia, container seedlings have also shown a good post-planting rooting and growth performance with site preparation in reforestation (Heiskanen and Rikala 2000; Laine et al. 2019; Uotila et al. 2022). Nordic outplanting experiences and tests with varying GM show that generally there are differences in the post-planting seedling growth among different GM (peat showing best growth), but these differences commonly disappear after the first growing season (Heiskanen and Rikala 2003; Heiskanen et al. 2009; Veijalainen et al. 2007). To deploy novel peatless and reduced-peat GM in nurseries, these GM should also possess the corresponding properties to those of Sphagnum peat during the nursery and post-planting growing phases.

Various biomasses, biochars, and recycled materials have been suggested for alternative GM and for cascade use, i.e., first as GM and finally as a C-rich soil improver (Vandecasteele et al. 2023). A variety of materials has been tested to find potential peat substituting GM for forest seedling production, such as bark, biochar, chips, coir, compost, manure, other organic waste, rice, sawdust, sewage sludge, and wood fiber (Landis and Morgan 2009; Heiskanen 2013, 2014; Dumroese et al. 2018; Mariotti et al. 2020, 2023; Köster et al. 2020; Adamczyk et al. 2022). Globally, composts are the most commonly studied materials for alternative GM, followed by bark, other organic materials, and manure, the applicability of which is based on their regional or local availability and performance during the nursery phase as well as after outplanting in the field (Mariotti et al. 2023). However, many potential alternative GM materials, whether virgin or recycled from industrial or household sidestreams and wastes with possible pretreatments such as composting (aging) or hydrothermal processing, may prove to be costly and have variable quality (Heiskanen 2013; Barrett et al. 2016; Dumroese et al. 2018; Gruda 2019; Van Gerrewey et al. 2020; Azori et al. 2021; Taparia et al. 2021; Hirschler et al. 2022; Adamczyk et al. 2022). For Nordic forest tree seedling production, no outstanding replacement GM for peat has been found thus far.

In this study, the water retention properties and the particle size distribution affecting them were found to vary among the studied GM and to have an effect on seedling growth. Easily available water and buffer water retention capacities of GM had a positive linear correlation (Fig. S1) with the mean final height of spruce and pine seedlings in the greenhouse experiments with artificial lightning. Good seedling growth has also previously been shown to prevail in GM at matric potentials from container capacity to -5 to -10 kPa (Heiskanen 1995). This relation implies that the irrigation need varied not only because of the specific water retention characteristics of the various GM but also because of transpiration, which was relatively high in the conditions used with artificial lightning. The applied fertigation therefore obviously did not fully meet the water and nutrient demand. On the other hand, if irrigation to the container capacity in GM with high water retention is too frequent, it can increase the risk of waterlogging (Heiskanen 1995).

Irrigation and fertilization requirements have also previously been found to vary according to the GM type and species grown (Rikala 2012; Heiskanen 2013; Dumroese et al. 2018). Fertigation should therefore be adjusted for each GM type and growing conditions separately to achieve the best possible water, oxygen, and nutrient availability from the GM (Heiskanen 1995, 2013; Dumroese et al. 2018). N supply especially needs to be adjusted during growing and particularly when N is leached out or immobilized due to high C content. During immobilization, microorganisms out-perform plants for NH_4+and NO_3- when plants may become N deficient (Recous et al. 1990; Domeño et al. 2013; Adamczyk et al. 2022). Alternative GM with recycled materials can contain both harmful and beneficial microbes, when residue streams may require pre-treatment of microbiomes (Heiskanen 2013, 2014; Van Gerrewey et al. 2020; Taparia et al. 2021). In this study, no clear evidence on seedling damage by pests or pathogens was observed (cf. Heiskanen 2014).

The GM with digestate showed wetness during growing but also surface hardness at the start when mist irrigation was used, which resulted in delayed initial primordial root penetration in these GM. Larch seedlings especially were observed to have superficial rooting in media with the digestate component, which tended to compact the GM surface structure. This probably contributed to the lower growth of seedlings in those digestates containing GM (cf. Heiskanen 2021). In reed compost (R100), moist conditions during the growing experiment tended to disintegrate crumbs, as silting up was observed, resulting in an almost slurry-like percolate. The high total N concentration of press water extract in R100 at the end phase of the growing experiment probably contributed to by the initial N content in R100 and possibly by N released due to advancing decomposition in moist conditions during the growing experiment.

Overall, pure Sphagnum peat (P100), which has conventionally been used in container seedling production, yielded the tallest seedlings in all this study's experiments. GM mixes, which contained peat of at least 50 vol% (P75W25c, P75W25f, P50M25W25), also produced seedlings that were as good and tall as or slightly smaller than pure peat. Similar results have also been reported previously (Heiskanen 2013, 2014; Srámek et al. 2010; Dumroese et al. 2018; Köster et al. 2020; Adamczyk et al. 2022). Peat-reduced, multi-component GM are thus potentially deployable in nursey production as such or after adjusting their properties and growing management procedures (handling and fertigation). However, no economic evaluation was made of the effects of lower seedling yields or the adjustments required in the growing practices of the tested alternative GM.

Pure Sphagnum moss (M100) also showed reasonable seedling growth compared with pure peat but was also observed to have issues with N availability (immobilization) and reduced water retention. Reducing the particle size could improve water retention properties, as well as aging the moss, and using slow-release N in GM base fertilization could improve N availability. Several previous studies indicate that raw Sphagnum moss, either harvested from bogs or cultivated, may provide an easily available peat-free constituent or a fully peat-free GM as such (Emmel 2008; Gaudig et al. 2008; Reinikainen et al. 2012; Caron and Rochefort 2013äräinen et al. 2018, 2020; Müller and Glatz 2021; Tommila et al. 2022). Sphagnum biomass harvesting is considered a more environmentally friendly GM compared with the conventionally extracted white horticultural peat (Silvan et al. 2017; Silvan 2019). In countries with abundant peatlands, such as the Nordic countries, Sphagnum moss may therefore provide a promising GM (Blievernicht et al. 2012; Reinikainen et al. 2012). However, Sphagnum moss biomass remains a more expensive material as a GM constituent compared with horticultural Sphagnum peat, for example (Silvan et al. 2019). Despite the potential of Sphagnum moss, its feasibility as a horticultural substrate has yet to be more thoroughly investigated.

The seedlings grown in GM with less than one third of wood fibers generally performed reasonably well in this study. Similar results have also been observed in petunia growing (Lahti 2022). Wood fibers used in GM in proportions of one third or more (P33M33W33, M50W50) exhibited the lowest N concentration both in GM and later in spruce foliage, which indicate N immobilization (Adamczyk et al. 2022) and reduced water retention due to coarse fresh particles. These issues may be alleviated by aging the wood fibers, reducing their particle size and using slow-release N in GM base fertilization. Wood materials are considered sustainable renewable natural resources, which can provide GM alternatives to peat (Gruda 2012; González-Orozco et al. 2018; Adamczyk et al. 2022). However, competition for wood resources, e.g. from the energy sector, could limit the use of wood fibers in the GM. Various economic, legal, and environmental footprint issues can also limit the availability of peatless materials for GM (Hirschler et al. 2022).

GM containing cow manure digestate exhibited high N and P concentrations, as well as a tendency to silt and compact during growing, which probably contributed to slow primordial rooting, an increased need for pricking, and reduced later growth (cf. Heiskanen 2014, 2021). These issues may be alleviated by composting the digestate and harmonizing its particle size before mixing into other GM components so that silting up of particles and excess wetness may be avoided. Reed compost (R100) yielded acceptable seedlings but of a reduced size, probably because of low water retention at the start and then because of consolidation resulting from the silting of the crumb structure (cf. Heiskanen 2014). These issues could also be addressed by harmonizing the particle size by cutting the longest particles into smaller ones and screening out the finest ones. Furthermore, the possible occurrence of weed seeds in GM may need to be prepared for, e.g., by using covered storage piles after composting (Heiskanen 2014). All GM with a very uneven particle size or very coarse fractions or lumps require the adjustment of their particle size to enable the machine filling of seedling trays.

In the practical nursery growing of this study, the tallest conifer seedlings and the largest proportion of marketable seedling were generally found in P100. However, GM of pure moss M100, M100+N and peat-reduced GM P75W25f and M75D25 showed seedling performance close to P100. M50W50 and M50W50+N preformed somewhat more weakly. Spruce and pine seedlings grown in these GM in nursery generally reached the target heights for the one-year-old container seedlings (Rikala 2012). W75D25 exhibited the weakest growth and proportion of marketable seedlings, which was observed mainly as a result of dryness. Consequently, a lack of water, nitrogen, and other nutrients probably limited growth. The long white unprocessed wood fibers yielded a coarse structure, which would have required much more frequent fertigation. These wood fibers would probably have provided better properties than GM if aged or otherwise processed resulting in a smaller particle size.

In nursery growing, birch especially exhibited sensitivity to water and nutrient availability from the GM, as seedling growth was found to be low and variable. In M100, the probable cause was a loose structure and low water retention and in M75D25 a more compacted structure. Fertigation was also obviously too infrequent, failing to meet the greater demand of water and nutrients for faster growth in comparison to the slower growing conifer seedlings (pine and spruce).

In conclusion, this study showed that pure Sphagnum peat generally yields the best growing results of tree seedlings. However, some peat-reduced GM containing peat of at least 50 vol% were able to provide growth that was as good as pure peat. In general, all the studied alternative peat-reduced and peatless GM can produce acceptable seedlings, although commonly of reduced size and requiring adjustment in growing management. On the other hand, small seedlings with poorer above ground growth but relatively good root growth or diameter at root collar in relation to height (i.e., sturdiness) may get a lower quality score or be even rejected although they may have a good rooting capacity and perform well after outplanting to a forest site. The studied GM therefore have a potential to replace peat in seedling production, but adjustments of their physical and chemical properties as well as of seedling fertigation and management procedures are usually required. Issues with availability and financial costs and the environmental sustainability of alternative GM need to be resolved before their extensive deployment in forest tree seedling production. The outplanting success of the seedlings grown in these GM also remain to be studied. It should also be noted that studying the effects of various GM with various physical and chemical variables on seedling shoot and root growth may result in varying and even contradictory results because of the varying requirements of the species grown, as well as varying levels in the GM product development and in the possibilities to monitor and adjust the growing conditions.

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Declarations

Competing interests The authors declare no competing interests.

Conflicts of interest All authors declare that they have no conflicts of interest.

References

Adamczyk B, Adamczyk S, Kitunen V, Hytönen T, Mäkipää R, Pennanen T (2022) Variation in the chemical quality of woody supplements for nursery growing media affects growth of tree seedlings. New for 53:797–810. https://doi.org/10.1007/s11056-021-09887-6

Barrett GE, Alexander PD, Robinson JS, Bragg NC (2016) Achieving environmentally sustainable growing media for soilless plant cultivation systems – A review. Sci Hortic 212:220–234. https://doi.org/10.1016/j.scienta.2016.09.030

Blake GR, Hartge KH (1986) Bulk Density. In: Methods of Soil Analysis. Part 1. Physical and Mineralogical Methods, 2nd ed.; Agronomy Monograph 9. Klute A (ed) American Society of Agronomy and Academic Press: Madison, WI, USA, pp. 363–375. https://doi.org/10.2136/sssabookser5.1.2ed.c13

Blievernicht A, Irrgang S, Zander M, Ulrichs C (2012) The youngest peat – sustainable production of peat moss and is use as growing medium in professional horticulture. Extended Abstract No. 247. Proc.14th Int. Peat Congress, Int. Peat Soc., Stockholm, 7 pp. https://peatlands.org/assets/uploads/2019/06/Blievernicht-247.pdf

Blok C, Eveleens B, van Winkel A (2021) Growing media for food and quality of life in the period 2020–2050. Acta Hortic 1305:341–356. https://doi.org/10.17660/ActaHortic.2021.1305.46

Caron J, Rochefort L (2013) Use of peat in growing media: state of the art on industrial and scientific efforts envisioning sustainability. Acta Hortic 982:15–22. https://doi.org/10.17660/ActaHortic.2013.982.1

Domeño I, Irigoyen I, Muro J (2013) Determination of nitrogen immobilization index in growing media: Effect of incubation time and inoculation with compost. Acta Hortic 1013:81–84. https://doi.org/10.17660/ActaHortic.2013.1013.6

Dumroese KR, Heiskanen J, Tervahauta A, Englund K (2011) Pelleted biochar: chemical and physical properties show potential use as a substrate in container nurseries. Biomass Bioenergy 35:2018–2027. https://doi.org/10.1016/j.biombioe.2011.01.053

Dumroese RK, Pinto JR, Heiskanen J, Tervahauta A, McBurney KG, Page-Dumroese DS, Englund K (2018) Biochar can be a suitable replacement for Sphagnum peat in nursery production of *Pinus ponderosa* seedlings. Forests 9:1–21. https://doi.org/10.3390/f9050232

Emmel M (2008) Growing ornamental plants in Sphagnum biomass. Acta Hortic 779:173–178. https://doi.org/10.17660/ActaHortic.2008.779.20

Gaudig G, Joosten H, Kamermann D (2008) Growing growing media: promises of Sphagnum biomass. Acta Hortic 779:165–171. https://doi.org/10.17660/ActaHortic.2008.779.19

GME (2021) Growing Media Environmental Footprint Guideline. GrowingMedia Europe. Version 1.0, 58 p. https://www.growing-media.eu/single-post/gme-publishes-lca-guideline-for-growing-media

González-Orozco MM, Prieto-Ruíz JÁ, Aldrete A, Hernández-Díaz JC, Chávez-Simental JA, Rodríguez-Laguna R (2018) Nursery production of *Pinus engelmannii* Carr. With substrates based on Fresh Sawdust. Forests 9:678. https://doi.org/10.3390/f9110678

Gruda NS (2012) Sustainable peat alternative growing media. Acta Hortic 927:973–980. https://doi.org/10.17660/ActaHortic.2012.927.120

Gruda NS (2019) Increasing sustainability of growing media constituents and stand-alone substrates in soilless culture systems. Agronomy 9:298. https://doi.org/10.3390/agronomy9060298

Heiskanen J (1992) Comparison of three methods for determining the particle density of soil with liquid pycnometers. Commun Soil Sci Plant Anal 23:841–846. https://doi.org/10.1080/00103629209368633

Heiskanen J (1994) Hydrological properties of peat-based growth media. Academic dissertation. The Finnish Forest Research Institute, Research Pap 524:1–41. http://urn.fi/URN:ISBN:951-40-1391-3

Heiskanen J (1995) Irrigation regime affects water and aeration conditions in peat growth medium and the growth of containerized scots pine seedings. New for 9:181–195. https://doi.org/10.1007/BF00035486

Heiskanen J (2013) Effects of compost additive in sphagnum peat growing medium on Norway spruce container seedlings. New for 44:101–118. https://doi.org/10.1007/s11056-011-9304-6

Heiskanen J (2014) Puun ja ruokohelpin kuitumassan soveltuvuus metsäpuiden taimien kasvualustoiksi. [Suitability of wood and reed pulp as growing media for forest tree seedlings]. Finnish Forest Research Institute, Suonenjoki, p 18. https://urn.fi/URN:NBN:fi-fe2015071710652

Heiskanen J (2021) Kuivatun karjanlannan mädätejäännöksen soveltuvuus kasvualustaksi - esikoe. [Suitability of cattle manure digestate as a growing medium - pilot study]. Pohjois-Savon liiton ja Luonnonvarakeskuksen rahoittaman tutkimushankkeen loppuraportti. Luonnonvarakeskus. 12 p. http://urn.fi/URN:NBN:fi-fe2021041510503

Heiskanen J, Rikala R (2000) Effect of peat-based container media on establishment of Scots pine, Norway spruce and silver birch seedlings after transplanting in contrasting water conditions. Scan J Res 15:49–57. https://doi.org/10.1080/02827580050160466

Heiskanen J, Rikala R (2003) Effect of peat-based container media on establishment of Scots pine, Norway spruce and silver birch seedlings. Tree Planters' Notes 50:28–33. https://rngr.net/publications/tpn/50-1/effect-of-peat-based-container-media-on-establishment-of-scots-pine-norway-spruce-and-silver-birch-seedlings

Heiskanen J, Lahti M, Luoranen J, Rikala R (2009) Nutrient loading has a transitory effect on the nitrogen status and growth of outplanted Norway spruce seedlings. Silva Fenn 43:249–260. https://doi.org/10.14214/sf.210

Heiskanen J, Hagner M, Ruhanen R, Mäkitalo M (2020) Addition of recyclable biochar, compost and fibre clay to the growth medium layer for the cover system of mine tailings: a bioassay in a greenhouse. Environ Sci Pollut Res 79:Article 422. https://doi.org/10.1007/s12665-020-09154-5

Heiskanen J, Ruhanen H, Hagner M (2022) Effects of compost, biochar and ash mixed in till soil cover of mine tailings on plant growth and bioaccumulation of elements: a growing test in a greenhouse. Heliyon 8:e08838. https://doi.org/10.1016/j.heliyon.2022.e08838

Hirschler O, Osterburg B, Weimar H, Glasenapp S, Ohmes M-F (2022) Peat replacement in horticultural growing media: availability of bio-based alternative materials. Thünen Working Paper 190:56. https://doi.org/10.3220/WP1648727744000

Kalra YP, Maynard DG (1991) Methods manual for forest soil and plant analysis. Forestry Canada, Inf Rep NOR-X-319E. 116 p. https://cfs.nrcan.gc.ca/publications/download-pdf/11845

Kämäräinen A, Simojoki A, Linden L, Jokinen K, Silvan N (2018) Physical growing media characteristics of Sphagnum biomass dominated by Sphagnum fuscum (Schimp.) Klinggr. Mires Peat 21:1–16. http://mires-and-peat.net/media/map21/map_21_17.pdf

Kämäräinen A, Jokinen K, Lindén L (2020) Adding Sphagnum to peat growing medium improves plant performance under water restricting conditions. Mires Peat 26:Article13. http://mires-and-peat.net/media/map26/map_26_13.pdf

Köster E, Pumpanen J, Palviainen M, Zhou X, Köster K (2020) Effect of biochar amendment on the properties of growing media and growth of containerized Norway spruce, Scots pine, and silver birch seedlings. Can J Res 51:31–40. https://doi.org/10.1139/cjfr-2019-039

Lahti S (2022) The effects of added wood fibre in peat-based growing medium on Petunia x hybrida. Degree Thesis for Master of Natural Resources, Degree Program in Natural Resource Management, 40 p. https://urn.fi/URN:NBN:fi:amk-2022061417843

Laine T, Luoranen J, Ilvesniemi H (2019) Metsämaan muokkaus: Kirjallisuuskatsaus maanmuokkauksen vaikutuksista metsänuudistamiseen, vesistöihin sekä ekologiseen ja sosiaaliseen kestävyyteen. [Forest soil preparation: Literature review on the effects of soil preparation on forest regeneration, water bodies, and ecological and social sustainability]. Luonnonvara- ja Biotalouden Tutkimus 58/2019:1–83. https://urn.fi/URN:ISBN:978-952-326-813-5

Landis TD, Morgan N (2009) Growing media alternatives for forest and native plant nurseries. In: Dumroese RK, Riley LE (tech. coords.) National Proceedings: Forest and Conservation Nursery Associations-2008. Proc. RMRS-P-58. Fort Collins, CO: U.S. Dept of Agric, For Serv, Rocky Mountain Research Station, pp 26–31. https://rngr.net/publications/proceedings/2008/growing-media-alternatives-for-forest-and-native-plant-nurseries/at_download/file

Leinonen A (ed) (2010) Turpeen tuotanto ja käyttö. Yhteenveto selvityksistä. [Peat production and use. Summary of reports] VTT Tiedotteita 2550, 104 p http://www.vtt.fi/inf/pdf/tiedotteet/2010/T2550.pdf

Mariotti B, Martini S, Raddi S, Tani A, Jacobs DF, Oliet JA, Maltoni A (2020) Coconut coir as a sustainable nursery growing media for Seedling production of the ecologically diverse Quercus species. Forests 11:522. https://doi.org/10.3390/f11050522

Mariotti B, Oliet JA, Andivia E, Tsakaldimi M, Villar-Salvador P, Ivetić V, Montagnoli A, Janković I, Bilir N, Bohlenius H, Cvjetković B, Dūmiņš K, Heiskanen J, Hinkov G, Fløistad IS, Cocozza C (2023) A global review on innovative, sustainable, and effective materials composing growing media for forest seedling production. Curr For Rep 9:413–428. https://doi.org/10.1007/s40725-023-00204-2

Müller R, Glatz S (2021) Sphagnum farming substrate is a competitive alternative to traditional horticultural substrates for achieving desired hydro-physical properties. Mires Peat 27:Article 21. http://www.mires-and-peat.net/media/map27/map_27_21.pdf

Nilsson U, Luoranen J, Kolström T, Örlander G, Puttonen P (2010) Reforestation with planting in northern Europe. Scand J Res 25:283–294. https://doi.org/10.1080/02827581.2010.498384

Ogle SM, Domke G, Kurz WA, Rocha MT, Huffman T, Swan A, Smith JE, Woodall C, Krug T (2018) Delineating managed land for reporting national greenhouse gas emissions and removals to the United Nations framework convention on climate change. Carbon Balance Manage 13:9. https://doi.org/10.1186/s13021-018-0095-3

Poteri M (2002) Forest nurseries in Finland. USDA for Service Rocky Mountain Res Stn Proceedings RMRS–P–28:59–63. https://rngr.net/publications/proceedings/2002/poteri.pdf

Recous S, Mary B, Faurie G (1990) Microbial immobilization of ammonium and nitrate in cultivated soils. Soil Biol Biochem 22:913–922. https://doi.org/10.1016/0038-0717(90)90129-N

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. Extended Abstract No. 137, Proc. 14th Int. Peat Congress, Int. Peat Soc., Stockholm, 6 pp. https://peatlands.org/assets/uploads/2019/06/Reinikainen-137.pdf

Rikala R (2012) Metsäpuiden paakkutaimien kasvatusopas. [Growing guide for container seedlings of forest trees]. Finnish Forest Research Institute, Vantaa, p 247. https://urn.fi/URN:ISBN:978-951-40-2359-0

Rikala R, Jozefek HJ (1990) Effect of dolomite lime and wood ash on peat substrate and development of tree seedlings. Silva Fenn 24:4 article id 5432. https://doi.org/10.14214/sf.a15586

Schmilewski G (2008) The role of peat in assuring the quality of growing media. Mires Peat 3:Article2. http://mires-and-peat.net/pages/volumes/map03/map0302.php

Silvan N (2019) Short-term effects of Shallow Sphagnum Moss Biomass Harvesting on the Runoff Water Quality. Int J Environ Monit Anal 7:34–39. https://doi.org/10.11648/j.ijema.20190701.15

Silvan N, Jokinen K, Näkkilä J, Tahvonen R (2017) Swift recovery of Sphagnum carpet and carbon sequestration after shallow Sphagnum biomass harvesting. Mires Peat 20:Article 01. http://mires-and-peat.net/media/map20/map_20_01.pdf

Silvan N, Sarkkola S, Laiho R (2019) Rahkasammalbiomassa ja sen korjuuseen soveltuvat suot Suomessa (Summary: Peatlands suitable for harvesting of renewable Sphagnum moss biomass in Finland). Suo - Mires and Peat 70:41–53. http://86.50.170.180/pdf/article10319.pdf

Srámek F, Dubský M, Weber M, Dostálek J, Skalo J (2010) Peat-reduced substrates with mineral components for growing of woody plants. Acta Hortic 885:361–366. https://doi.org/10.17660/ActaHortic.2010.885.51

Tahvonen R (1982) The suppressiveness of Finnish light coloured Sphagnum peat. J Agric Sci Finland 54:345–356. https://doi.org/10.23986/afsci.72115

Taparia T, Hendrixa E, Nijhuis E, Boer W, van der Wolf J (2021) Circular alternatives to peat in growing media: a microbiome perspective. J Clean Prod 327:129375. https://doi.org/10.1016/j.jclepro.2021.129375

Tommila T, Kämäräinen A, Kokko H, Palonen P (2022) Sphagnum Moss is a promising growth substrate in arctic bramble container cultivation. Acta Agric Scand B - Soil Plant Sci 72:997–1008. https://doi.org/10.1080/09064710.2022.2138778

Uotila K, Luoranen J, Saksa T, Laine T, Heiskanen J (2022) Long-term growth response of Norway spruce in different mounding and vegetation control treatments on fine-textured soils. Silva Fenn 56:articleid10762. https://doi.org/10.14214/sf.10762

Van Gerrewey T, Ameloot N, Navarrete O, Vandecruys M, Perneel M, Boon N, Geelen D (2020) Microbial activity in peat-reduced plant growing media: identifying influential growing medium constituents and physicochemical properties using fractional factorial design of experiments. J Clean Prod 256:120323. https://doi.org/10.1016/j.jclepro.2020.120323

Vandecasteele B, Similon L, Moelants J, Hofkens M, Melis P, Visser R (2023) Cascading use of renewable growing media versus peat or mineral wool: added value of biochar for end-of-life, recycling of nutrients and C storage potential. Nutr Cycling Agroecosyst. https://doi.org/10.21203/rs.3.rs-2399045/v1

Veijalainen A-M, Heiskanen J, Juntunen M-L, Lilja A (2007) Growing of Picea abies container seedlings in peat and composted forest-nursery waste mixtures for forest regeneration. Scand J Res 22:390–397. https://doi.org/10.1080/02827580701647271

Virkajärvi P, Hyrkäs M, Räty M, Pakarinen T, Pyykkönen V, Luostarinen S (2016) Biokaasuteknologiaa maatiloilla II. Biokaasulaitoksen käsittelyjäännöksen hyödyntäminen lannoitteena. [Biogas technology on farms II. Utilization of biogas plant processing residue as fertilizer]. Luonnonvara- ja Biotalouden Tutkimus 37:1–115. https://urn.fi/URN:ISBN:978-952-326-266-9

Vuorinen J, Mäkitie O (1955) The method of soil testing in use in Finland. Agrogeol Publ 63:1–44

World Energy Council (2013) World Energy resources. 2013 Surv Chapter 6: Peat:1–24. https://www.worldenergy.org/assets/images/imported/2013/10/WER_2013_6_Peat.pdf

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