Preliminary Assessment of Afforestation of Cutover Peatland with Spot Application of Sewage Sludge Compost

JÜRI JÄRVIS*, MARI IVASK, LEMBIT NEI, ANNELY KUU AND EGGE HAIBA

Tallinn University of Technology, Tartu College, Puiestee 78, 51008 Tartu, Estonia

** Corresponding author (jyri.jarvis@gmail.com, tel. +372 511 9714)*

Järvis, J., Ivask, M., Nei L., Kuu, A. and Haiba, E. 2017. Preliminary Assessment of Afforestation of Cutover Peatland with Spot Application of Sewage Sludge Compost. *Baltic Forestry* 23 (3): 644–657.

Abstract

The aim of the study was to seek a method for the quick revegetation of depleted peat mining areas in a near-city landscape, where the natural recovery of vegetation was impeded by a lack of some nutrients.

The test area was pure milled peat that remained mainly free of vegetation cover for ten years after the mining process ended. Seedlings of *Alnus glutinosa* (black alder) and *Betula pendula* (silver birch) were planted in sewage sludge compost-filled drill-holes with a diameter of 20 cm and depth of 50 cm. For comparison, spot-applied multicomponent fertiliser was used in drill-holes of the same size, which were back-filled with the same peat, for the test group. Seedlings with spot-applied fertiliser without drill-holes and control seedlings without treatment were also planted into cutover peatland. Significantly greater ($p < 0.001$) average annual growth of height (73 cm) was followed with one-year-old silver birches planted with sewage sludge compost at the end of the growing season compared to other seedlings treated with multicomponent fertiliser (56 cm with drill-holes and 55 cm without holes). Significantly longer ($p < 0.05$) root growth in the vertical direction (53 cm) was achieved for compost-treated birches compared to both fertiliser treatment groups (47 and 42 cm). The average values of the length of the largest leaves were determined in the case of the compost treatment group (83 mm) compared to fertiliser treatment groups (68 and 67 cm; $p < 0.05$). Similar growth trends of the same parameters were achieved with one-year-old black alder seedlings, but the differences were not statistically significant in most cases. Usage of sewage sludge compost with the current drill-hole planting method can be suggested for afforestation of cutover peatlands with silver birch for its remarkably high height growth-promoting efficiency compared to fertiliser treatments. With black alder, the height growth-promoting effect of the compost was weaker, being similar to the fertiliser treatments.

Keywords: reforestation, afforestation, reconstruction, sewage sludge compost, biosolids, height growth

Introduction

There are many different scenarios for abandoned cutover peatlands: recovering commercial peat production, afforesting the peat area (Nilson and Lundin 1996, Holden 2004, Lachance et al. 2005), leaving it to regenerate naturally (Ruseckas et al. 2015), restoring the bog plant community by blocking runoff (Gonzales et al. 2014, Jarašius et al. 2015), creating an artificial lake, etc. Afforestation of cutover peatland requires a different approach to afforestation of mineral soil. A serious lack of some nutrients in peat, like phosphorus and potassium, may make ordinary planting and seeding methods almost futile. Commonly practiced microsite preparation methods for afforestation planting as scalping and mounding have an effect on seedlings' growth in soils, where a formerly limiting factor water regime is improved (Londo and Mroz 2001, Pietrzykowski et al. 2015). Scalping and mounding may also have a growth-promoting effect, when availability of nutrients to seedlings is improved by opening the nutrient-rich soil layer for planting in the case of scalping or adding an upper nutrient-rich layer in the case of mounding (Londo and Mroz 2001, Pearson et al. 2011, Silvan and Hytönen 2016). Lack of at least some nutrients in soil layers can be compensated for only by adding the needed nutrients to the soil. If soil aeration and water availability are sufficient, then afforestation can be significantly supported with mineral fertilisers in nutrient-poor soils (Raid 1979, 1986, Valk 1992, Pikk 2001). Afforestation can be successfully supported with waste substances like wood ash or peat ash (Huotari et al. 2008, Pärn et al. 2009, Kikamägi et al. 2013, Hytönen 2016). Usage of oil shale ash mixed with phosphorus-enriched filter-peat from a wastewater treatment plant has shown promising results as a substrate in the test growing of silver birch seedlings (Kõiv et al. 2012). Application of sewage sludge before afforestation has resulted in high gains in height growth in peat (Pikka 2005, 2006). Usage of surface-spread sludge has caused high weed competition, which decreased the survival of seedlings (Lazdiņa et al. 2013) and required weeding every month (Pikka 2005).

In the current work, a new method of recycling sewage sludge compost for afforestation of cutaway peatland was tested. To test the composted sewage sludge's growth-promoting efficiency, the height growth of two domestic broadleaved forest tree seedlings (black alder and silver birch) were compared. The seedlings were grown with and without sewage sludge compost on cutover peatland. As a comparison, using green compost in drill-holes (20 cm diameter, 50 cm deep) in an earlier test resulted in significant height growth of tree seedlings on cutaway peatland (Järvis et al. 2016).

The selection of the species was grounded on the following assumptions. The black alder species tolerates high water levels in soil, which is common on peatlands during springtime. Black alder is also a common species in wet areas. Silver birch is a pioneer species that naturally spreads on cutover peatlands, when the peat contains enough nutrients to support its growth. The choice of seedlings was based on the fast-growing broadleaved tree seedling availability on the market (one- and two-year-old black alder seedlings and one-year-old silver birch seedlings). There was a question whether two-year-old black alder seedlings are as tolerant to transplanting into a completely different growth environment with a high soil fertility contrast; therefore, both one- and two-year-old seedlings were used in the test.

It is problematic to use sewage sludge compost for agricultural purposes because it may contain an excess number of chemical contaminants that can be assimilated by food crops (Määrus 2002, Lillenberg et al. 2010, Nei et al. 2011). However, sewage sludge compost is rich in minerals (McLaren and Smith 1996), enabling a long-lasting supply of these minerals for the fast growth of plants. Chemical contaminants are expected to be consumed from compost by forest tree plants and accumulate in their timber, enabling pollutants to be drawn out of circulation (López et al. 2014). The amount of compost needed to fill the planting holes is remarkably smaller and is expected to pose a less significant threat of components leaching into groundwater compared with the method of mixing the upper layer of the peat soil with a sewage sediment compost in afforestation (Pikka 2005). According to Valluru et al. (2010) even tiny amounts of P application (equivalent to 125-500 grams of phosphorus per hectare) close to root systems of pearl millet seedlings enhanced establishment under P-limiting conditions.

To increase its survival, it is important for a tree seedling to maximise its dimensions (stem height, root length and leaf size) as fast as possible after being planted into the destination ground. Large dimensions enable the exploitation of a sufficient growth area necessary for the future development of the tree. While the seedling is small in its dimensions at the moment of planting and has limited resources to spend on growth, every possible support that can be provided gives it a competitive edge over the surrounding weeds.

When plants have to spend less energy in penetrating their roots through thick soil, more energy remains for other vital expenditures like growing larger and more leaves. Larger total leaf area (more and larger leaves) in turn enables higher solar energy assimilation to support overall growth. The Leaf Area Index (LAI) is a more accurate indicator for describing plant growth than the length of the longest leaf. In this work, however, the longest leaf length as the growth speed-indicating parameter was used because it is the easiest to measure.

The compost doses do not support randomly situated weeds as much as the tree seedlings that are planted directly on top of the compost portions because the tree seedlings have a shorter distance to cover to reach the compost doses than do the weeds. The compost portions under the peat surface cannot be washed away by runoff water from springtime snowmelt. That reduces environmental risks.

Forestry regulations may require reforestation of an adjacent clearcut area before next clearcut is allowed. The reforestation requirement may state the number of trees per hectare and the minimum average height they should reach for an area to be considered reforested (Määrus 2006). The minimum height requirement, in particular, necessitates fast, firm and supported growth of planted seedlings. High seedlings (two or more years old) can be planted in order to meet the height requirement immediately, but the relatively small root systems of nursery-grown seedlings require a nutrient-rich soil solution to support crown growth. The current method can thus be especially helpful for supporting the early growth of tree seedlings in all unfertile but moist soils.

Economically it may be profitable to start the new forest generation as soon as possible after clear cutting and to speed its growth through the help of compost dosages to gain the maximum timber yield per year.

The general aim of the study was to test a method to achieve fast revegetation of cutover peatlands in a near-city landscape, where the natural revegetation process was hindered by a lack of some nutrients. The first accompanying aim was to find a near-city recycling option for composted city sewage sediment (industrial waste) to lower its recycling cost. The second accompanying aim was to create artificial composite soil that enables forest trees' fast growth for timber usage in the same city. In cutover peatland, there is an abundance of water and in compost there is an abundance of nutrients. Together, the two substances can support plants' growth remarkably.

The wider aim of the work was to create a reforestation method for water-sufficient forest areas near cities that are currently without significant economical production due to a deficit of some nutrients. These areas can be put into faster wood production by using the described method. Near cities the transportation costs for the compost to the growing site and for the wood back to the city would be relatively small due to short distances. Low transportation expenses can add economic viability to the method.

The hypothesis was developed that all the measured parameters that indicate growth speed of the seedlings (stem height growth, root horizontal and vertical growth, and the longest leaf length) will be improved with each treatment (compost, fertiliser and drilled planting hole).

Material and Methods

A planting test for afforestation of cutover peatland using sewage sludge compost was performed in the year of 2015.

General description of the cutover peatland test site

The test site is situated in the centre of Estonia, 30 km west from Tartu with coordinates N: 58°17'; E: 26°14'; altitude: 37 m above sea level (Figure 1).

Figure 1. Location of the test site

The **test site** was located on a depleted peat field (cutover peatland) that was most recently used 10 years ago, for producing peat for energy. The test site was a flat, levelled surface, mainly free of vegetation. The main weed species was the sparsely growing common reed (*Phragmites australis* Cav.) at the southern end of the test site. The soil upper layer, approximately 5 cm thick, was loose milled peat; the underlying peat layer was a thick, dark, moderately decomposed peat deposit with sparsely scattered softened tree trunk remains in its deeper part. The average depth of the peat layer was 150 cm (in the range of 110–250 cm). Under the peat layer was a yellowish-bluish clay layer that contained limestone grains. Remains of peat drainage ditches (with 40 m intervals) were merely twenty cm deep with willows and reed growing in rows in the locations of the ditches. The level of the groundwater changed during the test period from 40 cm in June and 95 cm in July to deeper than 100 cm in August and September. The nutrient content of the test site peat is shown in Table 1. The test site was exposed to direct sunlight throughout the day during the growing season.

The precipitation amounted to 291 mm and the sum of the effective temperatures (average day temperature over +5°C) was 1477°C during the period of 01 May–31 October 2015 as per information from the nearest weather station in Rannu-Jõesuu (N: 58°23'08"; E 26°08'03"; altitude: 33 m above sea level).

Compost

Compost was prepared from city sewage sediment by Tartu Veevärk AS, the local waterworks company (www.tartuvesi.ee). The process comprised heating the sediment for hygienisation at 70 °C for an hour followed by anaerobic digestion at 37 °C for 21 days with methane production. In the following composting process, the sludge was mixed with peat (in a volume ratio of 1:1) and allowed to decompose in stacks; mixing took place once a week for six months (Toomiste 2015). The peat mixed with sludge was a combination of different peats originating from several peat mines, all with low pH and low nutrient content. The mixed peat had been stacked for approximately 25 years in a near-city open storage yard and therefore was well decomposed (Vares 2016). The compost had 30.5% of dry matter content and an average specific gravity of 1 g/cm^3. The concentration of nutrients in the compost in Table 1, and the heavy metal concentrations in Table 2 are given in comparison with the allowed limit values.

The soil and compost samples were analyzed for chemical indicators as follows:

pH$_{KCl}$ (pH in KCl solution) and total nitrogen (N) were determined with the Kjeldahl method; available phosphorus (P) content, potassium (K) and calcium (Ca) were determined with flame photometry (AOAC 1990); magnesium (Mg) was determined by flow injection analysis (ASA and SSSA 1982), and soil organic matter content was determined with the method of loss on ignition (Schulte 1995). According to the existing classification (Raudväli and Kanger 1996), the compost was with high P and Ca content. In Table 1 are enumerated the results of analyses.

Also, compost samples were analysed for trace elements as follows: zinc (Zn), copper (Cu), chromium (Cr), nickel (Ni), lead (Pb), arsenic (As) and cadmium (Cd) were determined with the standard methods described in European Standard 13657 (EVS 2003) and ISO 11047:1998 (ISO 1998), and mercury (Hg) was determined with the standard method described in European Standard 13806 (EVS 2002). Table 2 lists the results of analyses.

Table 1. Concentration of nutrients in the sewage sludge compost (in absolute dry matter) used for filling the planting holes in the peat on the test site and concentration of nutrients in the peat (0-10 cm and 40-50-cm-deep peat layers)

Substrate	pH$_{KCL}$	Nitrogen %	Phosphorus mg kg^{-1}	Potassium mg kg^{-1}	Calcium mg kg^{-1}	Magnesium mg kg^{-1}	Organic matter %
Compost	5.85	2.82	4880.70	1004.65	4253.00	2345.10	50.25
Peat in depth 0-10 cm	5.13	2.78	5.58	26.90	11189.90	1123.10	70.22
Peat in depth 40-50 cm	5.28	2.96	3.01	113.63	11298.40	1274.00	71.27

Table 2. Concentrations of heavy metals in the sewage sludge compost used in current planting test and limit values allowed according to currently valid regulation, both in absolute dry matter (Määrus 2002)

Element	mg kg^{-1}	Limit value mg kg^{-1}
Chromium	53.1 ± 8.0	1000
Nickel	23.7 ± 5.8	300
Copper	125 ± 31	1000
Zinc	397 ± 99	2500
Arsenic	< 0.1	N/A
Cadmium	< 0.6	20
Mercury	0.411 ± 0.062	16
Lead	18.4 ± 4.6	750

Fertiliser

For comparison with the growth-enhancing effect of compost, two test series of seedlings with fertiliser additions were also planted. The fertiliser was produced by Yara Suomi OY (Yara 2015), product name "Yara Puutarhan PK 3-5-20-13 (with low chloride content)". The applied multicomponent fertiliser was specially designed for usage on peat soils and contained a variety of micronutrients. The list of components of the fertiliser is given in Table 3.

Table 3. Nutrients in the fertiliser that was used in planting of the third and fourth test groups of seedlings

Element	Gravimetric %	Element	Gravimetric %	Element	Gravimetric %	Element	Gravimetric %
Nitrogen	3.2	Magnesium	3	Copper	0.03	Zinc	0.02
Phosphorus	5	Sulphur	13	Manganese	0.03	Selenium	0.001
Potassium	20	Boron	0.01	Molybdenum	0.01		

Note: The data was provided by the producer of the fertiliser (Yara 2015).

A comparison of amounts of active nutrient ingredients given to test seedlings with compost and with fertiliser is given in Table 4.

Table 4. Comparison of amounts of active ingredients in the fertiliser and in the compost added to seedlings during planting

Active ingredient	Amounts of active ingredients in:				Amount of active ingredients in 13.5 litres of compost compared to 30 g of fertiliser (times)
	Fertiliser, g kg^{-1}	Compost, g kg^{-1} dry matter	Fertiliser, g in 30 g	Compost, g in 13.5 litres (30% dry matter)	
Nitrogen	32	28.2	0.96	116.1	121
Phosphorus	50	4.8	1.50	19.8	13
Potassium	200	1	6.00	4.12	0.69
Magnesium	30	2.3	0.90	9.47	11
Copper	0.3	0.1	0.01	0.41	46
Zinc	0.2	0.4	0.01	1.65	275

Planting material

Three types of broadleaved bare-rooted planting material were used: 452 one-year-old black alder (*Alnus glutinosa* (L.) Gaertn.) seedlings, 296 two-year-old black alder seedlings and 304 one-year-old silver birch (*Betula pendula* Roth) seedlings were planted into cutover peatland. All the seedlings were grown in the local RMK Tartu Tree Nursery (RMK 2015) from certified seeds. All the seedlings were planted manually during the period 03–13 May 2015. Each of the three planting material types was divided into four groups. Each group was planted in one row according to one of the methods described below. The rows were arranged side by side and approximately 2 meters apart.

Planting

The **first group** of seedlings was the **control group**. The seedlings were planted without treatment directly into unprepared peat. Planting holes were dug manually with a planting shovel preparing the planting hole for each seedling with a size sufficient to fit the roots of the seedlings into the peat.

The **second group** of seedlings was planted into **drilled holes filled with sewage sludge compost**. The holes were 20 cm in diameter and 50 cm deep and drilled using a Stihl BT 121 soil auger. The volume of each hole was approximately 15.7 litres. The holes were filled with the above-described sewage sludge compost, leaving approximately 5–10 cm of unfilled space at the top for seedlings roots (2–2.5 litres). In calculations, the volume of the compost was rounded to 13.5 litres. The specific gravity of the compost was close to 1 g / cm^3, its dry matter content was 30.5%, and the organic matter content in dry matter was 50.25%. Therefore, the dry matter content in one compost filling was around 4.1 kg and mineralized, and the readily available percentage for plant assimilation was hence 49.75%, thus approximately 2 kg of dry matter.

During planting, the roots of the seedlings were surrounded with the same peat that was drilled out. Only a few roots were left directly in contact with the sewage sludge compost; most of the roots were surrounded with back-filled peat. Contact of most of the roots with the compost was avoided because of the existing risk that its very high content of phosphorous and potassium could have inhibited root growth. According to former studies (Föhse and Jungk 1983, Zia et al. 1988), high P and K contents in the sewage sludge compost can inhibit growth of roots and the entire plant, when roots are put in direct contact with it. The drilled-out peat with low P and K content peat (see Table 1) was used to form a buffer between most of the roots and the compost.

The **third group** of seedlings was planted into drilled holes that were the same size as those for the second group, but the holes were **back-filled only with the same peat that was drilled out,** and **30 grams of multicomponent fertiliser was added**. The purpose of the third group was to compare its height growth results with the second group to test if the sewage sludge compost additions give an advantage compared with fertiliser additions. The goals of back-filling were: a) to allow better aeration for seedlings roots in naturally densely compacted peat, in expectation that roots would grow deeper inside the holes; and b) to enable easier and faster planting into pre-prepared soft peat. In order to make sure seedlings had the needed nutrients, approximately 30 g of PK fertiliser with microelements were inserted in peat soil-poked holes. Only one hole, 10 cm in the southern direction from each stem and 10–15 deep, was poked for each seedling. The deep-placement spot-fertilizing method is taken from orchard gardening, where it is used to fertilize already growing trees at their root levels without disturbing root systems (Watson 1994, Lin et al. 1996). This method is also used in afforestation (Koch and Pickersgill 1984, Vavříček et al. 2010) and for growing rice (Hasanuzzaman et al. 2012, Rahman and Barmon 2015).

The **fourth group** of seedlings was planted into **unprepared soil like the first group**. The only difference from the first group was that **the same fertiliser was added** in the same way (also 30 grams) as with the third group. The purpose of the fourth group was to compare its height growth results with the third group to test if the deeper planting holes with expectedly better root aeration accelerate seedling growth more than fertiliser without improving root aeration.

Watering

All of the seedlings were watered immediately after planting with approximately one litre of water to avoid root desiccation when planted into a peat mix that had partially dried in the sun. No other watering was made after planting.

The volumetric water content (VWC) of the soil was measured with a Fieldscout TDR 300 (time domain reflectometry) soil moisture meter using 200-mm long measuring rods. Measured space inside the soil was an elliptical cylinder with the longest diameter of 10 cm and a depth corresponding to the length of the measuring rods according to the tool manual. Measurement points were 10- and 100-cm distances from seedlings stems. The 10-cm distance measurement points were chosen to be as close to the tree stems as possible to describe water status in the area of the greatest amount of root mass after planting. It was not possible to measure close to the stems without injuring the roots. Volumetric water content values were measured on 05 June, 12 July, 12 August, and 13 September 2015.

Weeding

The test site was relatively free of weeds throughout the growing season. In order to gain uniform vegetation conditions throughout the test site and to reduce the probably moderate shadowing effect of the growing reed in the southern part of the test site, the reed and other weeds were cut on 25 July using a clearing saw. No other weeding was done during the vegetation period.

Measurements and statistical analysis of results

The seedlings' height growth was monitored by measuring their height with a measuring tape with 1-mm accuracy. For the first time, the height measurements were made after planting on 28–29 May 2015, when the seedlings were already rooted and the starting point of the new shoots was clearly distinguishable on the stems. The second height measurements were made after the height growth of the trees had stopped on 20 September 2015. The annual height growth for each seedling was calculated as the difference between the first and the second height values. All the seedlings with animal browsing damage were excluded from the data. All negative annual growth heights (diebacks) were also excluded from the growth height analysis.

The number of seedlings excavated for **root measurements** comprised 24 seedlings of two-year-old black alders, 40 one-year-old black alders, and 40 silver birches (104 seedlings in total). The trees were taken equally from each treatment group. Root lengths were measured at the horizontal level in four directions (the main cardinal points N, E, S, and W) and in the vertical direction. All the root lengths were measured from the root collar to the root tips. Average horizontal root length for each seedling was calculated based on the lengths of the four roots. The depth of the uppermost root layer, where the longest horizontal roots were situated, was in the range of 5–11 cm from ground level. For measurement of roots, the upper layer of the peat was removed and the longest roots in the cardinal directions were measured. For root depths, a vertical half-circle hole was dug under the seedling following the deepest root of the seedling. All root lengths were measured with a measuring tape.

From each tree, one leaf was picked that was estimated to be the longest leaf blade. **Leaf lengths** were measured on millimetre paper. The leaves were picked on 22 and 24 October 2015, when most trees still had leaves attached. Only some silver birch control seedlings had lost their leaves.

Statistical analyses were performed with MS Excel 2013 software. Two sample *t*-tests assuming unequal or equal variances were chosen according to F-test results. *T*-tests were used to test the effect of planting methods on seedling growth parameters. All statistical tests were considered significant at the level of $p < 0.05$.

Results

The promoting effect on the growth of the seedlings' dimensions that was proposed in the hypothesis appeared the most clearly in the case of silver birch seedlings treatment groups. The dimensions' growth decreased in the following order: compost treatment, fertiliser-in-hole treatment, only-fertiliser treatment, and control. The sequence is apparent in the case of stem height, vertical root growth and leaf size (Figures 2-4). The growth differences were significant, at least at the $p = 0.05$ level in most cases, except between the fertiliser-in-hole treatment group and the only-fertiliser treatment group, where the differences were not significant. For significance levels, see Tables 6 and 7.

The treatments' growth-promoting effect can also be seen in both the black alders' longest average leaf lengths and the one-year-old black alders' vertical root depths. It seems that black alders are less sensitive to the treatments than silver birches.

Height growth

Height growth of compost-treated silver birch seedlings was significantly ($p < 0.001$) higher (73 cm) than fertiliser-treated seedlings (56 cm with hole and 55 cm without hole). The finding suggests that when planting silver birches in peat it is advisable to fertilise them with sewage compost rather than applying mineral fertiliser. Compost-induced improvements in height growth were weak for one-year-old black alders (+ 3 cm) and missing for two-year-old black alder seedlings (-1 cm) compared to the fertiliser-in-hole treatment group.

Differences in annual average height growth were significant between most series of two-year-old black alder seedlings except with the compost and fertiliser-in-hole treatment groups.

With one-year-old black alder seedlings, annual average height growth differences were significant between the control group and the rest of the treatment groups, and between the compost and fertiliser-only treatment groups. With one-year-old silver birch seedlings, all treatments gave significantly different average annual height growth results except between the fertiliser-in-hole and fertiliser treatment groups (Figure 2).

According to Figure 2 and Table 5, remarkable height growth improvement (30-33%) was achieved with compost treatment for silver birch seedlings compared to fertiliser treatments.

Root lengths

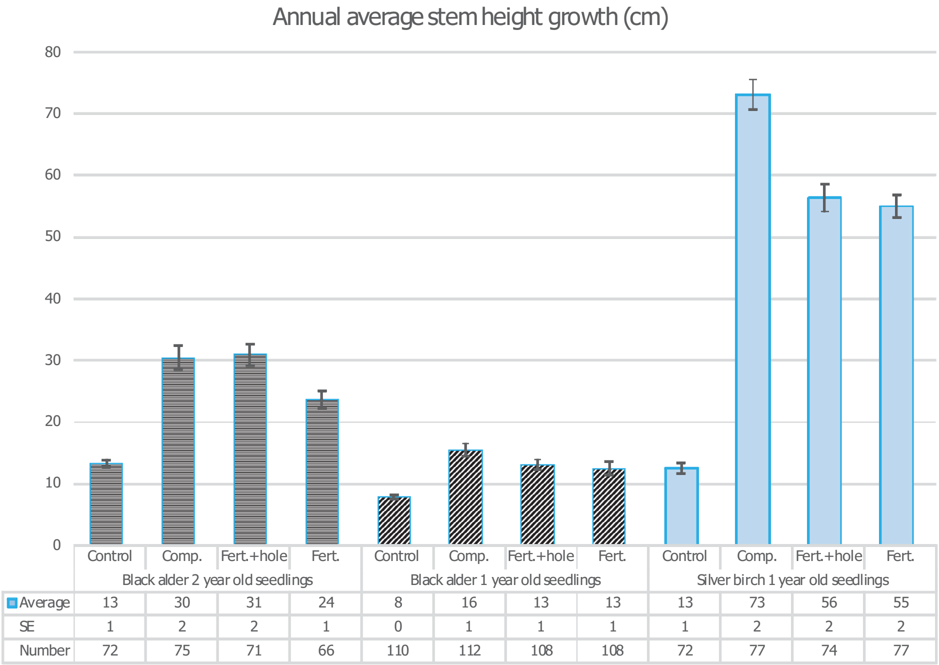
Roots' annual growth was calculated by subtracting average initial root length at the time of planting from final root length. The average initial root lengths were 10 cm in the vertical and horizontal direction for all seedlings, except for the one-year-old black alder seedlings, which measured 5 cm in the horizontal direction.

In the vertical direction, the root lengths increments were significantly shorter in all of the control groups compared to almost all of the test groups with all three types of tested planting material: one- and two-year-old black alder and one-year-old silver birch (see Table 6). Compost treatment resulted in significantly deeper roots compared to the other treatments with silver birches. The roots of all of three types of excavated test seedlings with compost always grew to the bottom of compost-filled holes (50 cm deep) and deeper in most cases. The result raises the question of how deep the roots might have grown if deeper holes had been dug.

In the case of the fertiliser-in-hole treatment, the roots of 7 out of 26 excavated seedlings from all three seedling types did not grow to the bottom of the 50-cm-deep holes. In the fertiliser-only treatment group, the roots of 11 out of 26 of the excavated three types of seedlings did not grow to the 50-cm depth level. The back-filled peat was remarkably softer compared to the surrounding unspoiled peat layers, and hence the roots must have penetrated it more easily.

In the horizontal direction, all silver birch test groups showed significantly longer root growth compared to the control group, and the compost group had significantly longer horizontal roots increments (122 cm) compared to the fertiliser-in-hole group (94 cm), (Figure 3, Table 6). Contrary to expectation, the seedlings treated only with fertiliser had a 102-cm-long horizontal root length increment on average. The root systems of seedlings in the fertiliser-in-hole treatment group were distributed a little deeper instead of growing in the horizontal direction. In all test groups of silver birches, the roots grew to around half of the 2-meter distance between seedlings (122, 94, and 102 cm), covering most of the peat area, and made colonisation of other plant species more difficult.

In the case of horizontal root growth of one- and two-year-old black alders, significant differences were



	Black alder 2 year old seedlings				Black alder 1 year old seedlings				Silver birch 1 year old seedlings			
	Control	Comp.	Fert.+hole	Fert.	Control	Comp.	Fert.+hole	Fert.	Control	Comp.	Fert.+hole	Fert.
■ Average	13	30	31	24	8	16	13	13	13	73	56	55
SE	1	2	2	1	0	1	1	1	1	2	2	2
Number	72	75	71	66	110	112	108	108	72	77	74	77

Figure 2. Annual average height growth (cm) of seedlings with different treatments. Error bars represent standard errors, and the numbers represent successfully grown seedlings in each series. Abbreviations: **Control** denotes control seedlings planted without treatment; **Comp**. denotes test seedlings planted into compost-filled hole; **Fert. + hole** denotes test seedlings planted into back-filled 50-cm deep, 20-cm in diameter holes with spot-applied fertiliser; **Fert.** denotes test seedlings with only spot-applied fertiliser; **SE** denotes standard errors of average height growth (cm), error bars on graph represent standard errors; **Number** denotes the number of seedlings measured

Table 5. *T*-test *p*-values comparison table for differences significances of average stem height growth. *P*-values < 0.05 are shown in bold

	Black alder 2 y	Black alder 1 y	Silver birch 1 y
Control			
Compost	**< 0.001**	**< 0.001**	**< 0.001**
Fertiliser in hole	**< 0.001**	**< 0.001**	**< 0.001**
Only fertiliser	**< 0.001**	**< 0.001**	**< 0.001**
Compost			
Fertiliser in hole	0.852	0.063	**< 0.001**
Only fertiliser	**0.004**	**0.035**	**< 0.001**
Fertiliser in hole			
Only fertiliser	**0.001**	0.619	0.629

seen between control and compost treatments. Differences were also significant between control and fertiliser-in-hole treatments in the case of one-year-old seedlings.

Leaf lengths

There was a significant difference between the longest leaf lengths of the control and test groups. The compost-treated seedlings' longest leaves were also significantly longer than with both fertiliser-treated seedling groups in the case of the one-year-old black alders and silver birches. In all the seedling groups, a trend in leaf length, from longest to shortest, for treatments was determined as follows: compost > fertiliser-in-hole > fertiliser > control (Figure 4, Table 7).

Weeding

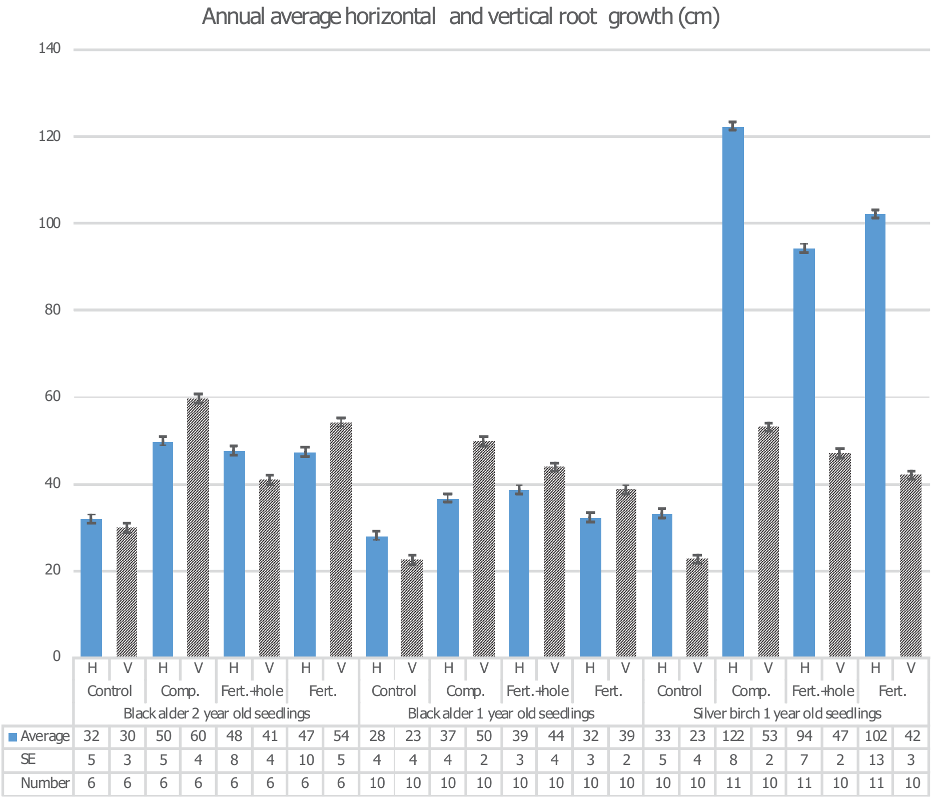
In the current work, in most cases (96%) neither sewage compost fillings nor the spot-applied fertiliser caused weed growth around the seedlings. In 2% of the cases the weeds grew high enough to create competition for light with the tree seedlings (they were as high or higher as the seedlings). All the competing weeds were cut once during the vegetation period, on 25 July. Another weeding was not observed as necessary.

Volumetric water content (VWC)

The average VWC values near the seedling roots (10 cm from stems) were always significantly smaller than when measured in equal distances between stems (one meter from stems), see Figure 5.

Figure 5 shows two overlapping influences on peat soil volumetric water content. Water content reduction appears 10 cm from the seedlings (columns marked with "A"): 1) due to seedlings' transpiration and 2) a reduced amount of absorbed water in loosened peat soil in drilled planting holes (in the cases of the compost and fertiliser-in-hole treatment groups). In the case of the control and fertiliser treatment groups, the influence of loosened peat soil around seedling roots was smaller to the measured results. This was due to their only 5–10-cm deep manually dug planting holes, which contained a smaller amount of loosened peat.

Volumetric water content was remarkably lower, being 18–28% 10 cm from the stems of the compost and fertiliser-in-hole treatment seedlings with all types of planting material compared to 42–49% measured 100 cm from stems. In comparison, while there were no drilled holes for the control and fertiliser-only treatment groups,



	H	V	H	V	H	V	H	V	H	V	H	V	H	V	H	V	H	V	H	V	H	V	H	V
	Control		Comp.		Fert.+hole		Fert.		Control		Comp.		Fert.+hole		Fert.		Control		Comp.		Fert.+hole		Fert.	
	Black alder 2 year old seedlings								Black alder 1 year old seedlings								Silver birch 1 year old seedlings							
■ Average	32	30	50	60	48	41	47	54	28	23	37	50	39	44	32	39	33	23	122	53	94	47	102	42
SE	5	3	5	4	8	4	10	5	4	4	4	2	3	4	3	2	5	4	8	2	7	2	13	3
Number	6	6	6	6	6	6	6	6	10	10	10	10	10	10	10	10	10	10	11	10	11	10	11	10

Figure 3. Comparison of the average root length growth (cm) in horizontal **(H)** and vertical **(V)** directions. **SE** denotes standard errors of average root length (cm), error bars on graph represent standard errors; **Number** denotes the number of seedlings measured

their volumetric water content was higher (35–43%) 10 cm from the seedling stems from June till September. Water consumption caused by the seedling roots significantly reduced water content near the stems in all tested seedling types and groups compared to peat at a distance of 100 cm from the tree stems.

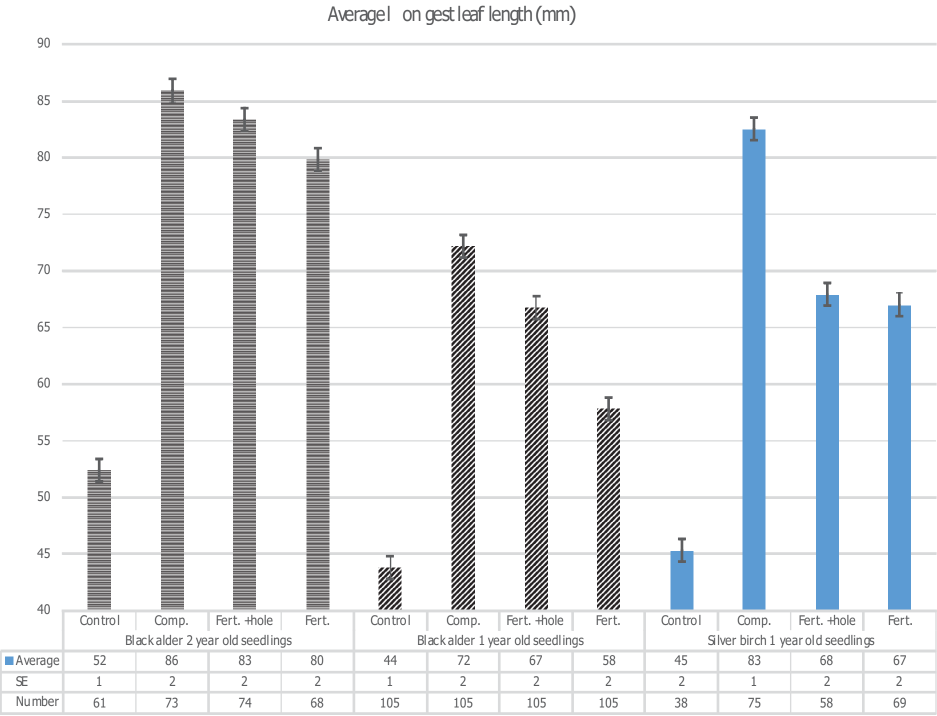
Discussion and conclusions

In the current test, significantly higher **height growth** of silver birch seedlings was achieved with city sewage compost compared to multicomponent fertiliser. Though the test was performed during only one growth season, the afforestation height requirement of 1 m (Määrus 2006) was achieved with compost application. Similar high stem height growth results have been achieved in previous studies with sewage sludge on cutover peatlands (Gradeckas et al. 1998, Pikka 2005). In another afforestation test, usage of sewage sludge for establishing forest on sand dunes gave a remarkably positive stem height growth effect, when the sludge was similarly inserted into holes (with dimensions of 40 × 40 × 40 cm) and covered with sand before planting. Sludge doses of 3–4 kg per planting spot (6–8 t ha^{-1} dry matter) were the most effective and using sludge as mulch on a sandy soil surface less effective (Kāposts et al 2000).

Table 6. *T*-test *p*-values comparison table for significant differences of average root length growth (coarse and fine roots together). *P*-values < 0.05 are shown in bold

	Black alder 2 y		Black alder 1 y		Silver birch 1 y	
	Horizontal	Vertical	Horizontal	Vertical	Horizontal	Vertical
Control						
Compost	**0.023**	**< 0.001**	**0.024**	**< 0.001**	**< 0.001**	**< 0.001**
Fertiliser in hole	0.114	0.069	**0.005**	**< 0.001**	**< 0.001**	**< 0.001**
Only fertiliser	0.149	**0.002**	0.057	**< 0.001**	**< 0.001**	**0.003**
Compost						
Fertiliser in hole	0.812	**0.010**	0.720	0.240	**0.015**	**0.043**
Only fertiliser	0.824	0.410	0.434	**0.004**	0.198	**0.010**
Fertiliser in hole						
Only fertiliser	0.981	0.076	0.180	0.302	0.587	0.230

If the peat layer was shallower (50 cm for example), then the compost-filled drill-holes helped the **vertical roots** to grow into the mineral soil underneath (see Figure 3) because the vertical roots reached to that depth on average compared to most other treatments. Interestingly, the vertical roots of fertiliser-only treated two-year-old black alders also reached a depth over 50 cm but not the roots of fertiliser-in-hole treated seedlings. It would have been interesting to test with deeper drill-holes to see how deep the compost-filled drill-holes could help to extend vertical root growth. For the trees growing in peat, it is beneficial to extend their roots into the mineral ground



	Control	Comp.	Fert. +hole	Fert.	Control	Comp.	Fert. +hole	Fert.	Control	Comp.	Fert. +hole	Fert.
	Black alder 2 year old seedlings				Black alder 1 year old seedlings				Silver birch 1 year old seedlings			
▮ Average	52	86	83	80	44	72	67	58	45	83	68	67
SE	1	2	2	2	1	2	2	2	2	1	2	2
Number	61	73	74	68	105	105	105	105	38	75	58	69

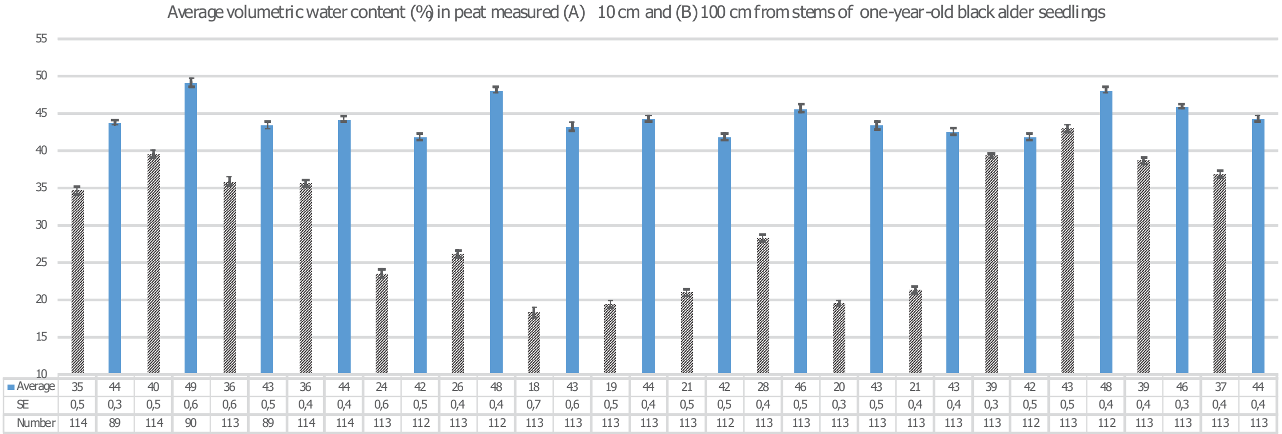
Figure 4. Comparison of the average longest leaf lengths (mm). **SE** denotes standard errors of average longest leaf (mm), error bars on graph represent standard errors; **Number** denotes the number of leaves measured

Table 7. *T*-test *p*-values comparison table for significant differences of average longest leaf lengths. *P*-values < 0.05 are shown in bold

	Black alder 2 y	Black alder 1 y	Silver birch 1 y
Control			
Compost	**< 0.001**	**< 0.001**	**< 0.001**
Fertiliser in hole	**< 0.001**	**< 0.001**	**< 0.001**
Only fertiliser	**< 0.001**	**< 0.001**	**< 0.001**
Compost			
Fertiliser in hole	0.340	**0.014**	**< 0.001**
Only fertiliser	**0.013**	**< 0.001**	**< 0.001**
Fertiliser in hole			
Only fertiliser	0.152	**< 0.001**	0.782

under the peat, which is richer in minerals compared to the peat. If the roots do not reach any other source of mineral nutrients, then the trees remain dependent on added nutrients.

In order to direct vertical roots into deeper soil layers, mineral fertiliser was also tested with and without drill-holes. Slow-moving and slow-dissolving P and K nutrients were put into the soil into trees' root zones for better assimilation from tree roots and in order to prevent weed proliferation, which may occur if fertiliser is spread on the ground under the trees (Huotari et al. 2007). In-



▮ Average	35	44	40	49	36	43	36	44	24	42	26	48	18	43	19	44
SE	0,5	0,3	0,5	0,6	0,6	0,5	0,4	0,4	0,6	0,5	0,4	0,4	0,7	0,6	0,5	0,4
Number	114	89	114	90	113	89	114	114	113	112	113	112	113	113	113	113

▮ Average	21	42	28	46	20	43	21	43	39	42	43	48	39	46	37	44
SE	0,5	0,5	0,4	0,5	0,3	0,5	0,4	0,4	0,3	0,5	0,5	0,4	0,4	0,3	0,4	0,4
Number	113	112	113	113	113	113	113	113	113	112	113	112	113	113	113	113

Figure 5. Comparison of volumetric water content (%) shows water removal by seedlings from stems' close vicinity in peat soil. Numbers in front of A and B indicate the month of the measurement (for example, 7 indicates July). **SE** denotes standard errors of average volumetric water content measured in peat (%), error bars on graph represent standard errors; **Number** denotes the number of measurement points

serting fertiliser into one spot in the soil is also technically easier than mixing it uniformly with the soil. The roots of trees tend to surround the spot-inserted fertiliser ration and get nutrients from the vicinity of the fertiliser spot in a water-dissolved form. It would have been interesting to test if mixing mineral fertiliser uniformly into back-filled holes (Lin et al. 1996) in peat would have prolonged roots' vertical growth compared to spot-fertilising. Plant roots have plastic reactions to heterogeneous supplies of nutrients in soil (Hodge 2003), therefore the shape of the nutrient-rich soil-space under the planting spot may affect the shape of the plant root system.

The **sizes of the leaves** describe nutrient availability for the plants (Müller et al. 2000, Niinemets et al. 2002). Their reduced size can be caused from reaction to lack of potassium (Jordan-Meille and Pellerin 2004) or lack of phosphorus (Fletcher et al. 2008). When leaf lengths of the untreated and test seedlings were compared, the difference was significant. One-year-old black alders' leaf sizes differed significantly among all the treatment groups (see Table 7). Granier and Tardieu (2009) claim that plant leaf sizes are indicators of many environmental stresses; in addition to lack of nutrients they can also react to salinity, low light, or water deficiency. In the current study the leaf size of one-year-old black alder seedlings reacted significantly positively to compost, having the longest length among the test groups (72 mm). Loosening soil around the roots of the fertiliser-in-hole seedlings resulted in a length of 67 mm, while the fertiliser-only treatment resulted in an average leaf length of 58 mm. The effect might be due to the improved respiration of roots, seedlings' lower energy consumption when growing their roots in less dense peat soil, or a combination of both of these factors. In comparison, control seedlings had an average leaf length of only 44 mm.

The current planting method with below-ground spot-applied compost and fertiliser shows **less need for weeding** compared to the method of mixing the upper layer of soil with a surface-applied sewage sediment layer for afforestation (Pikka 2005). In this case, it was necessary to weed every month. In the current test the sewage sludge was thermally treated for an hour before composting at 70°C, so any seeds in it lost their ability to germinate.

There is always a seed pool of ruderal plant species (seeds of weeds) available on cutover peatlands. The seed pool can germinate in improved moisture conditions as described by Triisberg et al. (2013) or in the case of improved nutrition availability (Huotari et al. 2007). In the current test the loose and relatively dry back-filled peat seemed to isolate the seeds of weeds from compost and spot-applied fertiliser. No remarkably higher occurrence of weeds in compost or spot-applied fertiliser locations was noticed. A germination test for finding weed seed occurrence density in peat was not performed.

The current method can be used, when the amount of compost applied to support seedlings growth is limited per hectare due to environmental restrictions (Määrus 2002). For example, the sewage sludge compost can contain some amount of heavy metals, which limits its usage (tonnes per hectare). The current method enables easy-to-measure application volume per hectare due to measurable dosage through the drill-holes' dimensions and their number per hectare. In addition, the compost portions are placed directly under the roots of the seedlings and are used up as the seedlings grow. Quick usage of compost with high nutrient content reduces the risk of the nutrients being displaced by soil water into other (protected) areas that may be sensitive to it (Dyderski et al. 2016).

This method can also be used in forestry for quick reforestation of clearcut areas. The need for quick and reliable reforestation comes both from regulations and economic need.

The sewage sludge compost used in the current study may cause **lack of potassium** for growing seedlings. In Table 4 the amount of potassium in the compost filling was around four grams. According to Uri et al. (2003) the above-ground part of an average grey alder seedling used around three grams of potassium during the first four years of growth. If a similar consumption rate is expected from black alder and silver birch species, a need for additional potassium will arise in the fifth year of growth. One possible solution for the elimination of the potassium depletion problem is to add wood ash to the sewage compost (Lazdina et al. 2013). Wood ash is a plentiful source of potassium (Huotari et al. 2008, Pärn et al. 2009, Mandre et al. 2010, Kikamägi et al. 2013) that enables remarkable results in seedling growth in afforestation.

It is advisable to perform a test application of sewage compost and wood ash together on cutover peatland in afforestation. If it is necessary to insert ash and compost separately into the planting holes, ash should be inserted into the bottom of the planting holes, not on top of compost, in order to prevent a thick, impenetrable layer of hardened ash from forming (Neuschütz et al. 2006, 2010).

An additional reserve supply of the compost can be added between plants into the same size drill-holes as a reserve for the plants for their further usage, when plant roots grow in length and extend to the reserve compost-filled drill-holes. An additional reserve compost supply inserted at the same time of planting may reduce long-term operational costs in growing forest on cutover peatland. When this is done, the allowed limits must be followed (Määrus 2002).

Hazardous components that exist in planting-applied sewage sludge compost have been studied in the current test and were found to be below regulatory pollution thresholds, particularly heavy metals (Määrus 2002, Galbally et al. 2013, Nogueira et al. 2013). Some pharmaceutical residues like antibiotics (fluoroquinolones and sulphonamides) tend to decompose during composting (Lillenberg et al. 2010, Haiba et al. 2013).

Achieving **faster growth of dimensions**, as with the sewage sludge compost-treated silver birch seedlings most noticeably, leads to seedlings' quicker proliferation and their ability to occupy the soil between themselves and the space above ground faster, leaving less room for weeds to compete. Faster initial growth therefore enables faster and firmer afforestation.

Conclusions

The hypothesis was proved in many cases that the measured parameters that indicate the growth speed of the seedlings (stem height growth, roots' horizontal and vertical growth, and the longest leaf length) can be improved with the following treatments: sewage sludge compost, and fertiliser and drilled planting hole. Silver birch seedlings were more sensitive to the treatments compared to black alder seedlings.

In the current afforestation test, the afforestation criterion (1 m stem height) according to the currently valid regulations was achieved with one-year-old silver birch seedlings in only one growing season. However, with black alder one- and two-year-old seedlings, the goal was not achieved.

The results of the current study suggest that sewage sludge compost acts as a firm height growth accelerator. It can be suggested for spot application in planting silver birch seedlings on cutover peatland because its height growth-promoting effect achieved in the test (73 cm) was significantly greater (30 and 33%) compared to multicomponent fertiliser spot applications (56 and 55 cm).

According to the preliminary results described in the current work, it is justified to utilise sewage sludge compost with the spot application method in afforestation.

Acknowledgements

This study was supported by the Estonian Science Foundation, Grant No. 9258.

References

AOAC, 1990. Official methods of analysis. Helrich, K. (Ed.). 15th ed. In 2 vols. Association of Official Analytical Chemists, Arlington, Virginia, USA. 1230 pp.

ASA and SSSA, 1982. Methods of soil analysis. Part 2-Chemical and microbiological properties. A.L. Page , R.H. Miller and D.R. Keeney (Eds.). 2nd ed. Number 9 (Part 2) in the series AGRONOMY. American Society of Agronomy (ASA) and Soil Science Society of America (SSSA). Academic Press, New York. 24 pp. ISBN 0-89118-072-9 (pt. 2)

Dyderski, M.K., Czapiewska, N., Zajdler, M., Tyborski, J. and Jagodziński, A.M. 2016 Functional diversity, succession, and human-mediated disturbances in raised bog vegetation. *Science of the Total Environment* 562: 648-657. Available online at: http://dx.doi.org/10.1016/j.scitotenv.2016.04.102

EVS, 2003. European Standard EN 13657. EVS-EN 13657:2003 Characterization of waste – Digestion for subsequent determination of aqua regia soluble portion of elements. 7 pp. Available online at: https://www.evs.ee/eelvaade/evs-en-13657-2003-en.pdf. Last accessed: 14 October 2015.

EVS, 2002. European Standard EN 13806. EVS-EN 13806:2002. Foodstuffs - determination of trace elements - Determination of mercury by cold-vapour atomic absorption spectrometry (CVAAS) after pressure digestion. 14 pp. Available online at: https://www.evs.ee/eelvaade/evs-en-13806-2002-en.pdf Last accessed: 14 October 2015.

Fletcher, A.L., Moot, D.J. and Stone, P.J. 2008. Solar radiation interception and canopy expansion of sweet corn in response to phosphorus. *European Journal of Agronomy* 29(2-3): 80-87. Available online at: http://dx.doi.org/10.1016/j.eja.2008.04.003

Föhse, D. and Jungk, A. 1983. Influence of phosphate and nitrate supply on root hair formation of rape, spinach and tomato plants. *Plant and Soil* 74(3): 359-368. Available online at: http://dx.doi.org/10.1007/bf02181353

Galbally, P., Ryan, D., Fagan, C.C., Finnan, J., Grant, J. and McDonnell, K. 2013. Biosolid and distillery effluent amendments to Irish short rotation coppiced willow plantations: Impacts on groundwater quality and soil. *Agricultural Water Management* 116: 193-203. Available online at: http://dx.doi.org/10.1016/j.agwat.2012.07.010

González, E., Henstra, S.W., Rochefort, L., Bradfield, G.E. and Poulin, M. 2013. Is rewetting enough to recover *Sphagnum* and associated peat-accumulating species in traditionally exploited bogs? *Wetlands Ecology and Management* 22 (1): 49-62. Available online at: http://dx.doi.org/10.1007/s11273-013-9322-6

Gradeckas, Algimantas, Kubertavičienė, L. and Gradeckas, Audrius. 1998. Utilization of wastewater sludge as a fertilizer in short rotation forests on cut away peatlands. *Baltic Forestry* 4 (2): 7-13.

Granier, C. and Tardieu, F. 2009. Multi-scale phenotyping of leaf expansion in response to environmental changes: the whole is more than the sum of parts. *Plant, Cell and Environment* 32(9): 1175-1187. Available online at: http:/ /dx.doi.org/10.1111/j.1365-3040.2009.01955.x

Haiba, E., Nei, L., Lillenberg, M., Kipper, K. and Herodes, K. 2013. Degradation of some pharmaceuticals during sewage sludge composting. *Global Journal on Advances in Pure & Applied Sciences* 1: 827-832. Available online at: http://www.world-education-center.org/index.php/paas/article/view/2503/3580 Last accessed: 31 March 2016.

Hasanuzzaman, M., Ali, M.H., Karim, M.F., Masum, S.M. and Mahmud, J.A. 2012. Response of hybrid rice to different levels of nitrogen and phosphorus *International Research Journal of Applied and Basic Sciences* 3 (12): 2522-2528. Available online at: http://www.irjabs.com/files_site/paperlist/r_544_121122163610.pdf Last accessed: 30 January 2016.

Hodge, A. 2004. The plastic plant: root responses to heterogeneous supplies of nutrients. *New Phytologist* 162(1): 9-24. Available online at: http://dx.doi.org/10.1111/j.1469-8137.2004.01015.x

Holden, J., Chapman, P.J. and Labadz, J.C. 2004. Artificial drainage of peatlands: hydrological and hydrochemical process and wetland restoration. *Progress in Physical Geography* 28 (1): 95-123. Available online at: http://dx.doi.org/10.1191/0309133304pp403ra

Huotari, N., Tillman-Sutela, E., Kauppi, A. and Kubin, E. 2007. Fertilisation ensures rapid formation of ground vegetation on cut-away peat land. *Canadian Journal of Forest Research* 37: 874–883. Available online at: http://dx.doi.org/10.1139/x06-292

Huotari, N., Tillman-Sutela, E., Pasanen, J. and Kubin, E. 2008. Ash-fertilization improves germination and early establishment of birch (*Betula pubescens* Ehrh.) seedlings on a cut-away peatland. *Forest Ecology and Management* 255: 2870–2875. Available online at: http://dx.doi.org/10.1016/j.foreco.2008.01.062

Hytönen, J. 2016. Wood Ash Fertilisation Increases Biomass Production and Improves Nutrient Concentrations in Birches and Willows on Two Cutaway Peats. *Baltic Forestry* 22(1): 98-106.

ISO, 1998. ISO 11047:1998. Soil – Quality – Determination of cadmium, chromium, cobalt, copper, lead, manganese, nickel and zinc in aqua regia extracts of soil – Flame and electrochemical atomic absorption spectrometric methods. Edition : 1. Publication date : 1998-05. 18 pp. Available online at: http://www.iso.org/iso/iso_catalogue/catalogue _tc/catalogue_detail.htm?csnumber=24010 Last accessed: 14 October 2015.

Jarašius, L., Lygis, V., Stendžikaitė, J. and Pakalnis, R. 2015. Effect of Different Hydrological Restoration Measures in Akštumala Raised Bog Damaged by Peat Harvesting Activities. *Baltic Forestry* 21(2): 192-203.

Jordan-Meille, L. and Pellerin, S. 2004. Leaf area establishment of a maize (*Zea mays* L.) field crop under potassium deficiency. *Plant and Soil* 265(1-2): 75-92. Available online at: http://dx.doi.org/10.1007/s11104-005-0695-z

Järvis, J., Ivask, M., Nei, L., Kuu, A. and Luud, A. 2016. Effect of Green Waste Compost on Afforestation Success. *Baltic Forestry* 22(1): 90-97.

Kāposts, V., Kariņš, Z. and Lazdiņš, A. 2000. Use of Sewage Sludge in Forest cultivation. *Baltic Forestry* 6 (2): 24-28.

Kikamägi, K., Ots, K. and Kuznetsova, T. 2013. Effect of wood ash on the biomass production and nutrient status of young silver birch (*Betula pendula* Roth) trees on cutaway peatlands in Estonia. *Ecological Engineering* 58: 17-25. DOI: 10.1016/j.ecoleng.2013.06.014 Available online at: https://www.researchgate.net/publication/273541119_Effect_of_wood_ash_on_the_biomass_production_and_nutrient_status_of_young_silver_birch_Betula_pendula_Roth_trees_on_cutaway_peatlands_in_Estonia

Koch, J.M., and Pickersgill, G.E. 1984. Timing and Placement of Fertilizer Application for Planted Eucalyptus Seedlings on Rehabilitated Bauxite Mined Areas. *Environmental Research Note Number 10.* Alcoa Australia Limited, Perth, W.A. 7 pp. Available online at: https://www.alcoa.com/australia/en/pdf/Research_Note_No_10.pdf Last accessed: 04 February 2016.

Kõiv, M., Ostonen, I., Vohla, C., Mõtlep, R., Liira, M., Lõhmus, K., Kirsimäe, K. and Mander, Ü. 2012. Reuse potential of phosphorus-rich filter materials from subsurface flow wastewater treatment filters for forest soil amendment. *Hydrobiologia* 692 (1): 145"156. Available online at: http://dx.doi.org/10.1007/s10750-011-0944-5

Lachance, D., Lavoie, C. and Desrochers, A. 2005. The impact of peatland afforestation on plant and bird diversity in southeastern Québec. *Ecoscience* 12 (2): 161-171. Available online at: http://dx.doi.org/10.2980/i1195-6860-12-2-161.1

Lazdiņa, D., Liepiņš, K., Bārdule, A., Liepiņš, J. and Bārdulis, A. 2013. Wood ash and wastewater sludge recycling success in fast-growing deciduous tree – birch and alder plantations. *Agronomy Research* 11(2): 347–356. Available online at: https://www.researchgate.net/publication/242024629_Wood_ash_and_wastewater_sludge_recycling_success_in_fast-growing_deciduous_tree_-_ Birch_and_alder _plantations Last accessed: 16 October 2015.

Lillenberg, M., Yurchenko, S., Kipper, K., Herodes, K., Pihl, V., Lõhmus, R., Ivask, M., Kuu, A., Kutti, S., Litvin, S. V. and Nei, L. 2010. Presence of fluoroquinolones and sulphonamides in urban sewage sludge and their degradation as a result of composting. *International Journal of Environmental Science and Technology* 7(2): 307–312. Available online at: http://dx.doi.org/10.1007/bf03326140

Lin, C.H., Lu, Y.C., Chiu, C.W. 1996. Development of a vertical fertilization applicator for fruit orchard. *Bulletin of the Hualien District Agricultural Improvement Station* 9: 33. Available online at: http://www.hdares.gov.tw/htmlarea_file/web_articles/hdais/1996/3.pdf Last accessed: 08 February 2016.

López, S.M., Sánchez J.M., Sirvent, C.P., Bech, J., Martínez M.C.G. and Fernandez, A.J.G. 2014. Screening of wild plants for use in the phytoremediation of mining-influenced soils containing arsenic in semiarid environments. *Journal of Soils and Sediments* 14: 794. doi:10.1007/s11368-013-0836-6. Available online at: http://link.springer.com/article/10.1007/s11368-013-0836-6/fulltext.html 10.1007/s11368-013-0836-6. Last accessed: 17 January 2014.

Londo, A.J. and Mroz, G.D. 2001. Bucket Mounding as a Mechanical Site Preparation Technique in Wetlands. *Northern Journal of Applied Forestry* 18 (1): 7-13. Available online at: http://www.ingentaconnect.com/content/saf/njaf/2001/00000018/00000001/art00001 Last accessed: 02 September 2016.

Mandre, M., Pärn, H., Klõšeiko, J., Ingerslev, M., Stupak, I. Kört, M. and Paasrand, K. 2010. Use of biofuel ashes for fertilisation of *Betula pendula* seedlings on nutrient-poor peat soil. *Biomass and Bioenergy* 34(9): 1384-1392. Available online at: http://dx.doi.org/10.1016/j.biombioe.2010.04.015

McLaren, R.G. and Smith, C.J. 1996. Issues in the disposal of industrial and urban wastes. Contaminants and the Soil Environment in the Australasia-Pacific Region. Kluwer Academic Publishers, pp. 183-212. Available online at: http://link.springer.com/chapter/10.1007/978-94-009-1626-5_6. Last accessed: 09 March 2016.

Müller, I., Schmid, B. and Weiner, J. 2000. The effect of nutrient availability on biomass allocation patterns in 27 species of herbaceous plants. *Perspectives in Plant Ecology, Evolution and Systematics* 3(2): 115-127. Available online at: http://dx.doi.org/10.1078/1433-8319-00007

Nei, L., Lillenberg, M., Haiba, E., E.Kipper, K. and Herodes, K. 2011. Pharmaceuticals in Sewage Sludge Compost and Their Uptake from Fertilized Soil by Food Plants. Abstract Book: Society of Environmental Toxicology and Chemistry North America 32nd Annual Meeting. Boston, Massachusetts, p. 241.

Neuschütz, C., Stoltz, E. and Greger, M. 2006. Root Penetration of Sealing Layers Made of Fly Ash and Sewage Sludge. *Journal of Environment Quality* 35(4): 1260-1268. Available online at: http://dx.doi.org/10.2134/jeq2005. 0229

Neuschütz, C., Boström, D. and Greger, M. 2010. Root growth into sealing layers of fly ash. *Journal of Plant Interactions* 5(2): 75-85. Available online at: http://dx.doi.org/10.1080/17429141003592853

Niinemets, Ü., Portsmuth, A. and Truus, L. 2002. Leaf Structural and Photosynthetic Characteristics, and Biomass Allocation to Foliage in Relation to Foliar Nitrogen Content and Tree Size in Three Betula Species. Annals of Botany 89(2): 191–204. Available online at: http://dx.doi.org/10.1093/aob/mcf025

Nilsson, T. and Lundin, L. 1996. Effects of drainage and wood ash fertilization on water chemistry at a cutover peatland. *Hydrobiologia* 335 (1): 3-18. Available online at: http://dx.doi.org/10.1007/bf00013678

Nogueira, T.A.R., Franco, A., He, Z., Braga, V.S., Firme, L.P. and Abreu-Junior, C.H. 2013. Short-term usage of sewage sludge as organic fertilizer to sugarcane in a tropical soil bears little threat of heavy metal contamination. *Journal of Environmental Management* 114: 168-177. Available online at: http://dx.doi.org/10.1016/j.jenvman.2012.09.012

Pearson, M., Saarinen, M., Minkkinen, K., Silvan, N. and Laine, J. 2011. Mounding and scalping prior to reforestation of hydrologically sensitive deep-peated sites: factors behind Scots pine regeneration success. *Silva Fennica* 45(4): 647-667. Available online at: http://dx.doi.org/10.14214/sf.98.

Pietrzykowski, M., Daniels, W.L. and Koropchak, S.C. 2015. Microtopographic effects on growth of young bald cypress (*Taxodium distichum* L.) in a created freshwater forested wetland in southeastern Virginia. *Ecological Engineering* 83: 135-143. Available online at: http://dx.doi.org/10.1016/j.ecoleng.2015.06.024

Pikk, J. 2001. Kased turvasmuldadel. [Birches on peatlands]. – Tullus, H., Vares, A. (Editors), Lehtpuupuistute kasvatamine Eestis. [Silviculture of deciduous in Estonia]. *Akadeemilise Metsaseltsi Toimetised* [*Proceedings of the Estonian Academical Forestry Society*], 14. Eesti Põllumajandusülikool, Metsanduslik Uurimisinstituut, Tartu: 95–102 (in Estonian with English abstract).

Pikka, J. 2005. Use of wastewater sludge for soil improvement in afforesting cutover peatlands. *Forestry Studies*, 42, 95–105. ISSN 1406-9954. Available online at: http://mi.emu. ee/userfiles/instituudid/mi/MI/FSMU/2005/42/mets_42-9.pdf. Last accessed: 03 October 2016.

Pikka, J. 2006. Effect of fertilization with wastewater sludge on the development of *Betula pendula* seedlings under experimental conditions. *Eesti Teaduste Akadeemia Toimetised*. Bioloogia. Ökoloogia, [Proceedings of the Estonian Academy of Sciences. Biology. Ecology], 55(2), 160 - 172. Available online at: http://www.kirj.ee/public/va_%20bo/bio-2006-2-6.pdf. Last accessed: 16 October 2015.

Pärn, H., Mandre, M. and Tilk, M. 2009. Changes in the Growth of Silver Birch (*Betula pendula Roth*) and Black Alder (*Alnus glutinosa* (L.) Gaertn.) Seedlings on Peat Soils Fertilised with Wood and Peat Ashes. *Baltic Forestry* 15(2): 168-176.

Rahman, S. and Barmon, B.K. 2015. Productivity and efficiency impacts of Urea Deep Placement technology in modern rice production: An empirical analysis from Bangladesh. *The Journal of Developing Areas* 49(3): 119-134. Available online at: http://dx.doi.org/10.1353/jda.2015.0158

Raid, L. 1979. Külvikultuuride väetamisest jääksoodel. [Fertilization of seedlings in peatlands]. *Mets. Puit. Paber* [*Forest. Wood. Paper*] 6: 16–18 (in Estonian).

Raid, L. 1986. Metsakultuuride väetamine. [Fertilization of cultivated forests]. *Mets. Puit. Paber* [*Forest. Wood. Paper*] 5: 7–10 (in Estonian).

Raudväli, E. and Kanger, J. 1996. Muld taimetoitainete allikana [Soil as a Source of Plant Nutrients]. In: Kärblane, H. (Ed.). Taimede toitumise ja väetamise käsiraamat [Handbook of Plants Nutrition and Fertilization]. Eesti Vabariigi Põllumajandusministeerium, Tallinn, p. 274-275 (in Estonian).

Ruseckas, J., Grigaliūnas, V., Suchockas, V., and Pliūra, A. 2015. Influence of Ground Water Table Depth, Ground Vegetation Coverage and Soil Chemical Properties on Forest Regeneration in Cutovers on Drained Fen Habitats. *Baltic Forestry* 21(1): 152-161.

Määrus [Regulation] 2002. Keskkonnaministri 30. detsembri 2002. a määrus nr 78 "Reoveesette põllumajanduses, haljastuses ja rekultiveerimisel kasutamise nõuded". [Regulation No. 78 of Minister of the Environment as of 30 December 2002 "Requirements for Use of Sewage Sludge in Agriculture, Landscaping and Recultivation"]. 8 pp. (in Estonian). Available online at: http://www.estlex.ee/tasuta/?id=7&aktid=52424&fd=1&leht=1. Last accessed: 31 March 2016.

Määrus [Regulation] 2006. Keskkonnaministri 27. detsembri 2006. a määrus nr 88 "Metsa majandamise eeskiri". [Regulation No. 88 of Minister of the Environment of 27 December 2006 "Rules of Forest Management"]. 14 pp. (in Estonian). Available online at: http://www.estlex.ee/tasuta/?id=7&aktid=80177&fd=1&leht=1 Last accessed: 23 September 2016.

RMK Tartu Tree Nursery, 2015. Seed and Plant Management Department. Available online at: http://www.rmk.ee/organisation/contact-information/seed-and-plant-management-department Last accessed: 07 May 2015.

Schulte, E.E. 1995. Recommended Soil Organic Matter Tests. In: Sims, J.T., Wolf, A. (Eds) Recommended Soil Testing Procedures for the Northeastern United States. *Northeast Regional Bulletin* 493. Agricultural Experiment Station, University of Delaware, Newark, pp. 47-56.

Silvan, N. and Hytönen, J. 2016. Impact of Ash-Fertilization and Soil Preparation on Soil Respiration and Vegetation Colonization on Cutaway Peatlands. *American Journal of Climate Change* 05(2): 178-192. Available online at: http://dx.doi.org/10.4236/ajcc.2016.52017

Toomiste, H. 2015. Personal communication with technologist of sewage plant AS Tartu Veevärk, Mr Toomiste. Available online at: http://www.tartuvesi.ee/kontakt Last accessed: 07 May 2015.

Triisberg, T., Karofeld, E. and Paal, J. 2013. Factors affecting the re-vegetation of abandoned extracted peatlands in Estonia: a synthesis from field and greenhouse studies. *Estonian Journal of Ecology* 62(3): 192–211. ISSN 1736-7549 (electronic). Available online at: http://dx.doi.org/10.3176/eco.2013.3.02

Uri, V., Tullus, H. and Lõhmus, K. 2003. Nutrient allocation, accumulation and above-ground biomass in grey alder and hybrid alder plantations. *Silva Fennica* 37(3): 301–311. Available online at: http://dx.doi.org/10.14214/sf.490

Valk, U. 1992. Turbaväljakute metsastamiskatsete tulemustest. [The results of forestation of peatlands]. *Eesti Mets* [*Estonian Forest*], 4–5, 13–16. (in Estonian).

Valluru, R., Vadez, V., Hash, C.T. and Karanam, P. 2010. A minute P application contributes to a better establishment of pearl millet (*Pennisetum glaucum* (L.) R. Br.) seedling in P deficient soils. *Soil Use and Management*

26 (1): 36-43. Available online at: http://dx.doi.org/10.1111/j.1475-2743.2009.00245.x

Vares, P. 2016. Personal communication with the production manager of AS Tartu Jõujaam (local fuel company). Available online at: http://www.fortumtartu.ee Last accessed: 20 September 2016.

Vavříček, D., Pecháček, J., Jonák, P. and Samec, P. 2010. The effect of point application of fertilizers on the soil environment of spread line windrows in the Krušné hory Mts. *Journal of Forest Science* 56(5): 195–208. Available online at: http://www.agriculturejournals.cz/publicFiles/21082.pdf Last accessed: 27 January 2016.

Yara, 2015. Kemikaalit [Chemicals]. Yara Suomi Oy (in Finnish). Available online at: www.yara.fi. Last accessed: 14 October 2015.

Watson, G.W. 1994. Root Growth Response to Fertilizers. *Journal of Arboriculture* 20(1): 4-8. Available online at: http://joa.isa-arbor.com/articles.asp?JournalID=1&VolumeID=20&IssueID=1 Last accessed: 20 April 2016.

Zia, M.S., Amin, R., Qayum, F.E. and Aslam, M. 1988. Plant Tissue Concentration and Uptake of Phosphorus by Maize as Affected by Level of P Fertilizer. *Pakistan Journal of Agricultural Research* 9(3): 335-338. Available online at: http://www.cabi.org/gara/FullTextPDF/Pre2000/19900732014.pdf Last accessed: 24 January 2015.

Received 23 April 2016
Accepted 24 February 2017